

Designing Robust 5G Power Amplifiers for the Real World

Authentic modulation sets the context for delivering predictable, high-performance 5G millimeter-wave systems

Shift Left for 5G Power Amplifier Predictability

Datasheets have been a mainstay of electronic design practices for decades. Manufacturers do their best to characterize the most important parameters of a component, leaving engineers to carefully select components and design them into systems. This approach relies on predictability — expecting a component placed in a system will not deviate from its advertised behavior under any conditions.

5G millimeter-wave (mmWave) design shatters naïve predictability assumptions. Parts tested in synthetic conditions with signals at a few frequencies fall under the influence of hard-to-predict effects when subjected to complex, wideband 5G modulation. Waiting until the hardware prototyping stage, where reduced performance or instability can trigger expensive respins, to run authentic modulation against a 5G power amplifier (PA) design is risky.

There is help for 5G PA manufacturers, 5G user equipment (UE) and gNodeB designers, and 5G system integrators in state-of-the-art RF electronic design automation (EDA) tools, such as Keysight PathWave Advanced Design System (ADS) 2024 and PathWave RFPro.

This solution brief discusses the 5G mmWave context and a three-phase RF EDA workflow enabling a shift left — simulating earlier in the design life cycle — for improved 5G PA predictability.

- Multi-technology placement automatically inserts 5G PAs, with their physical and behavioral modeling characteristics, into dense structures ready for electromagnetic (EM) simulation.
- High-fidelity EM / circuit co-simulation with authentic modulation over a sufficiently wide bandwidth sets up crucial stability and load-pull analysis for achieving 5G PA performance expectations.
- Iterative thermal, error vector magnitude (EVM), and predistortion analysis expose cross-domain effects, discovering hidden weaknesses and protecting against added costs.

Establishing a Virtual 5G mmWave Context

5G system designers face a gap: PAs designed and tested outside a 5G context will likely see anomalous behavior at hardware prototyping. Complex test setups followed by comprehensive measurements are often necessary to spot problems. Fixes range from minor modifications to substituting a PA with better specifications in a hardware respin, with potential schedule and supply chain disruptions.

Yet mmWave designs introduce even more risk amid heightened complexity and reduced margins. Small structures — with integrated circuit and board dimensions close to the wavelength of an mmWave signal — increase the chance for adverse interactions, with three primary root causes:

- Cross-coupling occurs when components are close together in three-dimensional space. A current flow in one section of the board can create EM fields or thermal heating that reaches other nearby parts, altering their behavior. Slightly moving or rotating a part can change coupling.
- Parasitics are instances of resistance, capacitance, and inductance not overtly placed in layouts as components but instead developing because of material properties and layout dimensions. The typical distribution of parasitics along a trace, not lumped at a single point, makes modeling more challenging.

- Cross-domain interactions (such as in Figure 1) happen as effects combine from one or more of the time, frequency, power, temperature, load, and bias domains. Designers often explore these domains one at a time, but in a complex 5G design, it may be difficult but necessary to analyze them all at once.

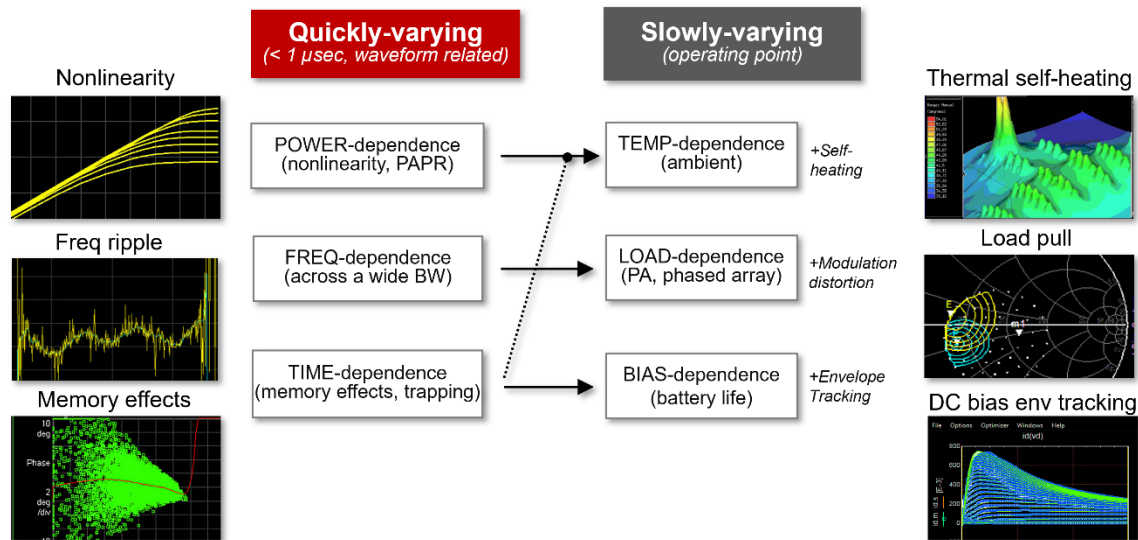


Figure 1. Cross-domain effects can vary quickly or slowly, with one event driving others in one or more domains

No designer would think to test 5G hardware for specification compliance without a 5G waveform. It is a logical step to verify whether the hardware works. Yet many teams still design systems with components, including PAs, that have never seen a 5G waveform. If they have, those PAs now find themselves surrounded by different structures in a new design context with untested cross-domain effects. At the same time, complex interactions happening simultaneously in multiple domains make it impractical to test 5G mmWave in hardware prototypes covering all scenarios.

