WHITE PAPER

Testing PAs under Digital Predistortion and Dynamic Power Supply Conditions

CONTENTS

Introduction

Throughout the history of wireless communications, researchers have found ways to pack more information into wireless communications channels. The evolution of mobile technology, from AMPS (1G) to LTE Advanced (4G), has introduced a myriad of multichannel, multicarrier, and multiple-access schemes to more efficiently use spectrum.

In the early 2000s, new mobile standards such as UMTS and CDMA2000 were designed to use spread-spectrum technology to achieve improved spectral efficiency. At the same time, IEEE 802.11 was pioneering the use of orthogonal frequency division multiplexing (OFDM) technology to better take advantage of wideband channels through the use of orthogonal subcarriers. In 2011, the deployment of LTE introduced OFDM technology into mobile applications with the uplink using a variant of OFDM known as single-carrier frequency division multiple access (SC-FDMA).

	GSM	EDGE	UMTS	HSPA+	LTE	LTE-A
Generation	2G	2.75G	3G	3.5G	3.9G	4G
Max Data Rate	14 kbps	59.2 kbps	5.76 Mbps	100 Mbps	100 Mbps	3 Gbps
Max Bandwidth	200 kHz	200 kHz	5 MHz	20 MHz	20 MHz	100 MHz
Signal Structure/ Modulation	Single Carrier—GMSK	Single Carrier—8-PSK	WCDMA—QPSK	WCDMA—16-QAM	OFDM—64-QAM	OFDM—64-QAM
Typical PAPR	0 dB	2 dB	5.5 dB	6.5 dB	8–10 dB	8–12 dB

Table 1. Comparison of 3GPP Mobile Communications Standards

Although each evolution of wireless communications allows for higher data throughput, the resulting waveform complexity places stringent requirements on the physical radio. Not only do modern wireless radios use significantly wider bandwidths (up to 160 MHz for 802.11ac), but also signal characteristics such as the peak to average power ratio (PAPR) drive difficult linearity and efficiency requirements on RF power amplifiers.

To address these linearity and efficiency requirements, system designers frequently use linearization techniques such as digital predistortion (DPD) to improve linearity and use dynamic power supply (DPS) techniques such as envelope tracking (ET) or direct polar (DP) modulation to improve efficiency. The use of these techniques tasks engineers with new test methods and requirements. Today, key power amplifier (PA) metrics such as power added efficiency (PAE) or LTE adjacent channel leakage ratio (ACLR) must be measured under DPD or DPS conditions. This document examines test practices for several advanced PA test techniques including DPD and DPS.

Behavioral Characteristics of Power Amplifiers

To better understand the measurement techniques associated with testing DPD- or DPS-enabled PAs, you first need to investigate the behavioral characteristics of RF PAs. An ideal PA would produce constant gain across a range of power levels and supply voltage levels, but this is not the case in practice because the underlying transistor technology is inherently nonlinear. In addition, PA efficiency is a function of output power, with greater efficiency generally being achieved closer to the saturation point of the PA.

FIELD-EFFECT TRANSISTOR

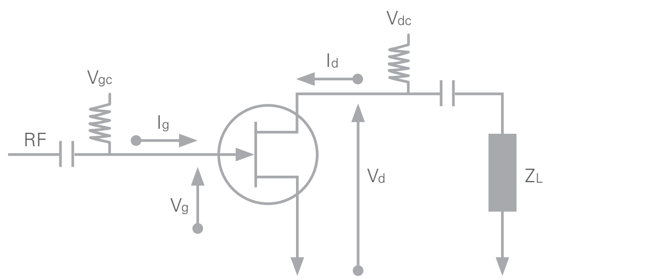


Figure 1. Block Diagram of Field-Effect Transistor

RELATIONSHIP OF POWER AND EFFICIENCY

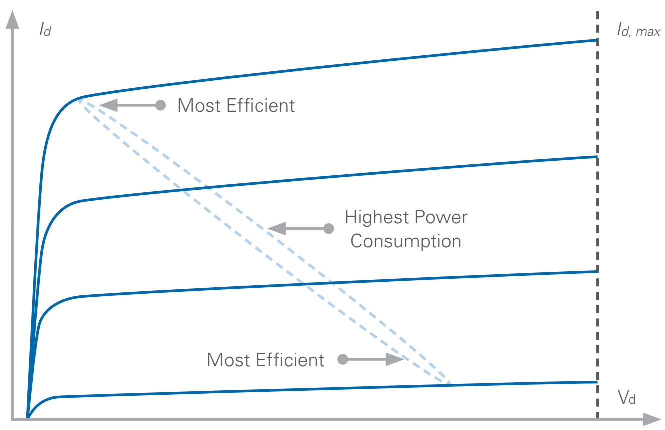


Figure 2. Fundamental Characteristic Curves of a Conceptual Field-Effect Transistor

You can examine the relationship between output power and efficiency by considering the characteristic curves of the field-effect transistor (FET) in figures 1 and 2. Observe that FET power consumption, which is the product of current and voltage, is minimal in operating ranges close to either the x-axis or y-axis. As a result, designers are motivated to keep the output signal as near to these axes as possible. By using the transistor across its full power range, including near these axes, the PA benefits from improved power efficiency. Thus, when optimizing a device for maximum efficiency, the peak of the waveforms should operate as close to the x-axis and y-axis as possible without introducing distortion.

AM-AM and AM-PM Measurements

One of the most fundamental methods to describe PA behavior is the AM-AM (amplitude modulation to amplitude modulation) and AM-PM (amplitude modulation to phase modulation) characteristics of a PA. Perhaps one of the best-known behavioral characteristics, AM-AM describes the output power as a function of input power. The phenomenon of PA gain decreasing as the PA enters compression at higher output power can be described by the AM-AM behavior in Figure 3.

PHASE DISTORTION AS A RESULT OF PA COMPRESSION

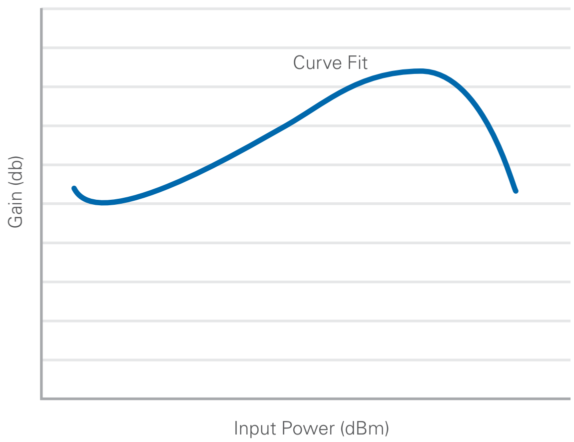
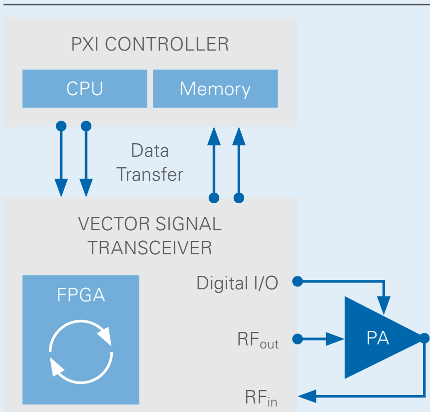


Figure 3. AM-AM (Gain) Behavior of a Nonlinear PA in Compression

Fast Power Level Servoing Using the NI Vector Signal Transceiver

A unique technology of the NI PA test solution is FPGA-based power level servoing using the NI Vector Signal Transceiver (VST). Power level servoing is traditionally a time-consuming process. However, you can achieve the fastest possible power level convergence by performing the control loop entirely on the instrument FPGA. If you decouple the power level servoing algorithm from the embedded controller and perform it on an FPGA, the test software can exploit dramatic measurement parallelism. This results in significant reductions in test time and test cost. For more information about fast power measurements using the NI VST, visit FPGA Servoing for Power Amplifier Test.

PXI SYSTEM



Similar to AM-AM, the AM-PM behavior describes the output phase of a PA as a function of input power and requires a stimulus to the PA at a range of input power levels. Figure 4 shows that as a PA approaches its output 1 dB compression point, the output phase of the signal becomes significantly distorted.

POWER ADDED EFFICIENCY

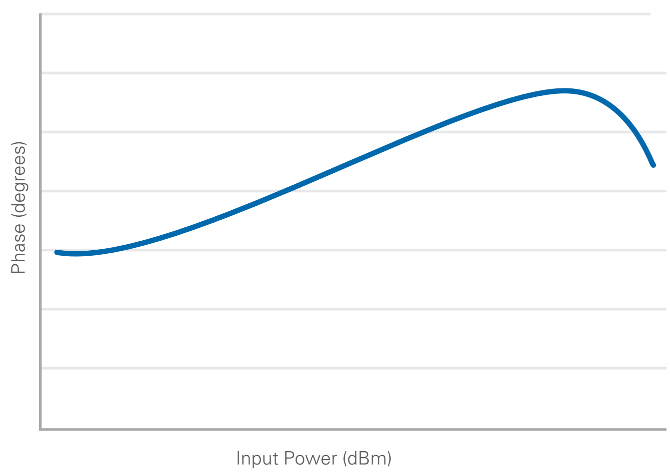
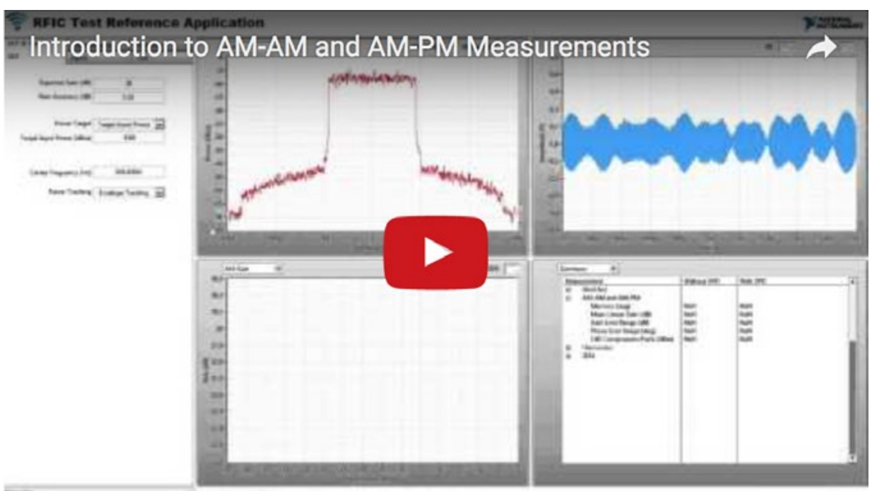


Figure 4. AM-PM Behavior of a Nonlinear PA



AM-AM and AM-PM distortion can have a significant impact on the modulation quality of wireless communications signals. In a linear PA, the output phase and magnitude of the modulated signal are not distorted even at higher output powers. However, in a nonlinear PA, AM-AM distortion results in the compression of the magnitude of the output signal.

