Test & Measurement

# A Product Development Flow for 5G/LTE Envelope Tracking Power Amplifiers, Part 2

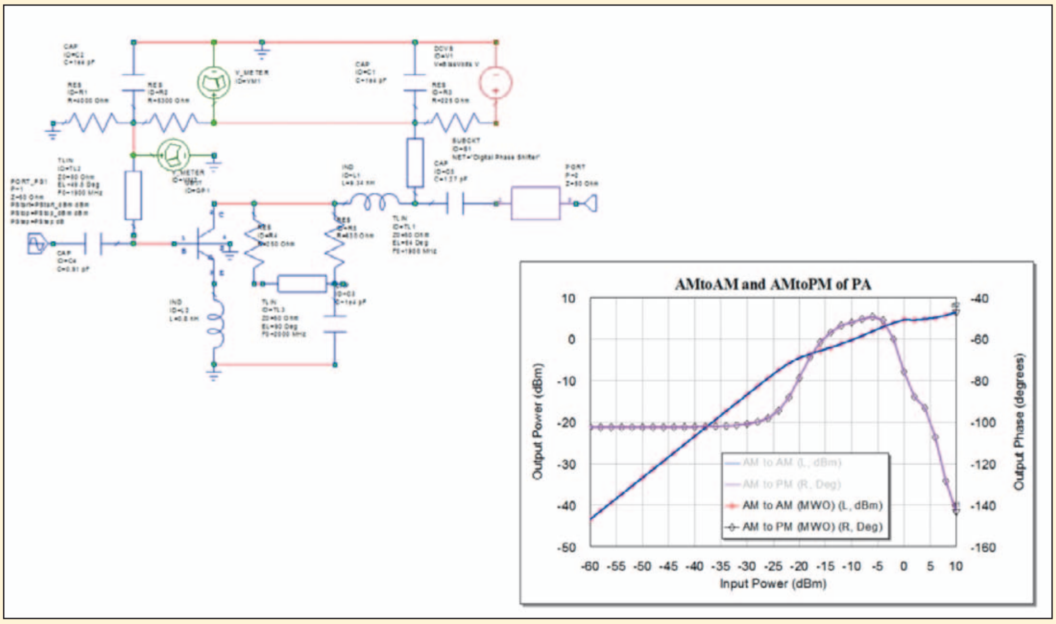


*Figure 12: Simulated AM-AM and AM-PM response plots for a power amplifier driving into compression*

## ET and DPD Enhance Efficiency and Linearity

As a result of the increased PAPR and peak power requirements of LTE-A and carrier aggregation, linearization and efficiency enhancement techniques such as DPD and ET will be even more crucial to the future of cellular standards than they already are for LTE today. DPD enables designers to operate in the efficient yet nonlinear region of an amplifier while retaining the transmitted-signal linearity required of most digital modulation formats. DPD does not produce dramatic improvements in PA efficiency, but it does improve the quality of a signal that a PA produces when operating at its peak efficiency point. The approach to DPD can range from simple solutions such as

