APPLICATION NOTE

PA/FEM Measurement Guide: Testing PAs under High-Power Conditions

Table of Contents

What is a High-Power RF PA?

The power amplifier (PA) is a crucial component in every RF transmitter. They are typically the last components in an RF transmit signal chain that provide gain to a signal before it is delivered to an antenna and sent over the air to a receiver, thus completing the wireless communication chain. Proper PA development, validation, and characterization is important since a PA often makes up a significant portion of the power consumption of a transmitting device. Operating a PA efficiently while ensuring reliable communication is a tough task in its own right.

This application note focuses specifically on test considerations around high-power PAs and how the steps taken in validation of these devices can be different from PAs that operate at lower power levels. It assumes a basic understanding of PA validation, including fundamental PA behaviors and basic measurements including EVM, channel power, third-order intercept (IP3), 1-dB compression (P1dB), and linearization techniques such as digital pre-distortion (DPD). For an overview of generic power amplifier measurements, refer to the following resource.

RFIC White Paper Series: Fundamentals of Power Amplifier Testing

Depending on the application, the definition of high-power may change—but in general, a high-power PA will have a P1dB compression point of at least 30 dBm, perhaps as high as 70 dBm. Because these PAs operate so far above the noise floor, noise figure is not as big of a concern. Due to these different tradeoffs, traditional LNA power amplifier topologies such as HBTs and pHEMT amplifiers on GaAs substrates are not as optimal. Instead, high-power PA designers typically opt for either LDMOS FETs on a SiC substrate or HEMT amplifiers built with a GaN layer on top of a SiC substrate.

A high-power PA is often a combination of multiple smaller PAs. Sometimes multiple stages are cascaded in series into a single high-gain PA. Another common amplifier architecture is known as a Doherty amplifier, in which two amplifiers are placed in parallel, both receiving a split copy of the signal. One amplifier (known as the carrier PA) is tuned to accurately amplify the lower-power portion of the signal while the other amplifier (known as the peaking PA) is tuned for the higher-power portion. The signals are then recombined, giving improved signal fidelity across both operating regions. Even with these multi-stage techniques, the amplifier's output power is often still not high enough for commercial applications. A driver amplifier is used to boost the signal power ahead of the high-power PA. The driver amplifier is normally optimized for high linearity and low noise figure since its input is closer to the noise floor.

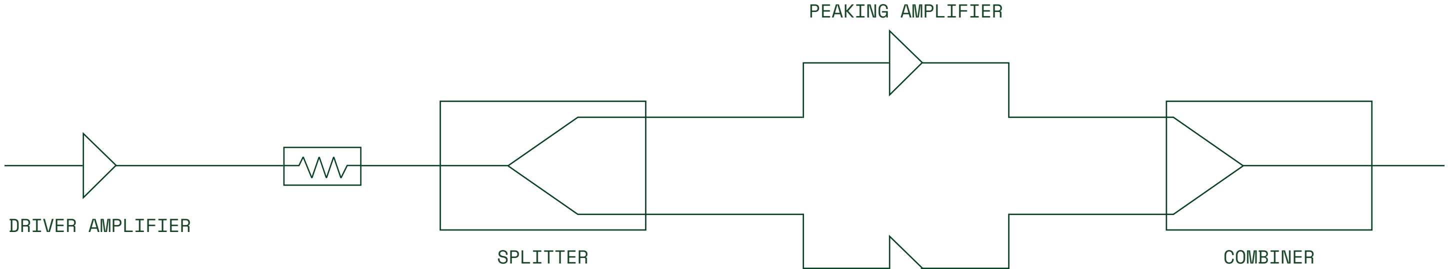

FIGURE 1

A block diagram of a common TX amplifier including a driver, attenuator for impedance matching, and Doherty high-power amplifier.