Figure 5 shows the compression in a modulated signal's magnitude using the constellation plot of a single-carrier, 64-QAM modulated signal. In this figure, observe that AM-AM distortion affects the outermost symbols most significantly because these are characteristic of a higher output power. Similar to how AM-AM affects magnitude, AM-PM distortion changes the phase of the output symbol. Visually, phase distortion appears as a rotation on the constellation plot. The resulting modulated signal is prone to a higher bit error rate (BER), and modulation quality metrics such as error vector magnitude (EVM) are degraded.

NORMAL VS. DISTORTED CONSTELLATION PLOT

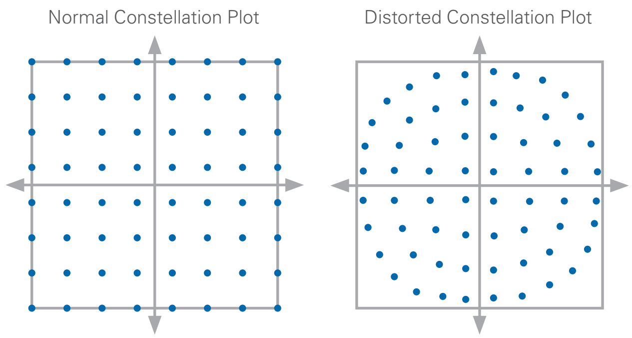


Figure 5. Constellation Plot of a 64-QAM Signal: Linear versus Compressed

Historically, the most common method to measure AM-AM/PM has involved conducting a power sweep with a vector network analyzer (VNA). Today, however, measuring this characteristic with a vector signal generator (VSG) and vector signal analyzer (VSA) is much more common. Because modern wireless communications signals use a wide range of power levels within a single waveform, you can measure AM-AM/PM behavior using power variations within the modulated waveform. For this approach, the AM-AM/PM measurement requires a simple comparison between the phase and magnitude of each input sample with each output sample. One of the benefits of using modulated waveforms to determine the AM-AM/PM characteristics is that you can evaluate the PA using the same type of waveform that it is ultimately designed to amplify.

Note that a given input signal can produce a range of measured output power and output phase results. At lower power levels, the spread in measured phase and magnitude is the result of the noise contribution. At higher power levels, the "spread" is often the result of PA memory effects. Because of this spread, software utilities for measuring AM-AM/PM typically use a curve fitting routine to determine the average response.

Memory Effects

Although behavioral characteristics such as AM-AM/PM are useful to describe the steady-state behavior of the RF PA, they do not fully depict all aspects of device behavior. In addition to these, PAs are subject to memory effects, which can be caused by frequency response, group delay, and thermal effects. Simply put, memory effects are those that describe the scenario where the current output signal level is not only a function of the current input signal level but also a function of previous input signal levels. These effects are most prevalent with amplitude-modulated signals and can result in signal distortion such as asymmetric ACLR or degraded EVM performance.

The consequences of PA memory on measured performance such as ACLR and EVM heavily depend on a range of factors. For example, these effects are often more pronounced near frequency band edges or when operating the device in a nonlinear region. Because memory effects are a result of many dependencies, they are not easily predicted. Additionally, they often require more sophisticated digital predistortion techniques if digital correction is desired.

You can both visualize and quantitatively measure the memory effects of a modulated signal by comparing the input and output waveform of a modulated signal in a manner that is similar to AM-PM behavior. However, instead of curve fitting the output phase of the PA, memory manifests itself as the phase and gain variation over output power. For example, Figure 6 compares the AM-PM response of a PA before (red trace) and after (blue trace) digital predistortion has been applied.

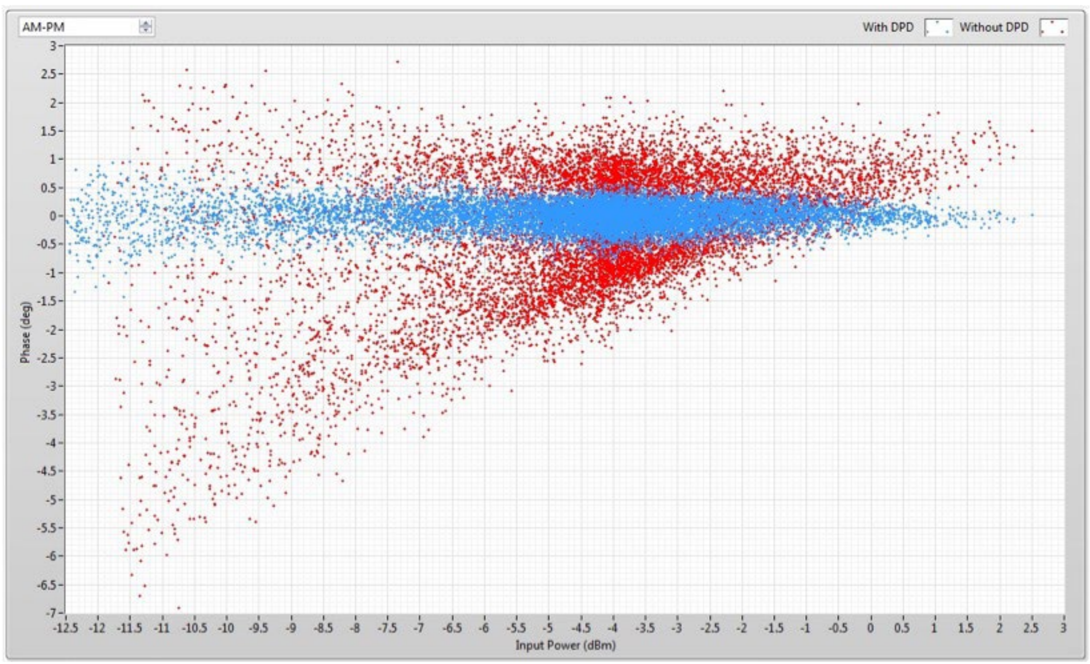


Figure 6. Memory effects are illustrated by the "spread" of samples on an AM-AM/PM plot.

Observe that the blue trace, which has less pronounced memory, has an RMS phase error of 0.22 degrees. By contrast, the red trace, which is subject to higher degrees of memory effects, has an RMS phase error of 0.72 degrees.

Measuring PA Behavior Using the NI Vector Signal Transceiver

The NI RFIC Test System uses PXI to measure various PA characteristics ranging from output power and gain to RMS memory. The NI RFIC Test System incorporates the unique NI Vector Signal Transceiver (VST). This instrument combines an RF signal generator, an RF signal analyzer, high-speed digital I/O, and a programmable FPGA into a single PXI module.

Understanding the Effects of Nonlinear Distortion

Although AM-AM and AM-PM measurements can provide a quantitative time-domain description of nonlinearity, you also can evaluate the effects of nonlinear distortion in the frequency domain. One of the simplest ways to visualize these effects is with a multitone signal. When introducing a two-tone signal to a nonlinear system such as a PA, distortion manifests itself as unwanted intermodulation distortion content both at the harmonics of the input tones and at the frequencies that are the sum and difference of each input tone frequency.

In a PA, third-order and often fifth-order intermodulation distortion products are some of the most challenging in a communications application. To better evaluate why this is the case, you can model the device response as an Nth order polynomial (see Figure 7). For example, the second-order distortion terms occur at every combination of fundamental terms. More specifically, second-order distortion results in spectral content at frequencies $f_2 - f_1$, $2f_1$, $f_1 + f_2$, and $2f_2$.

THEORY OF INTERMODULATION DISTORTION

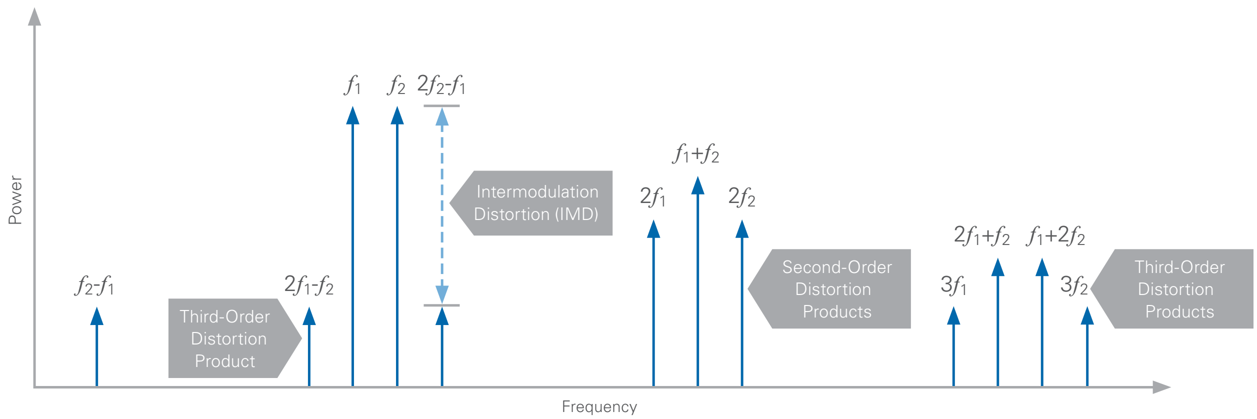


Figure 7. Intermodulation distortion products occur at various combinations of input tone frequencies.