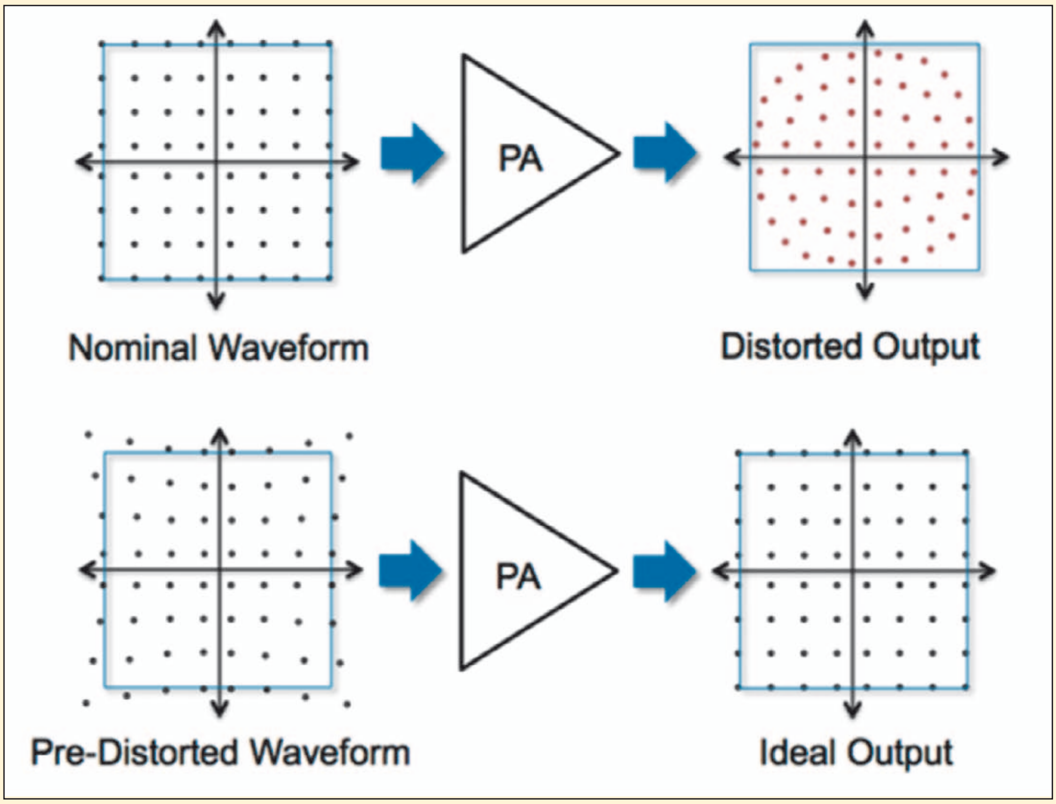


*Figure 13: Predisortion reverses the nonlinear behavior of the PA*

*National Instruments*
*ni.com/awr*

a basic look-up table (LUT) to more complex real-time signal processing approaches. To linearize a PA via an LUT, the measured or simulated output power and phase of the PA must be characterized as a function of input power (Figure 12) (simulations performed in Microwave Office based on shown PA circuit).

These measurements produce the AM-AM/AM-PM responses used to create an LUT that relates every input power/phase combination to the power/phase required to produce the desired linear output. By predistorting the input waveform, the PA can essentially be linearized. Figure 13 shows the compression of a nominal (64-QAM) waveform, which produces a constellation where the peak portions of the signal experience less gain than other portions. Thus, by predistorting the waveform such that the higher power symbols are amplified (gain expansion), the nonlinear behavior of the PA actually corrects the predistorted waveform. The resulting PA output using a predistorted waveform produces a more reasonable constellation. With NI design and test solutions, the LUT can be developed into hardware through a combination of simulated and measured data, progressively replacing simulation models/results with hardware and measured data (Figure 14). The LUT is initially implemented in $V_{SS}$ and used to predistort the waveform, exciting a simulated PA with nonlinearities represented with a behavioral model using measured or simulated data.

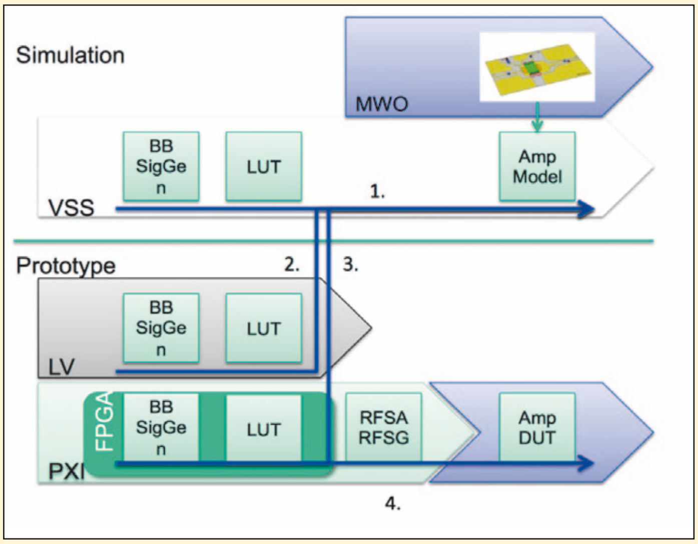


*Figure 14: LUT DPD development flow based on (1) full simulation in $V_{SS}$ (2) LabVIEW modeling of the LUT with simulated PA (3) LUT implemented in PXI hardware co-simulation with Microwave Office PA model (4) PXI-based LUT predistortion of waveform driving actual PA*