Significance for Base Station Infrastructure

A common application for high-power PA is cellular base stations sending downlink signals. In cellular communication, base stations will communicate with user equipment (UE) in the form of cellular handsets. As the number of UEs increases and the average UE demands more data, base stations must transmit large amounts of data over high bandwidth. These transmissions must be high enough power that UEs can interpret the transmission but also achieve sufficient power efficiency to maintain economic viability. High-power PAs are equipped to meet this unique need.

A typical base station includes three devices: a baseband unit (BBU) at the base of the tower, a remote radio unit (RRU) at the top of the tower, and an antenna. The RRU will include the hardware for separating the uplink and downlink signals, amplifying the signals, up/downconverting, and signal conditioning. The high-power PA resides on the TX path within the RRU.

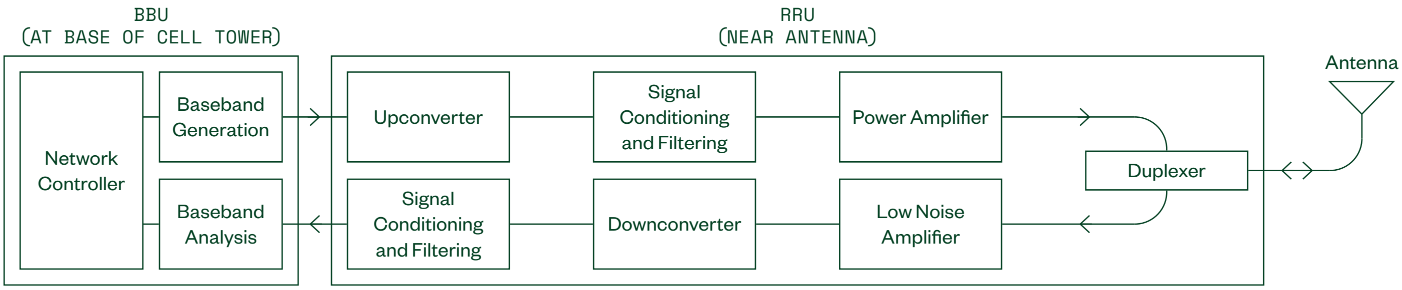

FIGURE 2

Block Diagram of a Typical Base Station Signal Chain

Learn more about NI's solutions for Wireless Infrastructure Development

Significance for Defense and Satellite Communications

While this application note focuses primarily on terrestrial base station infrastructure, it should be noted that high-power PAs have similar applications within aerospace/defense terrestrial and satellite communications systems—and similarly, radar/missile datalink systems.

High-power PAs also span into use within radar and electronic warfare (EW) applications with a similar set of test needs or a significant subset to which the methods described in this app note are also generally applicable. These considerations and differences will not be covered in depth in this app note.

High-Power PA Test Challenges

The process of characterizing a high-power PA requires the device to be tested in a lab environment. Going from a full application to a simulated lab environment always requires consideration so the test setup accurately reflects the final application of the device, and this is particularly true when testing high-power PAs. Here is an overview of some of the specific challenges that high-power PA test architects must consider in order to develop a safe test that reflects the real-world performance of the component.

Using and Accounting for Proper Components

Several differences in hardware setup between an RRU and a PA lab setup must be addressed and accounted for.

Because an RRU is a fully integrated device, it is packaged with large heat sinks. When a PA is installed on an evaluation board (EVB) to allow convenient testing, these heat sinks are not present. The EVB may need to be outfitted with heat sinks and fans to operate safely. The desired test cases will also influence the decision of how much heat dissipation to add: Will the part be powered continuously in the lab? Will it be transmitting RF continuously? Does the test involve changing input current or impedance to see how the device will react? Does it include a ruggedness test to see how the device operates as it pushes out of its typical temperature and power range? All these test decisions will require design decisions when choosing a heat dissipation strategy.

On a base station, the BBU transmits a baseband signal to a driver amplifier inside the RRU, which then transmits to the high-power PA. In a test setup, however, we want to isolate the behavior of the PA to understand it fully, meaning we replace the other components in the signal chain with test equipment. This can be done by creating the baseband test signal as a waveform file and uploading it to a signal generator. Signal generators are not typically capable of outputting the power levels needed to fully test a high-power PA's range, meaning a pre-amplifier must be used.