Figure 7 also illustrates that some of the most troubling distortion products are the third-order terms. More specifically, third-order terms at frequencies $2f_2 - f_1$ and $2f_1 - f_2$ are adjacent to the fundamental signal of interest and have the potential to interfere with adjacent channels in a wireless environment. The ratio of these third-order distortion tones to the output of the fundamental signal is called third-order intermodulation distortion (IMD). The term intermodulation comes from the view that these two input signals are in a sense mathematically convolving with each other internally, similar to the behavior of a three-port RF device like a mixer.

Translating the principle of intermodulation distortion to a wideband modulated signal, you can imagine that a modulated signal is spectrally equivalent to an infinite set of discrete tones all intermodulating with each other. Thus, in the frequency domain, distortion affects a modulated signal similarly by producing spectral regrowth on either side of the wideband modulated signal.

INTERMODULATION DISTORTION ON A WIDEBAND MODULATED SIGNAL

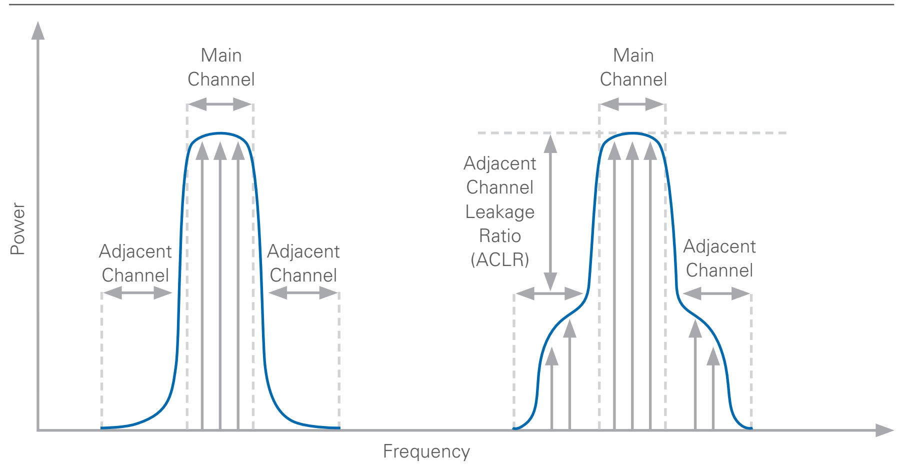


Figure 8. The Principle of Intermodulation Distortion Applied to a Wideband Modulated Signal

Wireless standards typically prescribe either a spectral mask (802.11) or an adjacent channel power measurement (UMTS and LTE) limit (shown in Figure 8) to ensure that a transmitter does not interfere with adjacent bands as a result of this fundamental behavior of a nonlinear transmitter. Although intermodulation is a spectral view of this distortion, significant ill effects are produced in the time domain as well. More specifically, in-band distortion as a result of nonlinearity also results in poor modulation accuracy.

Digital Predistortion (DPD)

DPD is a generic name for PA linearization techniques that correct for the nonlinear behavior of the device by modifying the complex waveform at the input prior to the digital-to-analog converter (DAC). DPD requires some degree of PA characterization or modeling, and correction techniques range from a basic look-up table (LUT) to full nonlinear Volterra series models.

GENERIC DPD

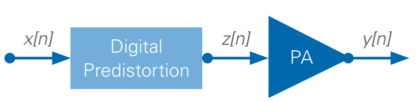


Figure 9. The DPD algorithm operates in the modulated input waveform.

Although engineers have historically reserved most DPD implementations for applications that required the highest PA linearity, such as base station PAs for multicarrier downlink signals, DPD technology today is becoming more widespread. The demands of modern communications signals such as LTE and 802.11ac, combined with the improved signal processing capabilities of mobile platforms, have made DPD more common in mobile devices as well. The use of DPD linearization techniques can significantly improve modulation quality and reduce unwanted spectral emissions into adjacent bands. Ultimately, DPD can increase the likelihood that a mobile device is compliant with radio conformance specifications dictated by a wireless standards body.

PA EFFICIENCY AND OUTPUT POWER

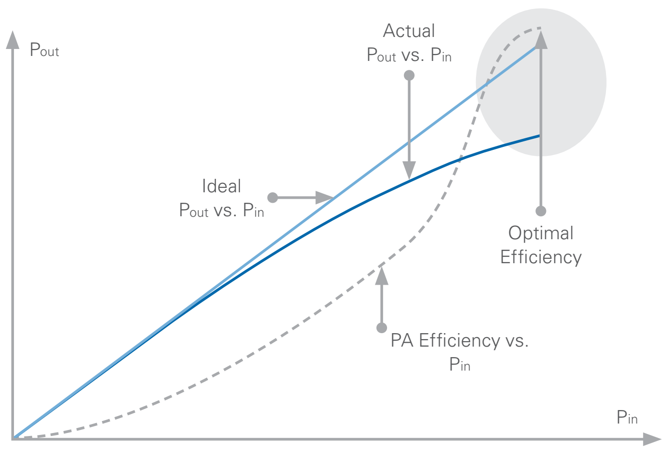


Figure 10. PA efficiency and output power are shown as a function of input power.

In PAs designed for wireless communications systems, the high PAPR characteristics of modern signals often produce a trade-off of linearity and low-power efficiency for nonlinearity and higher-power efficiency. As shown in Figure 10, the PA achieves its point of peak efficiency at an output level that approaches the saturation region of the amplifier. The benefit of DPD is that designers can push a PA into compression and achieve better efficiency while maintaining performance compliance. Alternatively, you can use DPD to correct for a physical design that is less linear but has better efficiency and/or cost than a truly linear design.

Effects of DPD on a Modulated Transmission

You can evaluate the performance benefit of linearization techniques like DPD on a modulated signal by measuring the improvement in modulation quality or out-of-band emissions. The benefits of DPD are often most clearly observed in the frequency domain with a reduction in spectral regrowth, as illustrated in Figure 11. In this figure, observe that DPD reduces spectral regrowth and increases the likelihood that a transmitter will adhere to the adjacent channel power (ACP) requirements of the standards body.

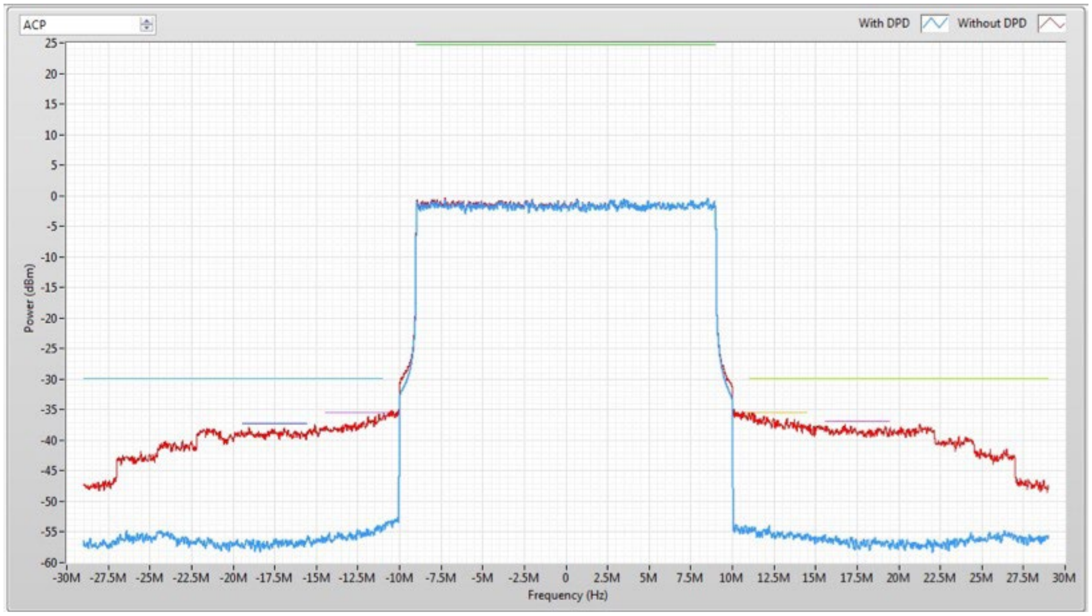


Figure 11. DPD reduces the spectral regrowth of modulated signals.

In addition, you can observe the benefits of DPD on modulation quality with a constellation plot. Figure 12 shows the compressed output of a distorted waveform on a single-carrier modulation scheme. In this figure, the top constellation plot shows both the phase and magnitude of each symbol of a modulated transmission. Here, observe that the peak portions of the signal experience less gain than other portions. Thus, by predistorting the waveform so that the higher power symbols are amplified, the nonlinear behavior of the PA actually corrects the predistorted waveform. The resulting PA output using a predistorted waveform produces a signal that appears to come from a highly linear transmitter despite it coming through a significantly nonlinear device.