Comparison of the original PA input/output power response (showing compression) and the response after predistortion is shown in Figure 15. ET technology enables operators to utilize only as much power as is necessary to provide the amplified output. This technology reduces energy consumption, thus significantly lowering operating costs while providing environmental sustainability. In addition, from the hardware system perspective, this means a smaller form factor, higher reliability due to lower junction temperatures, and much

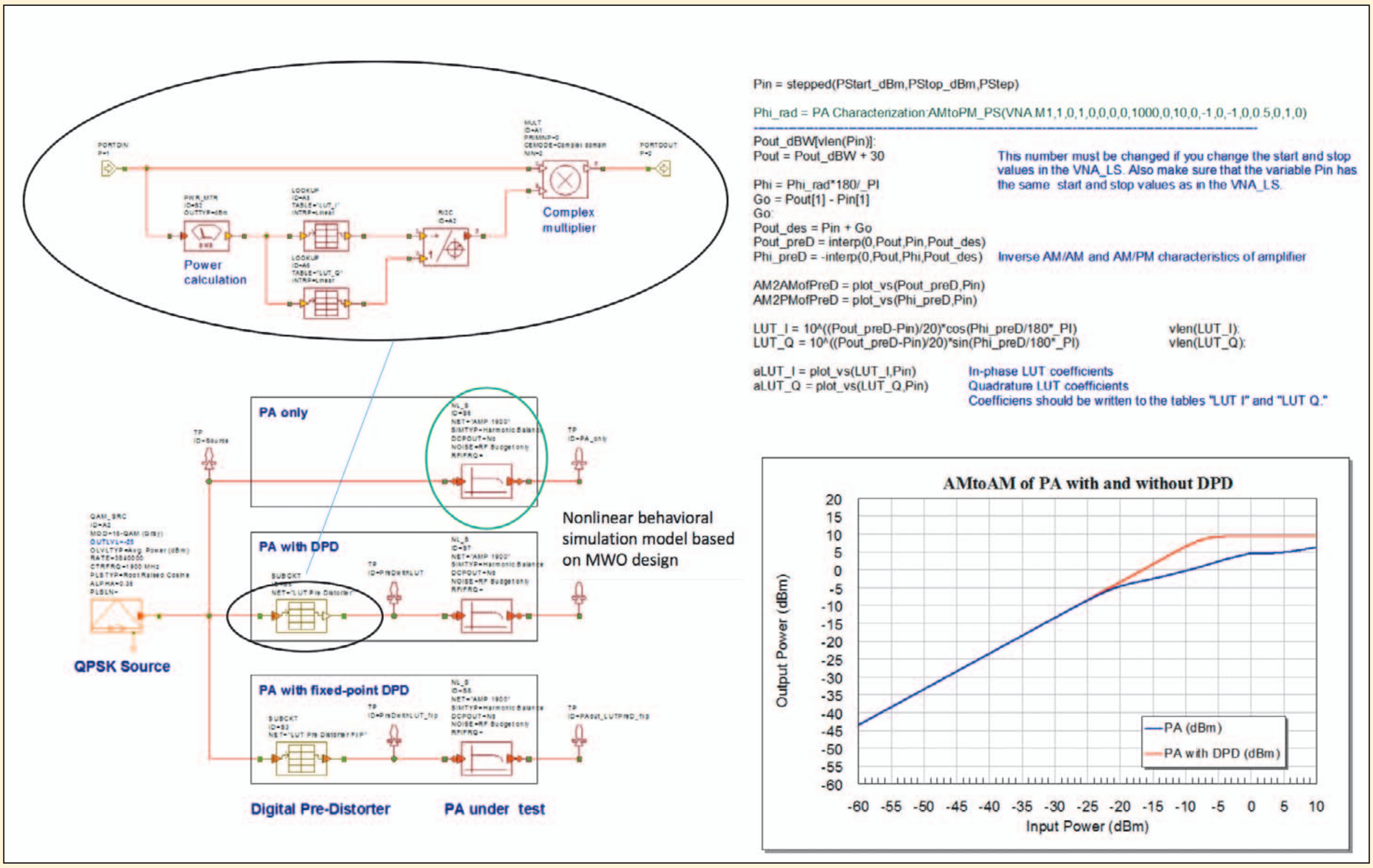


*Figure 15: $V_{SS}$ implementation of three simulations of PA (1) without DPD (2) PA with LUT (3) PA with fixed-point LUT and resulting $P_{out}$ vs. $P_{in}$. 55*