We must perform a similar process with the output of the PA. On a base station, the output of the high-power PA goes to the antenna for OTA transmission. In a lab environment, the output goes to a signal analyzer. Again, test equipment is rarely rated for the output power levels needed, so an attenuator is required. This attenuator may impact your physical test setup, as high-power attenuators are bulkier and more expensive than lower power variants.

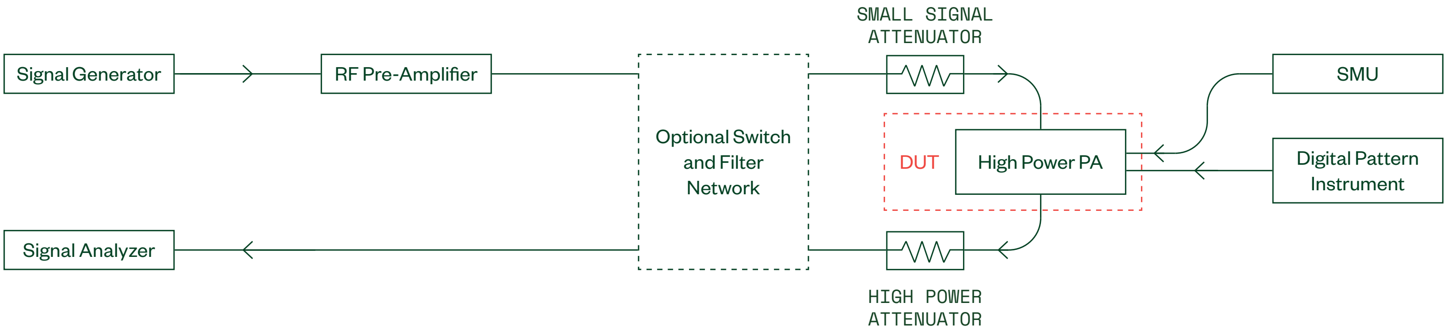

FIGURE 3

Block Diagram of a Typical Test Setup for a High-Power PA

Operating at high power levels will also impact the accuracy of power measurements in the test setup. Accurate power measurements require a process called system de-embedding or system calibration, in which the accuracy of the signal generator and analyzer are accounted for along with the losses or amplification in your signal chains. There are four common methods to do this:

1. Run a test signal through the signal generator path to a power meter to calculate an "SG external attenuation" value, then perform a similar process on the signal analyzer path and offset the generator and analyzer by these values. This is the simplest method but doesn't account for variation across frequency or power level.
2. Expand method 1 by sweeping frequency and/or power levels to build a de-embedding lookup table such that any generated or received signal can be offset accordingly.
3. Characterize the signal generator (SG) and signal analyzer (SA) signal paths using a VNA and offset the generation/measurement accordingly.
4. Put a coupler in the SG path immediately before the DUT and a coupler in the SA path immediately after the DUT and use power meters on both coupled ports to servo and measure power. This method takes the longest and requires the couplers and power meters to remain in the test setup after the de-embedding step and increases the amount of time it takes to change power levels. However, this method produces the most accurate power results since it is fine-tuned every time power is set.

Performing system de-embedding at high power becomes more complex because the nonlinearity of your signal chains becomes more pronounced. The pre-amplifier may compress, making power levels less repeatable. As a pre-amplifier heats up, the linearity will change, meaning the power offset you calculated during the de-embedding phase may no longer be accurate after sending RF to the PA for an extended period of time. Even a passive attenuator may behave like a nonlinear device and exhibit more loss if its input power and temperature get high enough. VNAs present challenges as well: a wide bandwidth signal may differ over its bandwidth from the offset calculated by the CW-based VNA. VNAs often lack the power range necessary to fully characterize the SA path. These factors combine to make methods 1, 2, and 3 less reliable. Method 4 is the best system de-embedding method for high power characterization.