EFFECTS OF DISTORTION ON A MODULATED SIGNAL

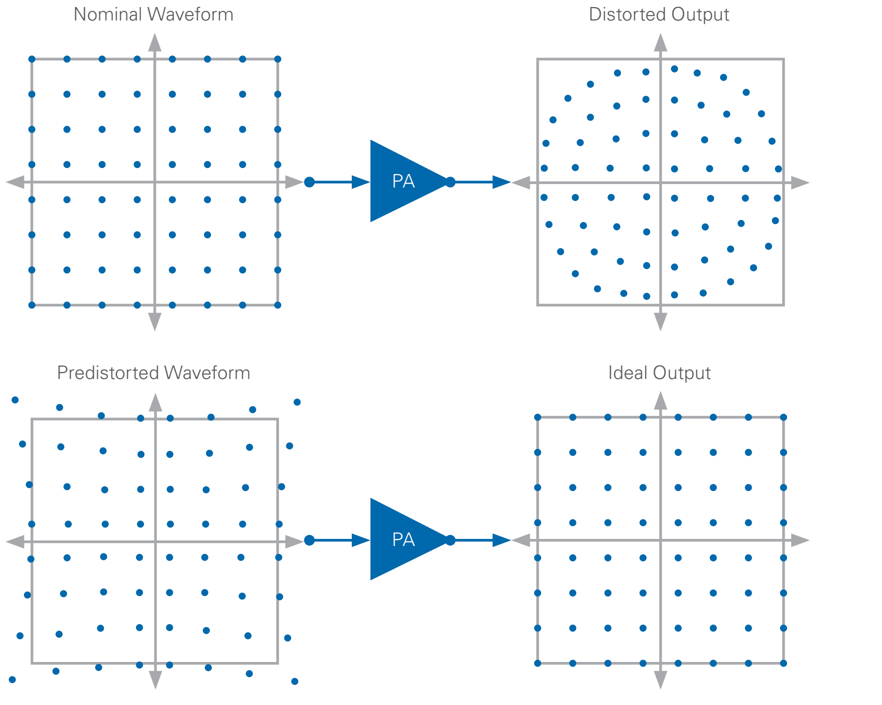


Figure 12. Predistortion improves the modulation quality of a transmission.

Although the basic principle of DPD is simple, performing corrections to maximize performance can be challenging in practice. The simplest distortion modes are visible with an AM-AM and AM-PM measurement and are easily corrected with a simple memoryless model. Devices that have more complex frequency, electrical, and thermal behaviors tend to exhibit memory effects that often require more advanced DPD algorithms. This document examines three algorithms in the following sections: memoryless look-up table, memory polynomial model, and generalized memory polynomial model.

Memoryless Look-Up Table (LUT)
PAs with negligible memory effects can be easily linearized with a simple LUT DPD algorithm. LUT-based DPD assumes that the instantaneous output signal distortion is a static memoryless function of the instantaneous input signal power. In this scenario, output sample N is merely a function of input sample n.

To calculate a DPD LUT, the test bench must first characterize the AM-AM and AM-PM behavior of the device. To measure this behavior, it then creates a mapping table that relates every input power/phase combination to the power/phase combination required to produce the desired linear output. The LUT DPD algorithm is visually simple to observe. In Figure 13, the nominal AM-AM response of the device is shown in blue and is clearly nonlinear. The grey line represents the ideal AM-AM response, which appears perfectly linear. Finally, the red line represents the numerically inverted AM-AM response and the LUT that must be applied to the stimulus to get a linear response. Note that the device can be linearized only up to a point of physical saturation, which is when the PA gain begins to drop off.

PREDISTORTION DPD COMPENSATION

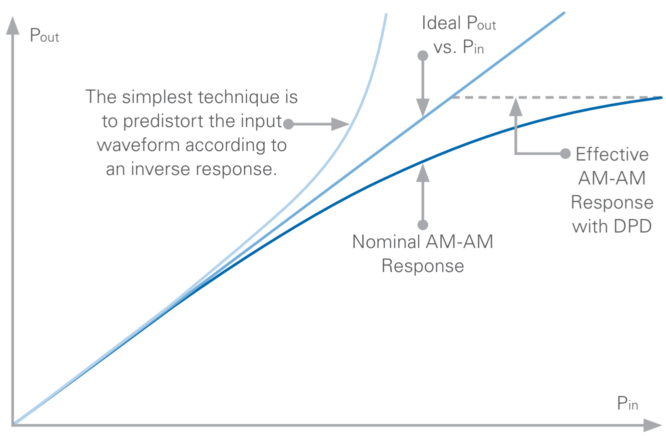


Figure 13. Predistortion DPD compensates for nominal AM-AM response.

Although Figure 13 illustrates the theoretical and corrected magnitude response of a PA, Figure 14 illustrates actual results from a physical part. Here, observe the AM-AM response of a device on a graph in which the y-axis has been normalized to gain. In red, the AM-AM (Gain) response illustrates that gain is clearly a function of input power and is, therefore, nonlinear. By contrast, the blue trace illustrates that the gain response has been linearized after applying a LUT DPD algorithm. Once DPD has been applied (blue trace), the average gain of the device deviates less than 1 dB across the same range of input power.

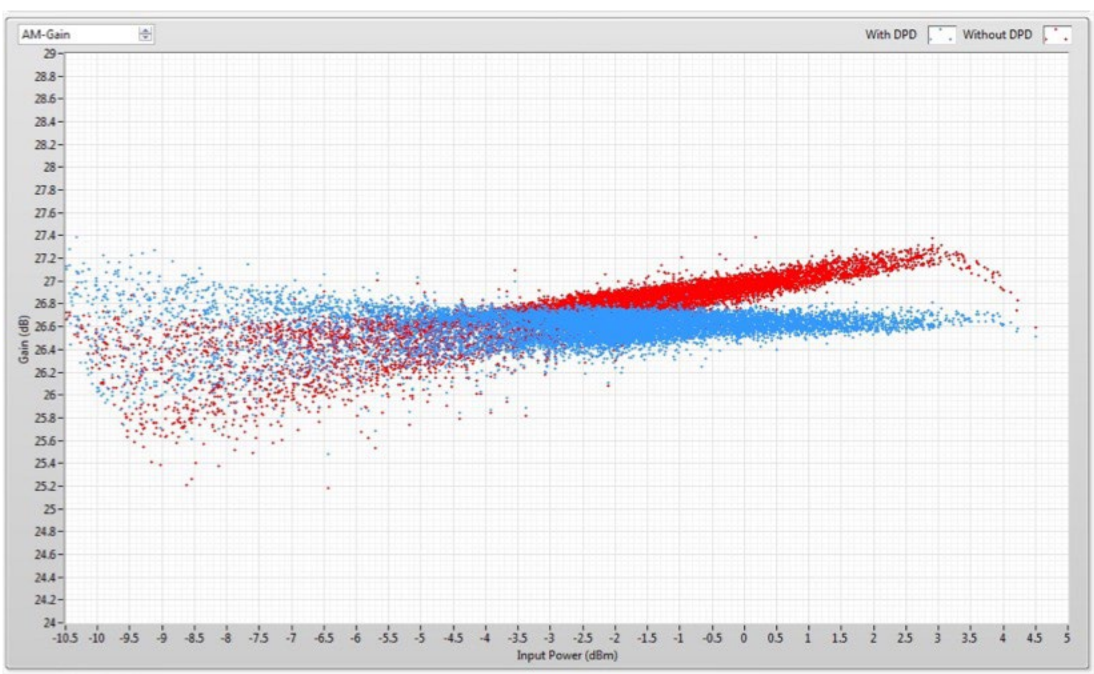


Figure 14. AM-AM (Gain) Response of the PA before and after LUT DPD

Although the LUT-based DPD approach is one of the simplest and most straightforward algorithms, it does not account for PA memory effects. These memory effects are visually apparent in both figures 13 and 14. In each of these figures, you can observe a substantial variation in the measured gain and phase on a sample-by-sample basis. The spread of the samples is evidence of residual memory effects. In addition, memory effects are often more exaggerated when the wideband frequency response of the device is not flat, similar to memory taps in a finite impulse response (FIR) filter. As a result, LUT-based DPD models are more effective when the signal bandwidth is relatively narrow and PA memory effects are small.

Digital Predistortion for PAs with Memory

Although the memoryless LUT is an effective and straightforward technique for PA linearization, it does not account for the memory effects of the PA. In PAs with memory, the instantaneous output power of the PA is a function not only of the input power but also past signal components. Mathematically, you can express the instantaneous output of a PA in Equation 1 as:

$$y(t) = f(x(\tau))$$

where:

$\tau \in (-\infty, t]$, f is a general nonlinear function
$x(t)$ is the input signal to the PA
$y(t)$ is the output signal from the PA

Equation 1. Instantaneous Output of a PA

The most straightforward approach to predistorting PAs with memory is to use models based on the Volterra series [2] as shown in Equation 2.

$$y[n] = h[0] + \sum_{q} h[q]x[n-q] + \sum_{q_1}\sum_{q_2} h[q_1, q_2]x[n-q_1]\,x[n-q_2] + \sum_{q_1}\sum_{q_2}\sum_{q_s} h[q_1, q_2, q_3]x[n-q_1]\,x[n-q_2]x[n-q_3] + \ldots$$

where:

$h[\ldots, q_i, \ldots]$ are voltage kernels
$x[n]$ is the discretized input signal to the PA
$y[n]$ is the discretized output signal from the PA

Equation 2. Modeling Device Behavior with a Volterra Series

To digitally compensate for PA memory and nonlinearity, the most general DPD structure takes the same form as Equation 2. Although the Volterra series provides a fairly complete model of a nonlinear system, the mathematical complexity is often undesirable. Systems with memory usually can be adequately modeled with only a subset of the terms in a full Volterra series. Common models based on this series include the memory polynomial, Wiener, and Hammerstein models.[1] Given their simplicity and widespread acceptance, the memory polynomial model and generalized memory polynomial model are some of the most common DPD algorithms used to evaluate PA behavior. For each of these algorithms, testing a PA under DPD conditions requires that the RF signal generator and analyzer have an instantaneous bandwidth that is three to five times the bandwidth of the fundamental waveform.

1 Martin Schetzen. "The Volterra and Wiener Theories of Nonlinear Systems" (1980).

Memory Polynomial Model (MPM)
The MPM is a well-known structure for memory and nonlinearity compensation.[2] This model is formed by taking a subset of terms from the Volterra series, as shown in Equation 3:

$$y[n] = \sum_{k=0}^{K-1} \sum_{q=0}^{Q} a_{k,q} x[n-q] \cdot |x[n-q]|^k$$

where:

$y[n]$ is the predistorted signal
$x[n]$ is the original input signal
$a_{k,q}$ are the DPD coefficients
K is the nonlinearity order
Q is the memory anticipated in the PA

Equation 3. Generalized Equation for the Memory Polynomial DPD Algorithm

Any cross terms involving x[n-q] and |x[n-q’]|k where q≠q’ are ignored in MPM. The coefficients a_{qk} are the DPD coefficients, K is the nonlinearity order, and Q is the memory anticipated in the PA.