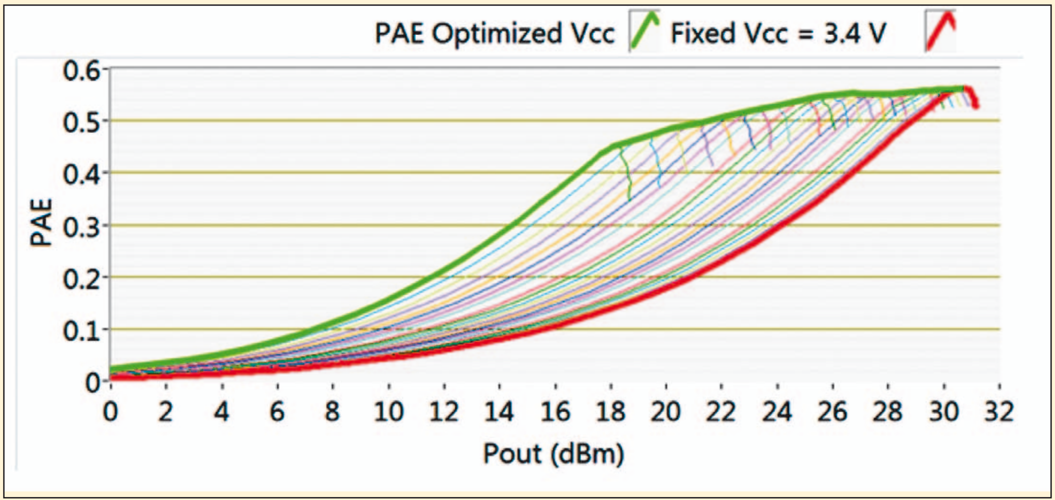


*Figure 16: $P_{AE}$ vs. $P_{out}$ across $V_{cc}$.*

lower weight due to reduced battery and energy requirements.

The principle behind ET is to operate the amplifier in compression as often as possible. This technique makes use of the fact that both the point of peak efficiency and the point of peak output power vary as the supply voltage changes. To illustrate this point, Figure 16 displays $P_{AE}$ as a function of output power for several $V_{cc}$ values. The output power of peak efficiency tends to increase with an increase in $V_{cc}$. The basic idea of ET is to map instantaneous output power to an optimal $V_{cc}$ value, thereby maximizing the time the amplifier spends on the edge of compression. While the idea of modulating the $V_{cc}$ signal to maximize $P_{AE}$ is good in theory, this is difficult to execute in practice. A consequence of varying $V_{cc}$ as a function of output power is that the amplifier's gain will dynamically change as $V_{cc}$ is changed, thus increasing AM-AM distortion. This effect can be reduced by using a smaller range of $V_{cc}$ levels, which leads to a design tradeoff between $P_{AE}$ and AM-AM distortion. DPD algorithms can be applied to the baseband RF waveform in order to correct for additional distortion introduced by ET.

## Real-World Example: ET PA with DPD

MaXentric Technologies, LLC is a specialty R&D firm that provides product design, development, and manufacturing services for the military defense market, as well as telecommunications/broadcast commercial markets. MaXentric products include simple low-cost mmWave broadband wireless transceivers, passive radio-frequency identification (RFID) readers, and high-efficiency ETPAs. Typical applications include intelligence, surveillance, and reconnaissance (ISR) components, high-bandwidth wireless communications, electronic warfare (EW), broadband high-efficiency PAs, and more.

The engineers at MaXentric were focused on developing the world's first integrated circuit (IC)-based envelope modulator (MaXEA 1.0) for use in envelop tracking applications to improve the efficiency of PAs operating with high PAPR signals found in LTE, LTE-A, and 5G communication systems. The PA chosen for their reference design was a 6 W GaN device, pre-matched for LTE band 1 (2.14 GHz). At saturation, the PA provided 11.5 dB of gain at 53 percent $P_{AE}$. To provide the required linearity, the PA needed to operate at an OBO of 0.5 W (PAPR of 10.8 dB), resulting in a $P_{AE}$ of less than 10 percent. With DPD, the PA was able to operate at a higher OBO of 2 W, resulting in a $P_{AE}$ of approximately 25 percent.