Isolating Impact and Understanding Full RF Chain

The purpose of testing the high-power PA is to understand how the signal and spectrum are affected by the amplification process. While the high-power PA is likely the main culprit of signal and spectrum degradation, it is not the only source. The driver amplifier may also contribute, and cascading the two amplifiers may cause mismatched impedances. An attenuator between the amplifiers may be needed to reduce this mismatch. To test this, each PA should be tested in isolation (using a pre-amplifier for the high-power PA), and the driver + PA should be tested as a composite device without a pre-amplifier. These three datasets will allow a test engineer to determine the source of the degradation.

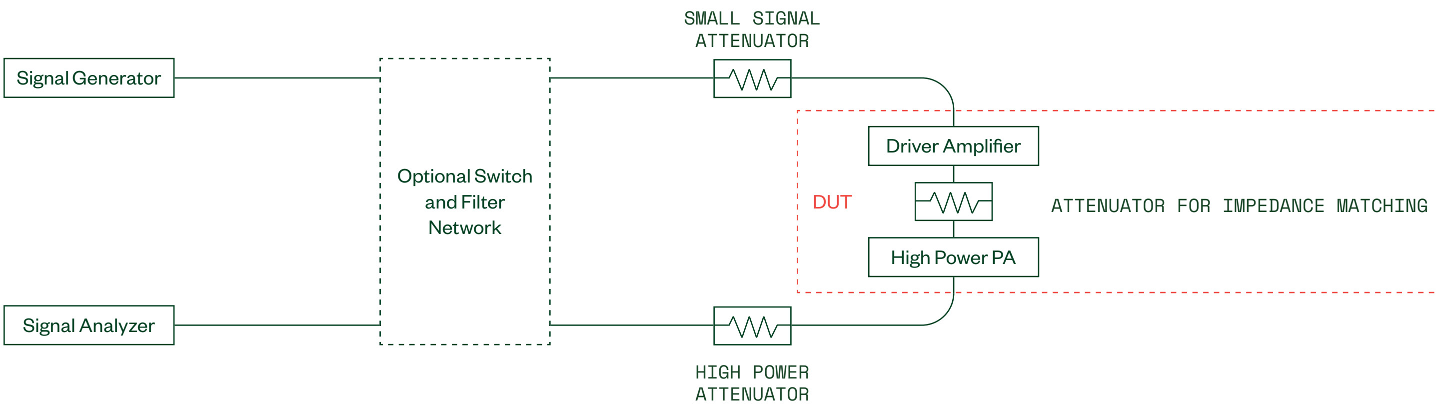

FIGURE 4

Test Setup Modified to Test Full TX Amplifier Chain

Transient versus Steady State Characterization

Pre-amplifiers and attenuators are not the only devices that may change performance over time. The PA itself may also exhibit different behavior depending on how long it has been operating. This may be due to the temperature profile of the part changing and is why it is important to test the device in a similar state to how it will be used in the field by using test signals and heat dissipation that simulate real-world performance. However, there is another potential source of behavior change in the time domain: when HEMT amplifiers are used, particularly if they are GaN on SiC substrate, a phenomenon known as charge trapping occurs. As electrons move between the layers of the amplifier, they occasionally get "trapped" between layers, reducing the effectiveness of the transistor. These electrons will eventually get free, meaning the steady state behavior of the PA may be different than the transient behavior right after it is enabled. The state of the PA in the field may not be immediately obvious, as the amount of time it takes for charge trapping to resolve itself varies widely based on PA design. It is up to the test engineer to ensure that the testing state of the PA closely aligns with its state in the field, whether the charge trapping has resolved itself or not.

High-Bandwidth Characterization

Base stations must analyze uplink signals and generate downlink signals across multiple bands simultaneously. With multiple antennas and signal chains active on a single tower, congestion can occur—both physically as towers become more crowded and spectrally as cellular traffic increases. This drives designers to optimize in several ways. Some signal chains will be optimized for multiple bands, meaning the PA must be capable of operating across these bands simultaneously. This also means that strict requirements must be placed on out-of-band spectral emissions, as nearby antennae are transmitting and receiving at those nearby frequencies. DPD becomes an important method of maintaining this delicate balance between signal fidelity and a clean spectrum.