Although the mathematics of implementing the MPM are complex, much of the derivation of the MPM model is often abstracted from the user by test software packages. You simply need to set the polynomial order and memory depth, and the algorithm will solve for coefficients and produce a predistorted waveform.

Generalized Memory Polynomial Model (GMP)
The GMP is a more sophisticated version of the MPM because it can correct for higher degrees of memory effects.[3] The equation of a GMP predistorter is mathematically similar to that of the MPM but with additional terms to account for the lag and lead between the

2 Lei Ding, et al. “Memory Polynomial Predistorter Based on the Indirect Learning Architecture,” Global Telecommunications (GLOBECOM) IEEE Conference and Exhibition 1.

3 Dennis R. Morgan, et al. “A Generalized Memory Polynomial Model for Digital Predistortion of RF Power Amplifiers,” IEEE Transactions on Signal Processing 54, no.10 (2006): 3852–60.

signal and envelope. These terms compensate for the staggered memory effects of the cross terms. For the purpose of further GMP discussion, review the following terms:

Expression	Type	Description
x[n]	Signal	Signal value at the current time index
x[n-q]	Signal	Signal value q samples before the current time index
$\|x[n]\|^k$	Envelope	Signal's k^{th} order envelope of the signal x[n]
$\|x[n-q]\|^k$	Envelope	Signal's k^{th} order envelope of the signal x[n-q]
$\|x[n-q-m]\|^k$	Envelope	Signal's k^{th} order envelope lagging behind the signal x[n-q] by m samples
$\|x[n-q+m]\|^k$	Envelope	Signal's k^{th} order envelope leading the signal x[n-q] by m samples

Equation 4 features a complex baseband representation of the GMP-based predistorter.

$$y[n] = \sum_{q=0}^{Q_a} \sum_{k=0}^{K_a-1} a_q x[n-q]|x[n-q]|^k + \sum_{q=0}^{Q_b} \sum_{m=1}^{M_b} \sum_{k=1}^{K_b} b_{mqk} x[n-q]|x[n-q-m]|^k + \sum_{m=1}^{M_c} \sum_{q=m}^{Q_c} \sum_{k=1}^{K_c} c_{mqk} x[n-q]|x[n-q+m]|^k$$

where:

K_a is sync order
Q_a is sync memory depth
K_b is lag order
Q_b is lag memory depth
M_b is maximum lag
K_c is lead order
Q_c is lead memory depth
M_c is maximum lead

Equation 4. The GMPM uses additional terms.

Similar to other DPD models, test solutions such as the NI RFIC Test System automate both model extraction and the implementation of the DPD GMP on a baseband waveform.

Typical settings you can adjust include both the depth and order of terms such as synchronization samples, memory lag, and memory lead.

Testing PAs under DPD Conditions

Given the growing use of DPD techniques in the final design of the mobile device, the importance of evaluating PA performance when applying a DPD model to the baseband waveform is increasing. Testing a PA under DPD conditions requires the test equipment to mimic the functionality of a DPD system. As a result, the test equipment must be able to extract a model of the PA and implement the linearizing DPD algorithm in software. The typical hardware configuration for a DPD test bench includes a VSG and a VSA as shown in Figure 15. A source measure unit (SMU) typically supplies the DC voltage, and can simultaneously measure current consumption. This hardware configuration can extract DPD models for both simple algorithms such as the LUT and more sophisticated models such as the GMP.

TYPICAL DPD TEST BENCH

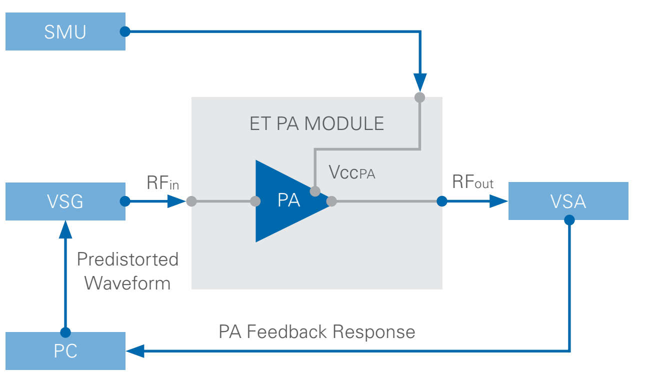
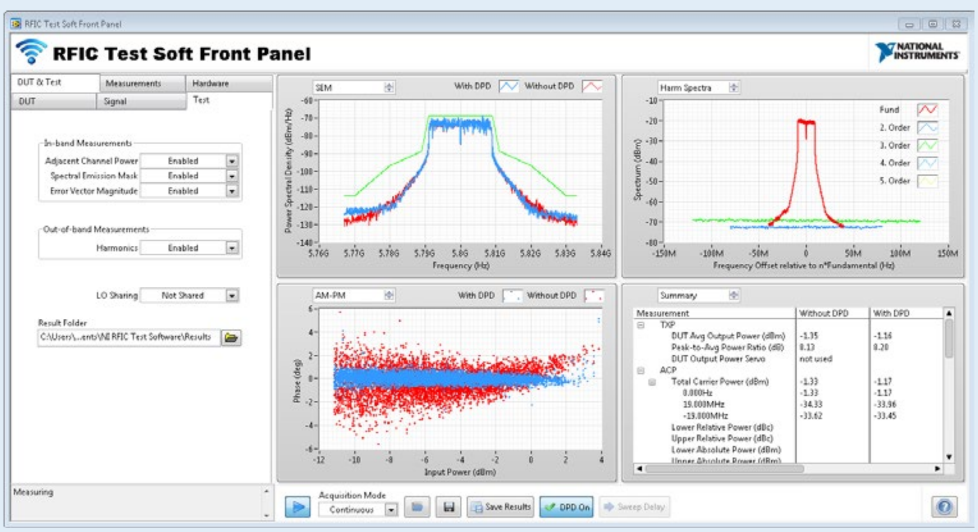


Figure 15. Typical DPD Test Bench

Applying DPD Using the NI RFIC Test Solution

The NI RFIC Test Solution provides easy-to-use LabVIEW example code to automate model extraction and DPD algorithm application. This solution works for common DPD models including the memoryless AM-AM/PM look-up table (LUT), the memory polynomial model (MPM), and the generalized memory polynomial model (GMP). You can also customize both the order and the number of taps when implementing the MPM or even use your own custom model. For more information, visit ni.com/pa.



Dynamic Power Supply Transmitters (Envelope Tracking)

Demand for the increased data capacity of wireless communications systems has resulted in more sophisticated modulation schemes. Early wireless standards such as GSM used Gaussian minimum shift keying (GMSK), and later evolutions such as EDGE used simple phase shift keying (8-PSK) techniques. By contrast, modern wireless standards such as 802.11ac and LTE use significantly higher-order modulation schemes such as 64-QAM and 256-QAM in conjunction with wideband carrier formats based on orthogonal frequency division multiplexing (OFDM) technology.

This combination of higher-order modulation and OFDM techniques is contributing to an expansion in signal peak to average power ratios (PAPRs) over earlier technology. To mitigate increases in PAPR, the LTE uplink uses a variation of OFDM known as single-carrier frequency division multiple access (SC-FDMA). Although the SC-FDMA technology's use of fast Fourier transform (FFT) precoding reduces the PAPR characteristics of the signal, LTE uplink signals can have a PAPR as high as 8 dB. In contrast, 802.11ac uses a more standard OFDM carrier structure, which yields PAPRs as high as 12 dB.

	GSM	UMTS	LTE (Uplink)	802.11ac
Carrier Structure	Single-Carrier	Wideband CDMA	SC-FDMA	OFDM
Modulation Scheme	GMSK	QPSK	64-QAM	256-QAM
PAPR	0.2 dB	3.5 dB	8 dB	12 dB

Table 2. PAPR Characteristics of Common Modulated Signals

The increasing PAPR of modern communications waveforms places more stringent linearity requirements on modern handset power amplifiers. High linearity is a key requirement that enables a PA to exhibit excellent modulation quality and spectral performance. Thus, for a traditional fixed power supply design, a PA must be linear across a wide range of output powers. This linearity requirement often forces the system designer to operate for the worst-case scenario and back off signal power from compression. Thus, PAs are often operated well below the peak power, where the device is less power efficient.

Introduction to Dynamic Power Supply Techniques

Using dynamic power supply transmitters (DPSTs) is an increasingly popular solution to the challenges introduced by high PAPR signals. This transmitter dynamically modulates the device power supply to keep it at a point of improved power efficiency throughout the power range of the waveform. An example of this is shown in Figure 16, where the supply voltage dynamically tracks the power envelope of the RF signal.

Although dynamic power supply techniques are not new, technological advances in DSP and wideband power supplies have made these techniques more viable for mobile platforms. As a result, mobile devices are increasingly adopting this technology to improve power consumption and ultimately extend battery life.

