

# Improving the Efficiency of RF Power Amplifiers with Digital Predistortion

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When operating at near-peak efficiency, the RF power amplifiers commonly used in wireless base stations distort the signal they amplify. The distortions not only affect signal clarity, they also make it difficult to keep the signal within its assigned frequency band. Base station operators risk violating FCC and international regulatory agency standards if they cannot keep spurious amplifier emissions from interfering with adjacent frequencies. Today's WCDMA and LTE carriers have wider bandwidths than their predecessors, increasing the likelihood of interference from spurious emissions.

To reduce these emissions and achieve more linear amplifier output, base station operators can reduce the power output of the amplifier, but this practice also reduces efficiency. Amplifiers operating below peak efficiency dissipate more energy and get hot, sometimes requiring costly cooling equipment to prevent overheating.

At CommScope, we develop digital predistortion (DPD) systems that provide a way to operate amplifiers efficiently while improving linearity and minimizing spurious emissions. DPD alters the signal before it is amplified, counteracting the amplifier's distortion to produce a clearer output signal. Unlike their analog counterparts, DPD systems operate in the digital domain, enabling engineers to build flexible and adaptive solutions that produce a cleaner output signal.

We have developed, implemented, and patented DPD technology that enables wireless base stations to operate more efficiently while complying with stringent regulatory requirements. We rely on MATLAB® and Simulink® to characterize power amplifiers and their distortion, model and simulate DPD designs, and verify our hardware implementations.

## Characterizing the Power Amplifier

DPD addresses two types of distortion. Type 1 distortion results from curvature of the amplifier transfer function. Also known as amplitude modulation-to-amplitude modulation (AM-AM) and amplitude modulation-to-phase modulation (AM-PM) distortion, this effect is not a function of signal bandwidth. In contrast, Type 2 distortion, also known as memory effect, is a function of signal bandwidth, becoming more prominent as bandwidth increases.

The first step in designing a DPD system is to characterize fully the Type 1 and Type 2 distortion caused by the amplifier to which it will be coupled. At CommScope, we use MATLAB to characterize power amplifiers in the lab. After generating the baseband waveform with MATLAB, we download it to a signal generation chain that produces the signal to the amplifier. A second chain captures the amplifier output and feeds it back into MATLAB (Figure 1).

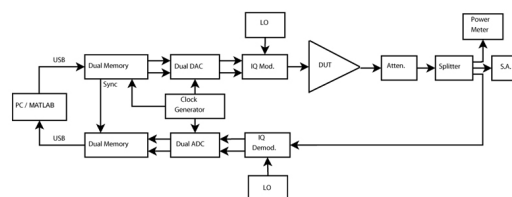


Figure 1. Diagram of the lab setup for amplifier characterization.

## Tackling Type 1 Distortion

After running tests of the actual amplifier in the lab, we use MATLAB to compare the input waveform to the output and determine how the amplifier is distorting the signal. This data processing includes time, gain, and phase alignment of the two signals. Based on our analysis, we generate a plot of the amplifier's transfer function to visualize the Type 1 distortion (Figure 2).

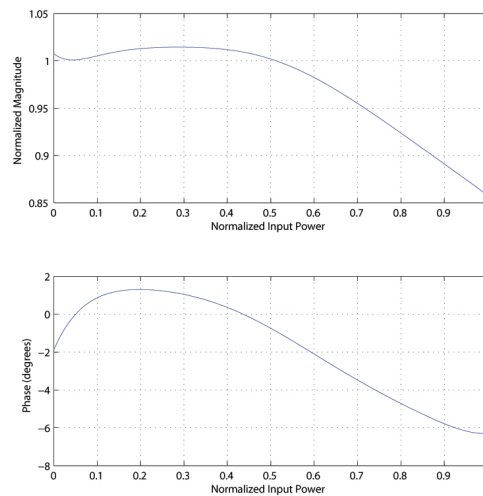


Figure 2. Magnitude transfer function (top) and phase transfer function (bottom) showing Type 1 distortion. The raw data has been fitted to a pair of polynomials to average the fluctuations and produce smooth curves.

If the amplifier did not distort the signal at all, the normalized magnitude would be plotted as a horizontal line with a value of 1, and the phase would be constant at 0 degrees. Instead, however, the normalized magnitude and phase of a typical amplifier vary as a function of input power. We obtain the complex gain of the amplifier by dividing the output samples by the input samples in MATLAB. The Type 1 DPD correction is simply the inverse of this complex gain.