Optimizing Efficiency with Time Domain Synchronization

The significant power consumption of a high-power PA leads designers to invest in optimizing power efficiency. This is a critical metric for any infrastructure hardware provider because energy is a primary cost associated with operating a base station. It is in a designer's best interest to characterize and optimize the power efficiency of the amplifier. One important strategy for conserving energy is managing when the PA is enabled. Some PAs do this by providing an enable pin that can be toggled, while others require the power supply to start and stop at the proper time. Either way, synchronization between the DUT, power supply, and SG are required. This synchronization is especially important for TDD waveform tests, where certain time slots in the transmission are reserved for uplink communication and the downlink chain can be disabled.

NI's Advantages for High-Power PA Test

High-power PA designers are getting pushed for improved performance from every angle: higher power transmission, higher signal fidelity, higher spectral purity, higher power efficiency, and smaller footprint. NI is investing a lot in creating ways for our customers to meet the challenges presented by high-power PA technology in the whole product lifecycle from R&D through validation, production, and aftermarket services. Here are a few example of what we can offer with our technology.

Digital Pre-Distortion Algorithms

Maximizing the performance tradeoff between in-band signal accuracy and out-of-band leakage requires DPD. The DPD is performed in real-time in the BBU, often using proprietary hardware and algorithms. This means PA designers have hurdles to cross when showing performance of their PAs under DPD conditions; they may not have access to the hardware provider's DPD algorithm or a way to apply DPD to a streaming signal in real time. The best solution to this is for the provider and designer to agree on a set of test waveforms and DPD algorithms, either standardizing on a publicly available algorithm or allowing the designer to tune their DPD algorithm to offer the best result possible. In either case, NI can equip a customer for success.

NI's drivers support several public DPD algorithms out of the box: lookup table, memory polynomial, and general memory polynomial. These algorithms are fully open source: the equations are publicly available, all parameters can be modified, and the calculated coefficients and pre-distorted waveform can be accessed. For more information on these algorithms, refer to Part 2 of the **RFIC White Paper Series: Fundamentals of Power Amplifier Testing** also linked in the first section of this document.

NI also offers integration for high-performance DPD algorithms developed by NanoSemi. These closed-source algorithms typically show superior performance to the open-source algorithms previously listed. Their portfolio also includes a dual-band algorithm tuned for simultaneous transmission in Band 1 and Band 3 and may help designers to publish the best results possible. Finally, if a designer wishes to investigate their own algorithm, our drivers provide simple entry points to export received waveforms and import pre-distorted waveforms so the DPD can be trained and applied offline.