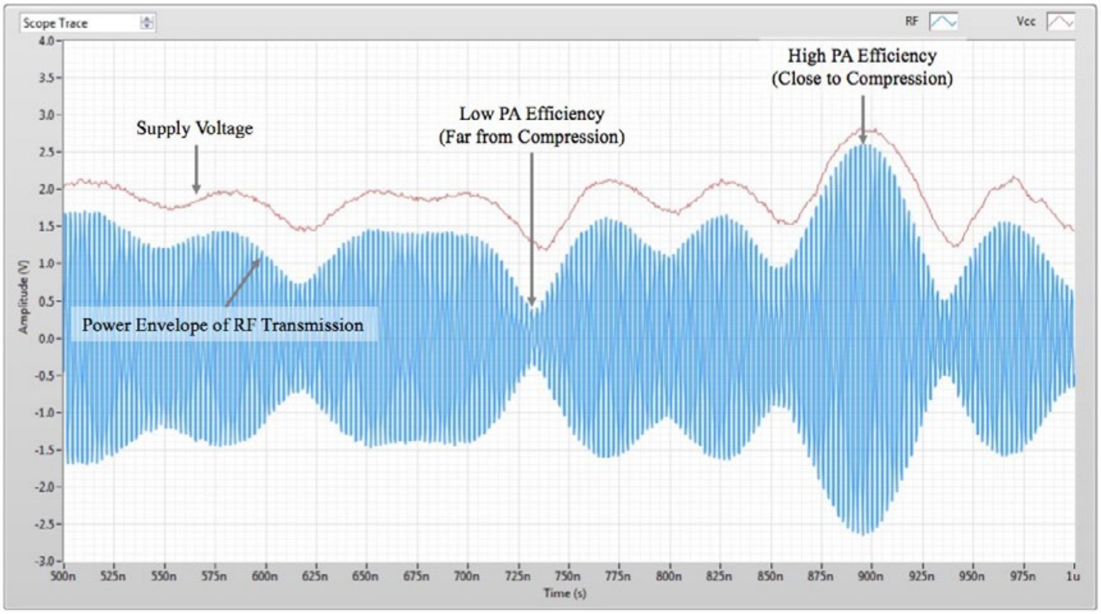


Figure 16. Time Domain View of a DPST Signal

You can evaluate the efficiency improvements due to DPST techniques by investigating the fundamental transistor characteristic behavior. Empirically, if you characterize a device's AM-AM response for various fixed power supplies, you find that the point of peak efficiency for a given output power is a function of the supply voltage. Figure 17 shows the power added efficiency (PAE) on the y-axis as a function of output power on the x-axis. In Figure 17, each line represents PAE versus output power for a unique supply voltage (V_{CC}).

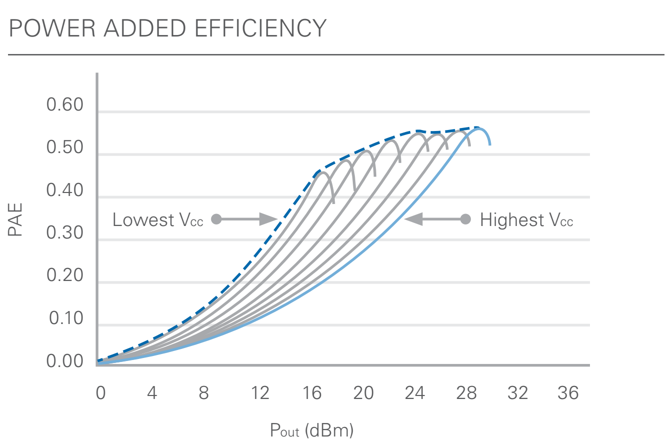


Figure 17. PAE versus Output Power for Various Supply Voltages

For example, suppose that a PA with a supply voltage of 3.4 V can achieve an efficiency of 55 percent and an output power of +28 dBm as shown in Figure 17. Moreover, with the same supply voltage level of 3.4 V, the efficiency drops to 20 percent at an output power of +16 dBm. Thus, when using a fixed power supply to transmit a signal with 12 dB PAPR (in this case, the peak output power is +28 dBm), the average efficiency is only 20 percent.

Because efficiency is a function of supply voltage and output power, one method to improve PA efficiency is to dynamically change the power supply so that the device is consistently operating near its point of peak efficiency. In this scenario, the aggregate efficiency of the device is described by combining the curves of multiple supply voltages. This aggregate is shown as a dotted line in Figure 17 and illustrates that 50 percent efficiency can be achieved across a wider range of output power.

Efficiency at the Transistor Level

You can examine the benefits of a dynamic power supply in more depth by evaluating the underlying transistor characteristic curves in Figure 18. As Figure 18 shows, for a given load impedance ZL, the large signal on the left (a) spends more time near the graph axis than the smaller signal on the right (b). For larger signals, the average product of current and voltage is minimized and power consumed is less than that consumed by a smaller signal. For the smaller signal case on the right (b), observe that the signal is spending most of the time in the middle of the graph where total power consumption is higher.

CHARACTERISTIC CURVE FOR A DYNAMIC POWER SUPPLY TRANSMITTER (DPST)

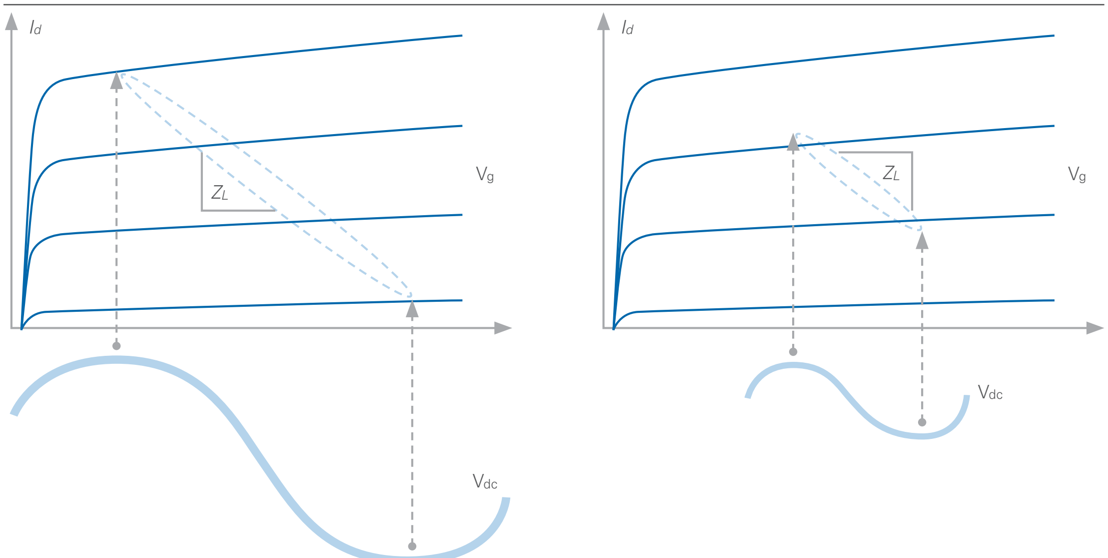


Figure 18. IV Characteristic Curve: (a) Large Signal Applied and (b) Small Signal Applied

The efficiency characteristics illustrated in Figure 18 fuel the need for a dynamic power supply transmitter (DPST) to modulate both V_g and V_{dc} synchronously with the rapidly changing power envelope of the RF signal. Figure 19 shows this concept with two discrete signal levels overlaid on the same characteristic curve. In Figure 19, observe that the transistor moving downward and to the left on the curve allows it to operate in a point of higher efficiency.

CHARACTERISTIC CURVE FOR A DPST

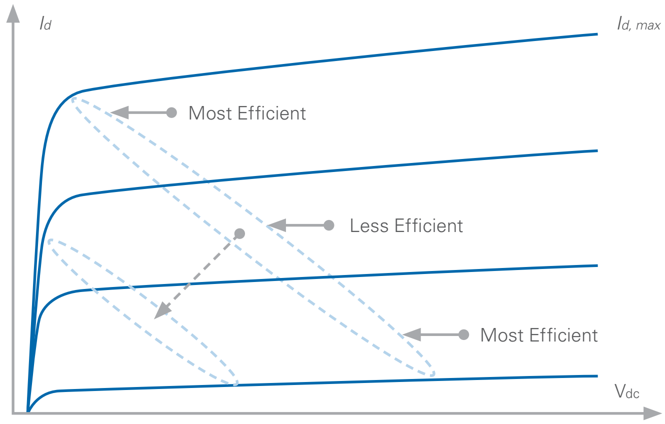


Figure 19. IV Characteristic Curve for a Dynamic Power Supply Transmitter (DPST): Two Signal Levels

Although the theory of power supply modulation to improve efficiency is simple, you can choose from several methods to apply this technique in practice. Each of these methods requires trade-offs in distortion versus efficiency. For example, when pursuing the design goal of reduced distortion, it is important to operate the transistor in linear mode. However, if the design goal is maximum efficiency at the expense of distortion, then operating the PA deep into compression is beneficial.

DPST devices offer three distinct operating modes: direct polar, envelope tracking (ET), and hybrid combinations. The distinction between each operating mode is related to the linear and compression regions of the AM-AM curve as shown in Figure 20. For a given power supply voltage if the device is well within the linear range, the device is said to be in envelope tracking mode. This is the most common mode of operation because it is easier to implement than the other two modes. When operating the device deep in compression, it is said to be in direct polar mode. This term emphasizes how the device is behaving as a three-port RF device and performing polar modulation.

COMPRESSION MODE, LINEAR MODE, AND HYBRID MODE

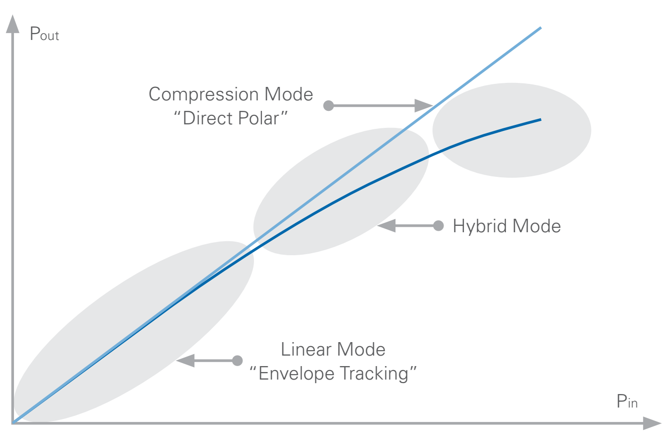


Figure 20. DPST Direct Polar, Envelope Tracking, and Hybrid Operating Modes

Note that in direct polar mode, the RF output signal power is actually independent of the RF input signal power. As a result, the device is operating similar to a mixer. In this mode, all modulation on the output comes only from the power supply signal. Often devices vary between direct polar and envelope tracking modes and thus are said to be a hybrid combination.