Through the use of DPD, ET, and optimization of the output

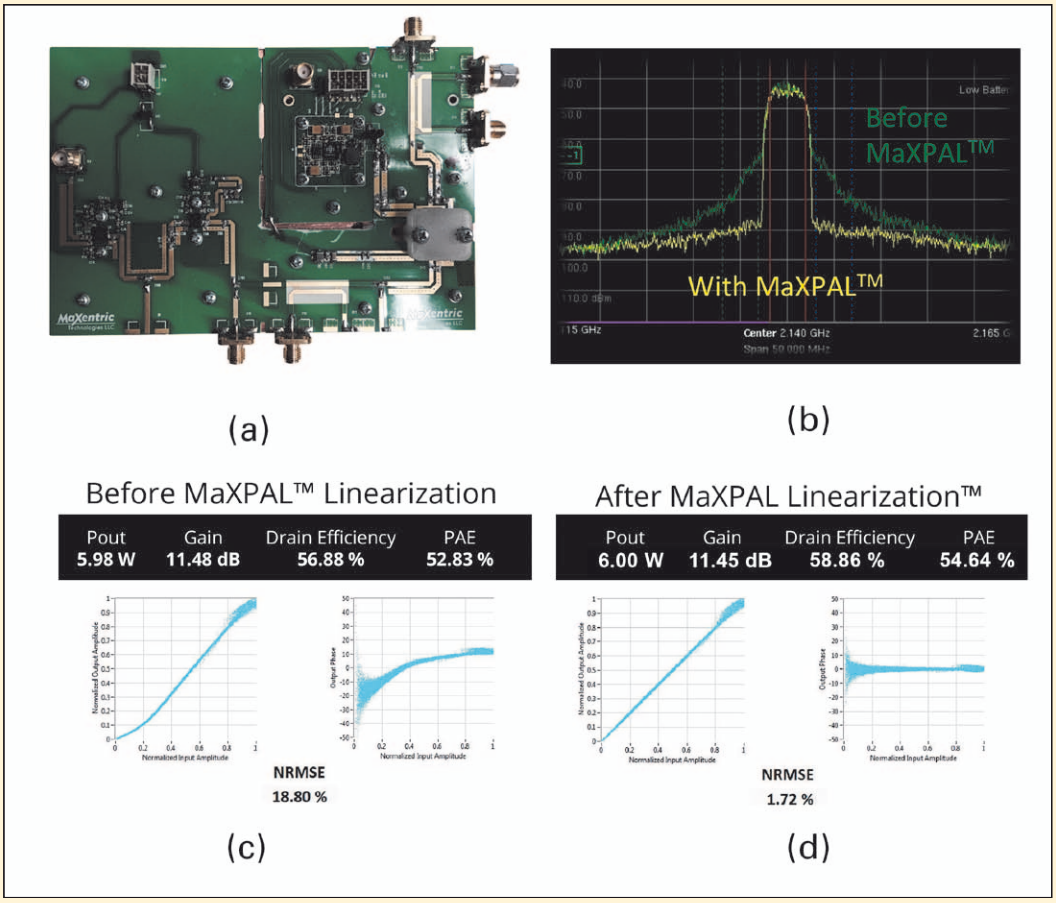


*Figure 17: (a) MaXentric ETPA with MaXEA, (b) spectra before and after MaXPAL linearization, (c) AM-AM and AM-PM before MaXPAL linearizaton, and (d) AM-AM and AM-PM after MaXPAL linearization*