## Characterizing Type 2 Distortion

Characterizing Type 2 distortion requires a more sophisticated approach, because this type of distortion depends on signal bandwidth. We begin by driving the amplifier with a signal generated in MATLAB that consists of two narrow-bandwidth carriers separated by a gap. After applying the Type 1 DPD to remove AM-AM and AM-PM effects, we add third-order predistortion with adjustable magnitude and phase. Using MATLAB optimization functions, including `fminbnd` and `fminsearch`, we optimize the magnitude and phase to minimize the third-order distortion exhibited by the amplifier, first on one side of the center frequency and then on the other. We repeat this process for multiple carrier spacings to map fully the amplifier's Type 2 distortion as a function of frequency. Using third-order predistortion is sufficient to characterize the amplifier because the frequency dependence of the higher-order distortions follows that of the third-order distortion.

The plot shown in Figure 3 illustrates this process. The two large spikes closest to the center frequency represent the modulated carriers. The two next largest spikes, rising about 2.5 divisions above the noise floor, represent the third-order distortion exhibited by the amplifier. In the spike to the left of the center frequency, the red line shows the amplifier's third-order distortion. The orange line below the red shows the distortion after applying Type 1 DPD. The green line shows the distortion after adding third-order predistortion with magnitude and phase determined by MATLAB optimization functions. Notice that the corresponding peak to the right is not reduced by this step; in fact, the distortion has been exacerbated. After noting the optimum magnitude and phase on the low-frequency side of the spectrum, we readjust the magnitude and phase to reduce the peak on the high-frequency side.

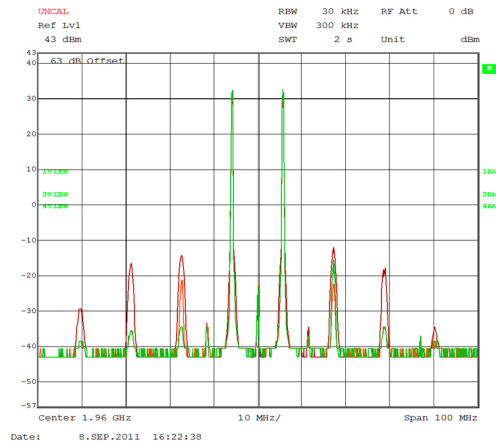


Figure 3. Spectrum of a waveform used to characterize Type 2 distortion.

Using a series of MATLAB generated waveforms with different spacing between the two carriers, the magnitude and phase of Type 2 distortion is measured for various frequencies across the bandwidth of interest. Then we generate a plot in MATLAB to visualize the results (Figure 4). The magnitude of the distortion increases as the frequency moves away from the center, supporting our observation that Type 2 distortion worsens as the bandwidth of the signal increases. Likewise, the 180-degree jump in the phase plot supports our observation that minimizing distortion on one side of the center frequency makes it worse on the opposite side.

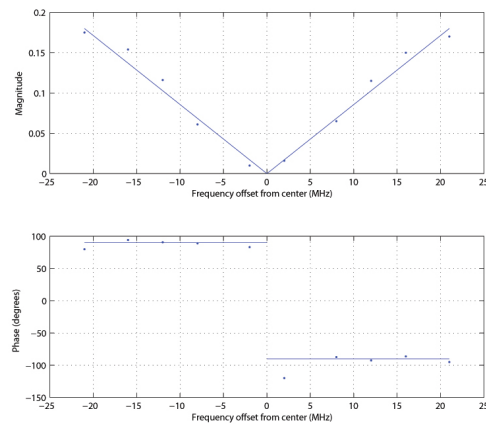


Figure 4. Magnitude and phase of Type 2 distortion.

We developed a mathematical model of the amplifier and its distortion. The general form of this model is

$$Y = X + \underbrace{X f_1(P)}_{\text{Type 1}} + d \underbrace{\{X f_2(P)\}}_{\text{Type 2}} / dt$$

where  $X$  is the amplifier input,  $Y$  is the amplifier output, and  $P$  is the instantaneous envelope power. Modeling the Type 2 distortion requires a differentiation with respect to time in order to match the characteristics shown in Figure 4 (a magnitude that varies linearly with frequency offset from center, and a phase that changes by 180 degrees at zero offset frequency). Using MATLAB, we fit the parameters of this model to the data gathered during the characterization process. The parameters we fit are complex values that are used to multiply the third-order and fifth-order Type 2 distortion (higher orders of distortion are typically not required). We verify that the model accurately reflects the behavior of the amplifier by supplying the amplifier and the model with the same input and comparing the output.

Once we have an accurate model of the amplifier, we develop a DPD model that corrects the distortion caused by the amplifier. Figure 5 is a block diagram showing how the model can be implemented in an FPGA or ASIC. Figure 5 also shows the operations that we perform in MATLAB (without the delay blocks) to implement this model in the lab for amplifier development. The values in the lookup tables are adjusted adaptively to minimize the discrepancy between the input waveform and the output of the amplifier.