Understanding the fundamental characteristics of each operating mode is key to successfully implementing a dynamic power supply technique. For example, when operating in compression mode or hybrid mode, noise from the power supply is transmitted on the device RF output signal. Also, in compression mode, the synchronization and timing alignment between the power supply and the RF is more important. Note that timing alignment is somewhat less critical when operating the device in envelope tracking mode. For deeper insight into the theory, practical considerations, and technology survey for DPST designs, consider reading *Dynamic Power Supply Transmitters: Envelope Tracking, Direct Polar, and Hybrid Combinations*, written by Earl McCune and published by Cambridge University Press.

Testing Dynamic Power Supply PAs

Testing a PA's behavior for use in a DPST design requires a flexible, multifunction bench environment. A typical test bench includes a source measure unit (SMU) combined with an RF signal generator and analyzer as shown in Figure 21. This test equipment is sufficient to measure device characteristics such as the AM-AM/PM response and other fundamental device behavior. Given the measured behavior, you can extract the mathematical relationship between the input RF signal and the supply voltage signal to produce a mapping often called "the shaping table." Once the shaping table is complete, you can modify it to optimize the device for improved distortion, efficiency, or reduced DPD requirements.

SIMPLIFIED ENVELOPE TRACKING PA TEST

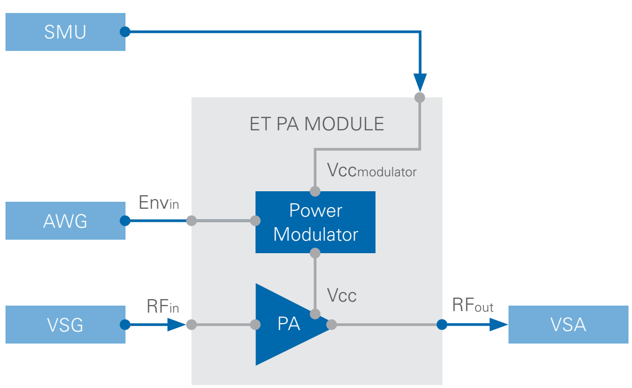


Figure 21. An arbitrary waveform generator drives the power modulator in an ET test configuration.

One key requirement of PA testing under dynamic power supply conditions is an arbitrary waveform generator (AWG) to produce the modulated supply voltage (Vcc) signal. In addition, an oscilloscope is useful to evaluate time domain waveform relationships between the dynamic supply voltage and output power. These measurements typically require a differential probe and current test point on the test board of the PA.

Note that in many instances, the mathematical relationship between the RF to the modulated supply voltage is a nonlinear function. As a result, the power supply waveform is subject to spectral regrowth, and has a bandwidth that can be many times greater than the bandwidth of the fundamental RF signal. In addition, because the current draw of a typical PA is often much greater than an AWG can supply, test setups typically require a power modulator to ensure that the PA is appropriately powered (see Figure 22).

TYPICAL PA TEST UNDER DPS CONDITIONS

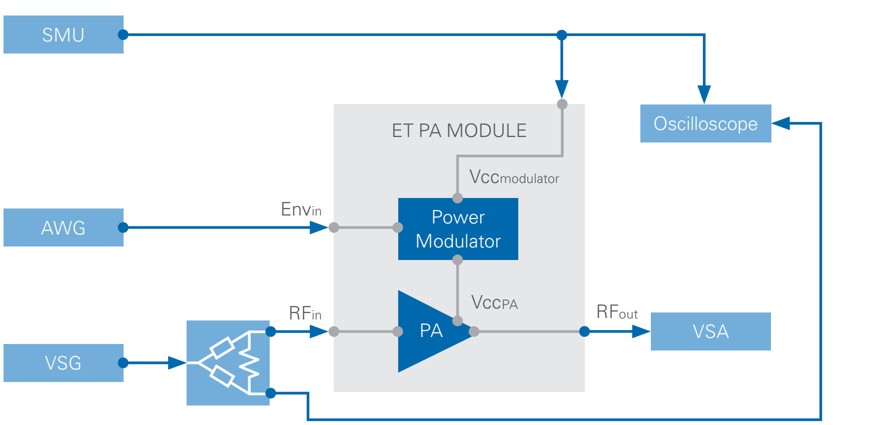
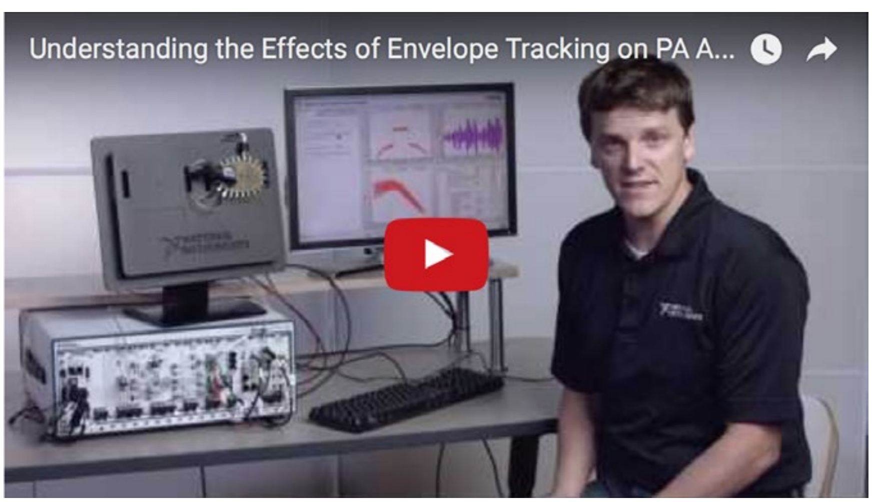


Figure 22. Typical PA Test under DPS Conditions

Testing under DPS conditions introduces unique test challenges such as linearization, synchronization, and the alignment of the supply voltage and RF stimulus signals. Depending on the optimization parameters for the shaping table design, the device can require advanced DPD linearization such as the GMP or none at all.



Addressing Synchronization and Alignment Challenges

The synchronization and alignment between the AWG and the RF VSG is one of the most critical elements in a DPST test bench. Because the mechanism by which a DPST PA achieves higher PAE is dependent on matching the precise RF signal input power envelope with a corresponding supply voltage, poor synchronization and alignment between the supply voltage and RF signal can cause significant distortion. You cannot merely start generating the AWG and VSG at the same time because these two signals must also have excellent stability and low jitter relative to each other. Finally, you must achieve alignment between the RF and supply voltage signals at the device pin interface and not the instrument interface. As a result, the ability to dynamically skew either signal in time is required to ensure appropriate alignment. PXI instruments are an increasingly common solution to DPST test benches because of their inherent synchronization performance.

The negative effects of AWG-to-VSG skew are most evident in the measured AM-PM distortion and are shown in figures 23 and 24. In Figure 23, you can observe that with 10 ns of skew, the "spread" in phase measurements on the AM-PM plot is significant. In fact, the data in Figure 24 illustrates an RMS phase deviation of greater than 4 degrees prior to DPD and 0.8 degrees once DPD has been applied. In addition to AM-PM distortion, you can see the negative effects of AWG-to-VSG skew in the spectrum plot. Although the DPD model (in this case the MPM) does improve ACP performance, the performance improvement is only by approximately 7 dB.

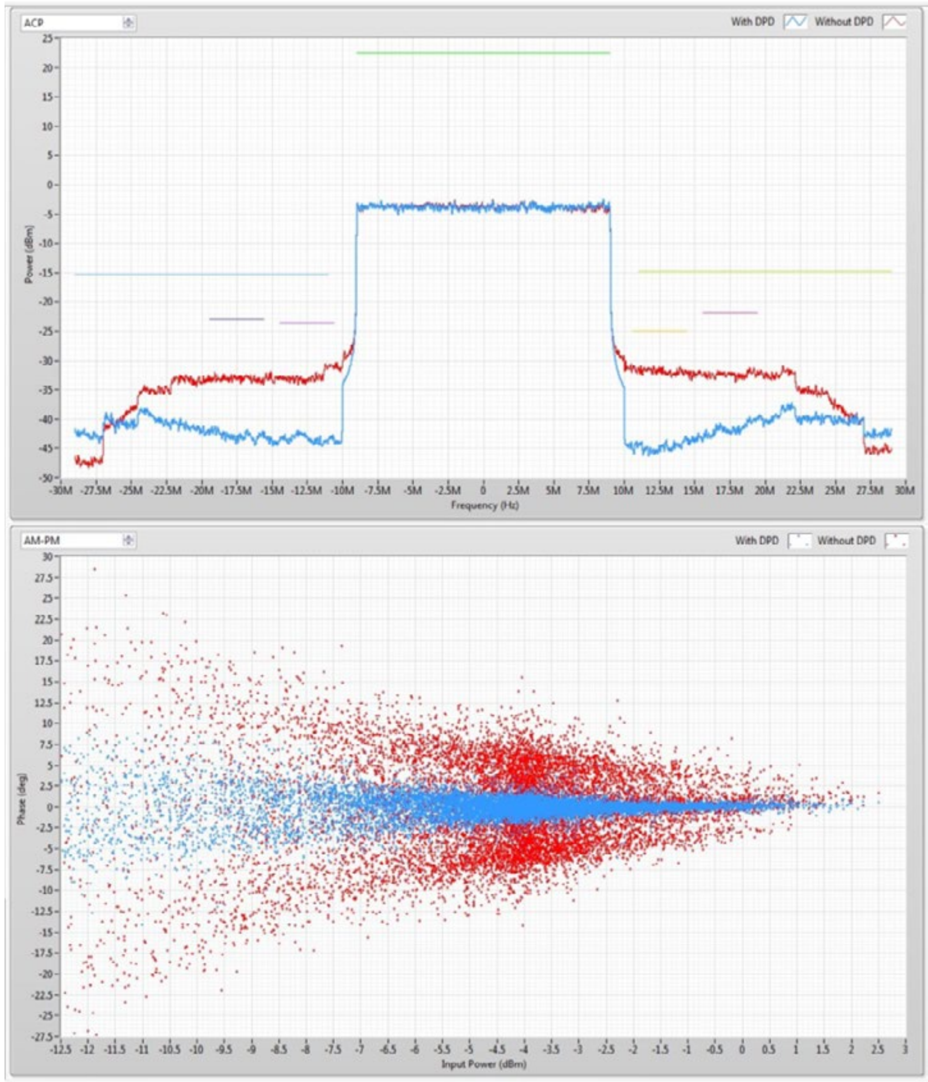


Figure 23. AM-PM Performance of a PA with 10 ns of AWG-to-VSG Skew

In contrast to Figure 23, Figure 24 illustrates the AM-PM performance of a scenario where the AWG-to-VST skew has been reduced to less than 1 ns. In Figure 24, you can observe that the "spread" around the AM-PM plot is reduced, and this is numerically quantified by an RMS phase deviation of less than 0.5 degrees. Note that the improvement in AM-PM performance also translates to an improvement in the frequency domain. Here, observe in Figure 24 that the ACP improvement using an MPM DPD algorithm is approximately 20 dB. In addition, the raw ACP performance in Figure 24 is approximately 8 dB better than the raw ACP performance in Figure 23.