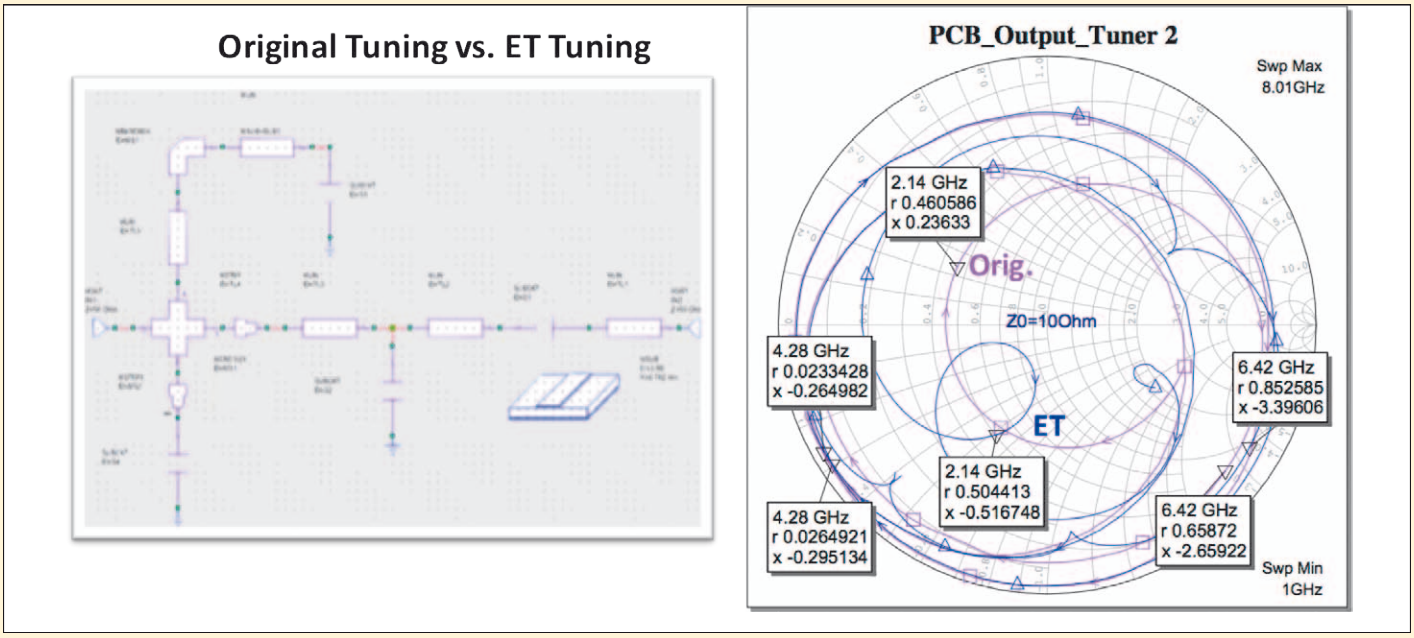


*Figure 18: Retuning of the ETPA using Microwave Office software*

match using on-board tuning designed with Microwave Office software and measured load-pull data, the PA was able to operate at the saturated output power of 6 W, with a slight improvement in $P_{AE}$ of 54.6 percent and excellent linearity with a measured ACPR of 74.5 dBc (Figure 17). The PCB output matching circuit and its frequency-swept impedance as seen from the output of the PA are shown in Figure 18. The design and its response were generated in Microwave Office software by simulating a microstrip-based impedance transformer composed of transmission-line models and verified with AXIEM, 3D planar EM simulator within NI AWR Design Environment. The design's physical dimensions were determined through optimization to match the measured impedances of the load-pull tuners used to optimize the performance of the PA on the load-pull test bench.

## Test Solutions for ETPA Development

The success of this project was made possible by the development of an ETPA test bench capability for real-time efficiency and linearity measurements supporting the optimization of PA design utilizing ET and DPD, and the flexibility to accommodate different LTE and 5G signals. The test bench uses LabVIEW software to design and optimize the ETPA, along with the NI vector signal transceiver (VST) for RF signal generation and the NI arbitrary waveform generator (AWG) for envelope signal generation.