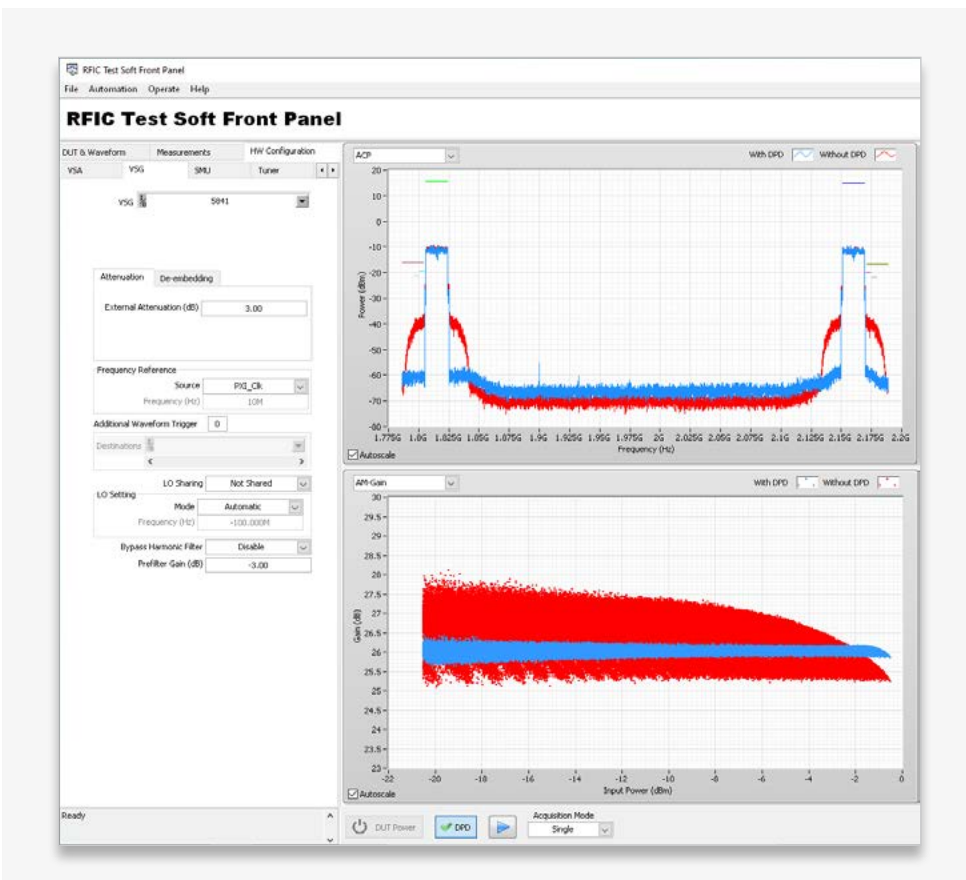

FIGURE 5

A Screenshot of RFIC Test Soft Front Panel Showing Digital Pre-Distortion on a Downlink Signal in Both Band 1 and Band 3

Learn more about implementing DPD algorithms for RFFE validation

Tight Module Synchronization

Because NI's solution for PA test includes multiple modules within a single PXI chassis, these modules can communicate and synchronize seamlessly. A shared frequency reference and trigger bus between your SA, SG, SMUs, and digital pattern instrument allows you to synchronize all these devices easily. The simplest method is to use the signal generation portion of a vector signal transceiver as the master device. The SG can run in script mode, allowing the user to determine a certain waveform generation routine with the same resolution as the SG's sample clock. This routine can also include exporting markers to other devices.

This is particularly useful when testing TDD waveforms or test cases where enabling and disabling the PA is desired. If the PA has an enable pin, the marker can be sent directly to that pin to toggle it with precise timing. If the PA uses MIPI or another digital protocol, the marker can instead trigger a digital pattern instrument, telling it to send the appropriate commands. The SG script can also send a trigger to the signal analyzer, starting an acquisition. Handshaking between the SG and SA allows the next measurement to begin the moment the previous one completes. This means every aspect of the timing of your test can be fine-tuned for speed and precision, allowing a full test suite to occur quickly enough that the PA thermal state changes as little as possible.