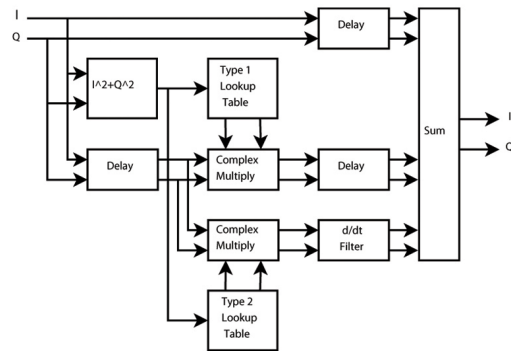


Figure 5. Block diagram of the DPD model.

## The Doherty Complication

Our initial DPD development process focused on class AB amplifiers, which were a staple of the industry until a few years ago. As WCDMA and LTE systems became more popular, engineers began exploring amplifier designs capable of efficiently handling signals with high peak-to-average ratios. At CommScope, we returned to an old idea: the Doherty amplifier. First described in 1936, the Doherty amplifier is now the predominant choice in wireless transmitters for WCDMA and LTE systems.

With class AB amplifiers, the magnitude of the Type 2 distortion is symmetric about the center frequency, whereas with Doherty amplifiers, it is not (Figure 6). Also, in a Doherty amplifier the change of phase angle is not 180 degrees.

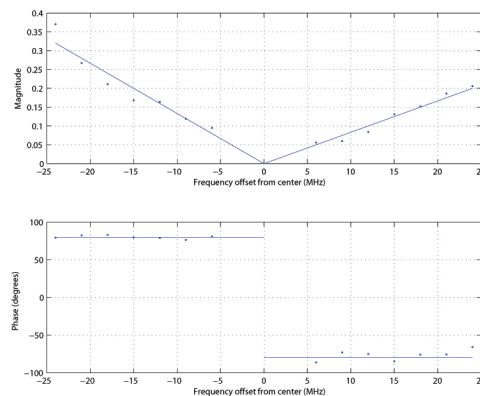


Figure 6. Magnitude and phase of Type 2 distortion for a Doherty amplifier.

Handling this asymmetry requires a minor modification to the mathematical model of the amplifier:

$$Y = X + X f_1(P) + P[d \{X f_2(P)\} / dt] + N[d \{X f_3(P)\} / dt]$$

where  $X$  is the amplifier input,  $Y$  is the amplifier output,  $P$  is the instantaneous envelope power,  $P$  is a positive frequency pass filter, and  $N$  is a negative frequency pass filter.

This model includes separate terms for positive and negative frequencies. We use frequency pass filters to apply these terms to the appropriate frequencies. We designed the filters using the Filter Design and Analysis Tool in Signal Processing Toolbox™. Figure 7 compares the original output spectrum of a Doherty amplifier for two WCDMA carriers with the output spectrum after applying Type 1 and Type 2 digital predistortion.

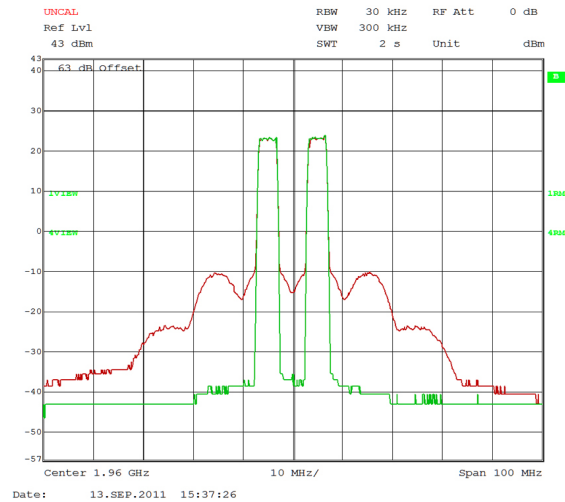


Figure 7. Doherty amplifier spectra for WCDMA carriers. Red = the original output spectrum. Green = the spectrum after applying Type 1 and Type 2 digital predistortion.

## Making the Most of the Models

The MATLAB models that we created for RF power amplifier DPD are exceptionally versatile and useful for many other groups in CommScope, both in the U.S. and elsewhere. We used MATLAB Compiler™ to create standalone versions of the models. Now, other teams within CommScope can use the models even on computers that do not have MATLAB installed.

We've incorporated the MATLAB based DPD algorithms into larger Simulink models that perform crest factor reduction, digital up-conversion, and digital down-conversion on the transmitted signal. These larger models are implemented on DSPs and FPGAs and delivered as complete production systems.

A key advantage of the DPD model is its simplicity, which enables fast response times across a wide range of transistor technologies, including Si-LDMOS, GaN HEMT, and GaAs HV-HBT.

CommScope engineers continue to push the boundaries of power amplifier efficiency with seventh-order predistortion and other technologies. As with the development of our original DPD technology, MATLAB is essential to this process because it lets us rapidly try different approaches and identify the best one before committing our designs to hardware.

### Products Used

- [MATLAB®](#)
- [Simulink®](#)
- [Signal Processing Toolbox™](#)
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