Traditional test benches are made to test PAs with a constant sup-

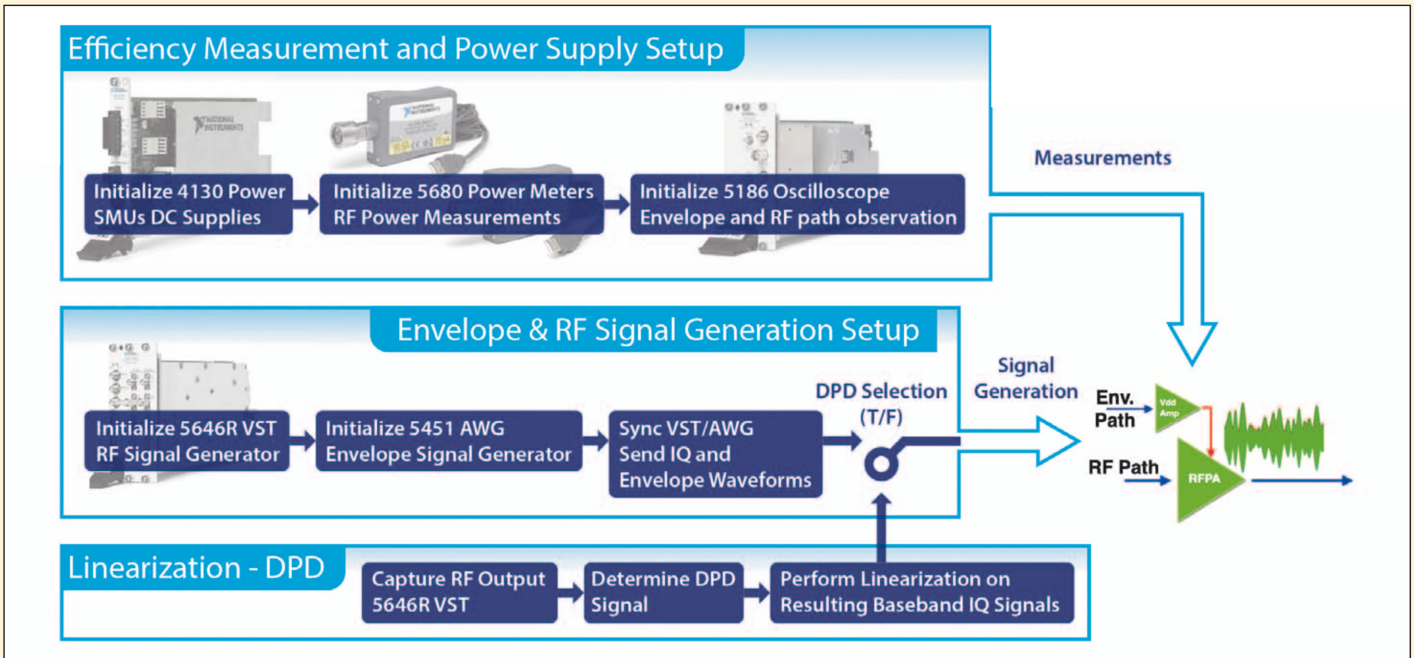


*Figure 19: Test modules used in the development of an ETPA test bench*

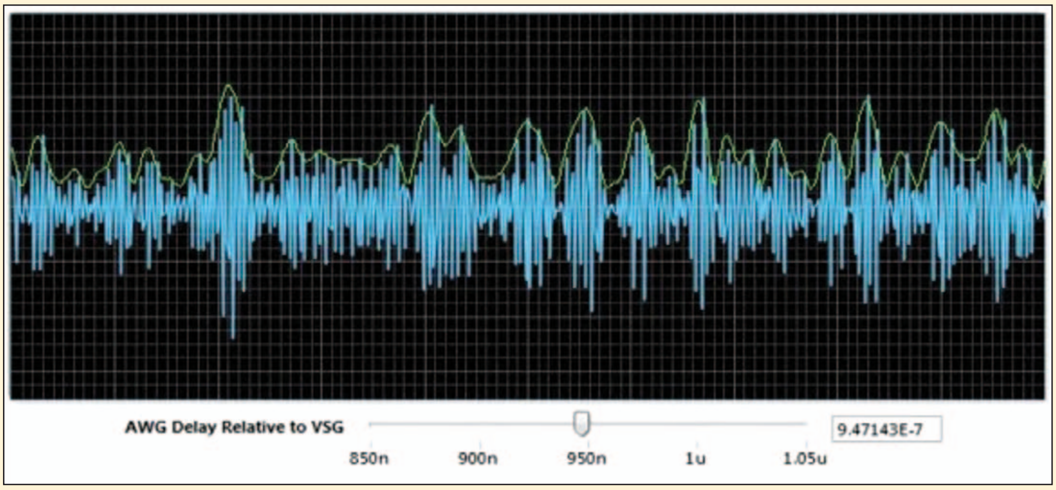


*Figure 20: Time alignment between RF signal and envelope supply*

ply voltage. In ET, a modulator is used as a dynamic power supply that varies as a function of the signal's envelope. This technique is deliberately designed for signals with high PAPR and hence, traditional PA tests cannot be used to optimize its performance. The average performance for a modulated signal is what needs to be evaluated in an ETPA, as opposed to continuous wave (CW) performance at the peak supply voltage. The problem is further complicated by the lack of accurate models over a wide range of supply voltages. Most device models are valid at the nominal constant supply voltage ±10%, while in ET the supply voltage can be 90% lower than the peak supply voltage. Hence, real-time performance measurements are highly desired for optimizing the ETPA.