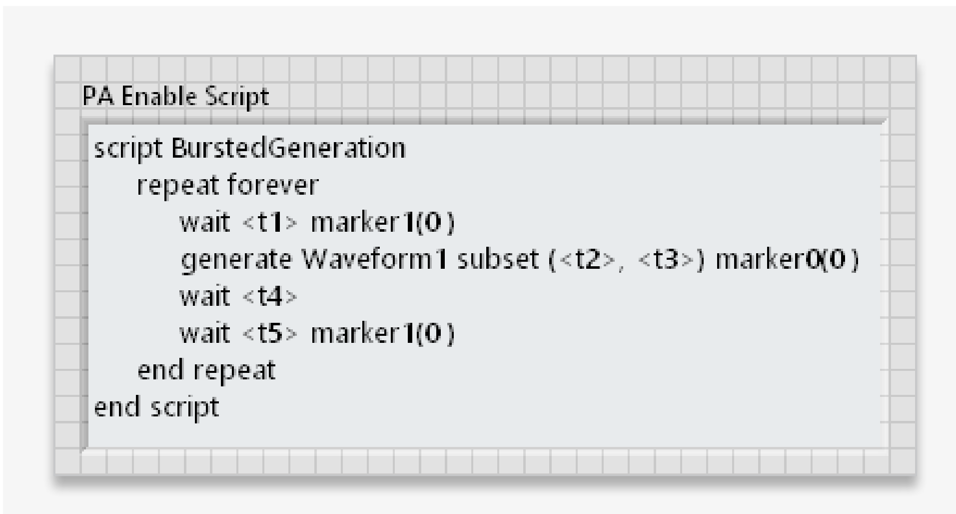

FIGURE 6

Here is a sample generator script used to synchronize other modules. Marker 1 toggles the PA Enable pin, while Marker 0 triggers the analyzer at the beginning of the RF burst. T1 through T5 allow full customization of the PA Enable timing, as well as the duty cycle of the waveform.

The interplay between modules often contributes to the complexity of a test sequence. For instance, while bringing up a PA, a designer often must bias the transistor in a certain order and carefully increase one voltage while monitoring how much current flows through the transistor, setting it to an ideal current draw. They then bring the RF power to a certain point, run a DPD sequence (perhaps involving multiple iterations of DPD), then perform a series of measurements. This process must be approachable from both a manual soft front panel experience and a programming experience, all while allowing for quick modifications. NI's panels and drivers allow these routines to be performed quickly and effectively.

Customizable Hardware and Software

Leveraging the PXI platform allows NI to take a modular approach to automated test. Any PXI module can be added to a tester and programmed accordingly. This means customers are not limited to a specific set of devices that may become obsolete and require the purchase of an entirely new tester. Likewise, as test needs and volume change over time, modules may be repurposed accordingly. Peripheral modules such as switches, oscilloscopes, and SMUs can be implemented in any quantity, providing further tester customization. Software product licensing gives users access to quarterly driver updates, ensuring that every tester always has the latest measurements, implemented according to the 3GPP specification.

Another advantage in the NI portfolio is the latest vector signal transceiver, the PXIe-5842. It provides continuous frequency coverage from 30 MHz to 26.5 GHz, with a mmWave extension option that increases that coverage to 55 GHz. With 2 GHz of RF bandwidth across most of this spectrum and best-in-class EVM, the 5842 is an attractive option for base station PA test.

Learn more about the PXIe-5842

Flexible Input Waveforms

Because of the impact heat has on the performance of a PA, tests must be designed in a way that ensures test cases properly simulate real-world use cases. One way the thermal profile of the part can be fine-tuned is by altering the duty cycle of the input waveform, allowing time for the part to cool between test transmissions. Providers may also require measurement results for the PA under single-tone or multi-tone transmission cases, with specific criteria depending on the waveform. Given the number of input waveforms, duty cycles, and other customizations a provider may request, waveform generation can become a confusing mess. NI's SG script and powerful APIs solve these challenges by allowing an arbitrary number of waveforms to be generated, pulsed, and swept on both the SG and SA side, scaling to handle any combination of these cases.

Conclusion

High-power PA test requires careful consideration due to the unique operating conditions and desired data from these high-performance parts. NI has an extensive portfolio of RF and peripheral PXI modules and an adaptable software strategy; our approach to high-power PA test allows for specific solutions tailored to the needs of engineers in every phase of the design and manufacturing process. Designers and applications engineers looking for quick measurements in a benchtop-like environment will find products like InstrumentStudio™ software and RFIC Test Software to meet their needs. Characterization engineers looking to stand up a full test architecture to automate in-depth test routines will find NI's powerful APIs helpful in programming their own test architectures. Production test engineers will find the Semiconductor Test System (STS) helpful for high-volume test solutions at the wafer or packaged phase of the manufacturing process. NI understands the problems faced by high-power PA designers and is committed to meeting these challenges as they continue to evolve.

Learn more about NI Semiconductor Test System (STS)