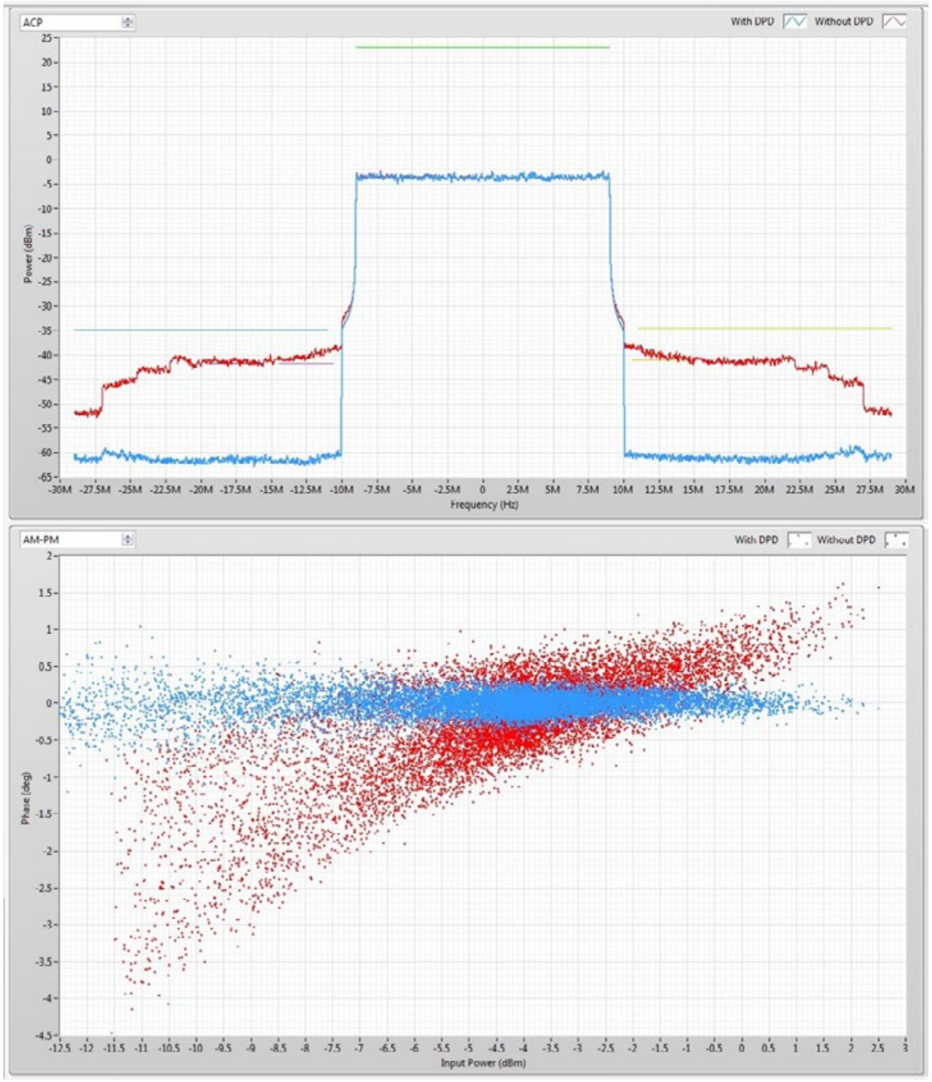


Figure 24. AM-AM Distortion with <1 ns Skew

Because measuring the skew between these two signals directly is difficult, a common approach to calibration is to sweep the delay of the AWG relative to the RF signal generator. For this technique, you measure ACLR, EVM, or RMS memory as a function of skew. Because skew ultimately results in worse ACLR, EVM, and RMS memory, you can identify the optimal AWG-to-VSG delay by choosing the best case as a function of the programmatic delay. By measuring the metric of choice as a function of skew, you can quickly determine the precise amount of delay required to operate the PA. As an example, Figure 25 illustrates RMS memory as a function of AWG-to-VSG delay. As this figure shows, the lowest memory occurs with a skew of approximately 7 ns.

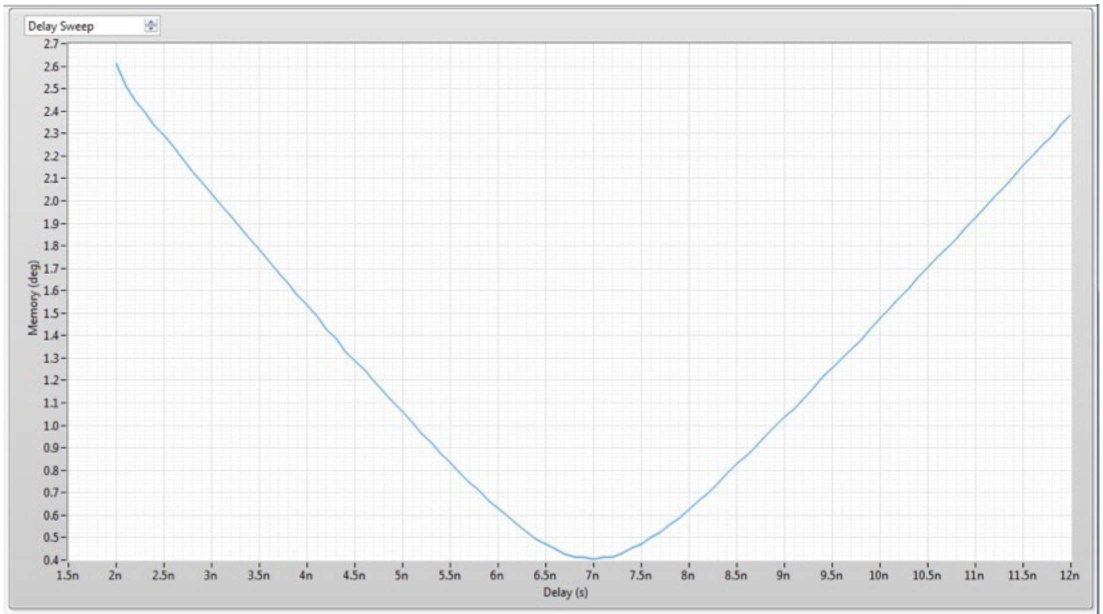
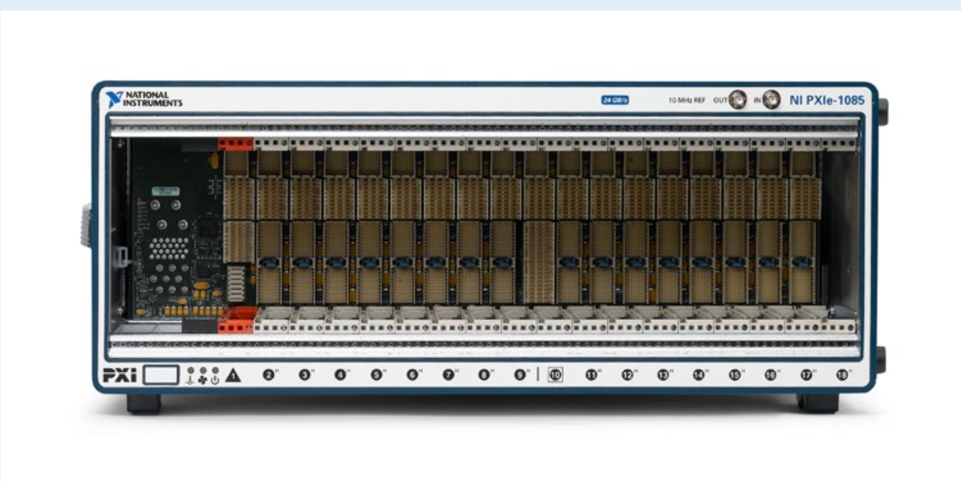


Figure 25. A delay sweep plots the RMS memory as a function of AWG-to-VSG delay

Instrument Synchronization in PXI

One of the benefits of PXI for dynamic power supply PA test is the ability to share timing and synchronization signals between PXI modules on the PXI backplane. In PXI, the backplane delivers each module with a common 10 MHz reference clock, with typical skew between modules at 100 ps. By synchronizing them to a common reference clock, you can adjust the timing output of PXI modules such as arbitrary waveform generators and RF signal generators down to picoseconds of precision.



Conclusion

As the demands for higher data throughput continue to push the capabilities of the modern radio, the RF power amplifier remains an increasingly important element of this design. However, the development of new PA technologies such as DPD and DPST continues to drive the cost and complexity of PA testing. Increasingly, engineers require highly flexible test systems that can evolve to address new test requirements.

Going forward, software will remain a core element of the PA test bench. Through software, modular PA test systems are able to scale to address new wireless standards and new DPD models. More importantly, software is the underlying technology that makes the automation of test equipment possible. As PAs, and ultimately front end modules, continue to become more complex, software is the only technology that can turn discrete instruments into a complete measurement system.