There are many benefits to using the NI PXI, VST, and AWG for ET. Similar test benches have been built in the past and have taken a year or more to complete. With NI's excellent integration and the use of LabVIEW, the designers were able to complete the NI envelope-tracking test bench in less than two months. An important feature that PXI offers is the ease of synchronization between the equipment modules. Due to the nature of ET, it is critical that the supply envelope signal arrive at a specific time with respect to the RF signal. Additionally, 5G PAs need to support various types of modulations, which the VST can easily generate. Another advantage to the VST is the widely tunable RF frequency it offers (65 MHz to 6 GHz). The second generation VST, introduced in the summer of 2016, provides even greater capabilities with an operating frequency range from 9 kHz to 6.5 GHz, 1 GHz of instantaneous bandwidth, and a large Virtex 7 onboard field-programmable gate array (FPGA) for signal processing such as real-time DPD. This covers most of the non-mmWave LTE bands of interest with 200 MHz of instantaneous bandwidth, allowing system flexibility for various applications in addition to LTE. Because ET is inherently wideband in terms of tunable RF bandwidth, a wideband ETPA with this NI ET test bench can be used to test various LTE bands, GPS, and military applications, all on the same day with simply a click to change the RF frequency.

To develop a test bench for optimizing ET, the various modules described in Figure 19 were used. Power source measurement units (SMUs) were used to allow for real-time DC power consumption measurements. RF power meters enable users to monitor the input and output power. In LabVIEW, these measurements are put together and calculations are done to allow for instantaneous monitoring of the efficiency, gain, and output. The envelope signal was generated using the AWG. The VST served as the RF signal generator as well as the RF feedback analyzer. Leveraging the feedback signal and MathScript, DPD was used to improve the linearity of the ETPA. The envelope shaping relationship between the true envelope of the signal and the supply voltage was optimized easily by simply loading a different equation. As mentioned earlier, impedance tuning for best performance can be done by load pulling and source pulling with external tuners and Microwave Office software was used to apply the optimized tuning to the on-board ETPA. The reduced characterization time and ability to optimize the ETPA in real time offers a significant game changer for PA designers.

The time alignment of the amplitude signal and RF signal at the RF transistor is critical for optimizing the ETPA's performance. A time misalignment in these two signals will produce signal distortion, degrade ACPR performance, and reduce efficiency. Characterization of the time-delay difference between these two signal paths will allow for time alignment. This delay difference may vary with temperature or aging and therefore the system would need to compensate for this variation in order to ensure optimum performance. Using PXI, a VST, an AWG, and LabVIEW, the designers were able to visually see the improvement/degradation in linearity and efficiency as the alignment between the RF signal and the envelope supply was altered in real time (Figure 20).

## Results of Envelope Tracking using PXI, VST, and NI AWR Design Environment

The NI VST and PXI were used to optimize the LTE Band 1 (2.14 GHz) PA using MaXentric's MaXEA 1.0 modulator. The MaXEA 1.0 is a 30 V integrated envelope modulator with greater than 70% modulator efficiency, capable of outputting up to 7 W of average envelope power. The modulator was designed to support signals with high PAPRs such as those used in LTE and 5G and is compatible with various PA technologies such as LDMOS, GaN, GaAs, and more.

## Conclusion

A consequence of high data-rate communications such as LTE, LTE-A, and future 5G systems offering greater spectral efficiency based on carrier aggregation and OFDMA (or other modulation schemes) will be the increase in the PAPR of the time-domain signal. Signals with large PAPR will experience nonlinear distortions at the transmit power amplifier, resulting in in-band distortion and out-of- band spectral leakage, which cause performance degradation, interference to other systems, energy inefficiency, reduced cell coverage, and system capacity loss. Hence, RF components in the transmitter front-end must be designed for linearity and efficiency.

This white paper has described the combined use of circuit/system/electromagnetic co-simulation available in NI AWR Design Environment, inclusive of Microwave Office, $V_{SS}$, and AXIEM software, along with a measurement solution based on NI PXI, VST, and LabVIEW to significantly reduce the optimization and product development time for a wideband ETPA across different bands and applications. ◄