However, in EM / circuit co-simulation space, 5G mmWave setups and parameter sweeping are more manageable and take far less time. Keysight's measurement science aligns its test and measurement equipment and RF EDA software to deliver these results:

- Multi-technology design automatically meshes each PA into a system layout at full modeling fidelity.
- Stability analysis accounts for real-world EM structures without the uncertainty injected by probes.
- Load-pull analysis represents accurate loading across the 5G PA operating bandwidth at all points.
- Simulation of system-level metrics, including error vector magnitude (EVM), occurs at near-prototype levels.
- Digital predistortion (DPD) for a PA accounts for all signaling, layout and packaging, and thermal effects.

Authentic modulation now becomes a valuable tool for 5G design instead of just end-of-the-project verification. If every 5G PA came with a complete behavioral model in parametric form, designers could rapidly insert it in their designs, thoroughly evaluate the 5G mmWave context accurately, and adjust to meet system-level metrics — all in a single interface using Keysight EDA tools.

Creating Dense Designs That Work

PathWave ADS provides the 5G PA ecosystem with a more predictable design approach. The solution for high-performance 5G PA design is the Keysight W3608B plus the W3050E PathWave ADS electrothermal simulator, W4540E PathWave DPD Explorer, and the 5G mmWave design kit with its 50 GHz transistor models. W3608B bundles the PathWave ADS Core with SmartMount technology, RFPro, and virtual test bench (VTB) libraries.

SmartMount streamlines dense structure layouts

SmartMount enables designers to add a component built with one technology into a design using different technologies without manual steps, estimation, or modification of the base design. PathWave ADS layout automatically maps details from a SmartMount component into the host design, meshing material parameters, layers, orientation, and alignment. This detailed mapping flows into automatically created EM / circuit co-simulation models in RFPro, including accurate representations of parasitics.

At a minimum, manufacturers can optimize and characterize components in PathWave ADS with authentic 5G modulation applied before device and equipment designers select their components. SmartMount takes 5G PA design workflows to another level. Manufacturers can share an executable datasheet of a fully modeled 5G PA, which their customers can drag and drop into their PathWave ADS designs.

SmartMount accepts the PathWave ADS-modeled 5G PA placed in any orientation on any layer of the base stack (Figure 2) and automatically updates the entire stack model. If the 5G PA needs to move in the PathWave ADS layout, designers do not have to reconfigure the stack model manually. Automatic mapping of stacks improves stability, load-pull, thermal, EVM, and DPD evaluation accuracy. Smart Mount also streamlines workflows in two other important ways:

- 5G PAs can combine with other chips in mmWave integrated circuits (MMICs).
- Multiple 5G PAs may appear in a board design, which is often the case when you have channels of multiple-input / multiple-output signal processing.

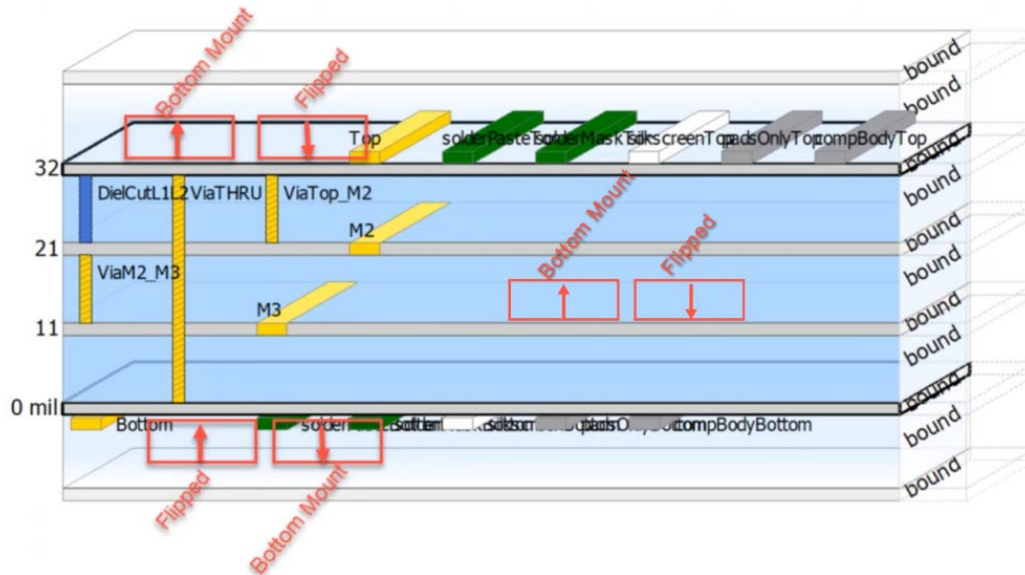


Figure 2. 5G PAs and other chips can bottom-mount or flip-mount on any layer in a base stack using Keysight SmartMount technology

Figure 3 shows a portion of a board design with two MMICs combining 5G PAs and phase shifters for beamforming, placed in a PathWave ADS layout. Once one MMIC is in place with its structures and successfully simulated, cloning the layout for additional channels is easy. SmartMount automatically keeps up with the multi-technology stack at each step in layout — in this case, including the packaging and substrate in the MMICs and the base board layers and conductive vias.

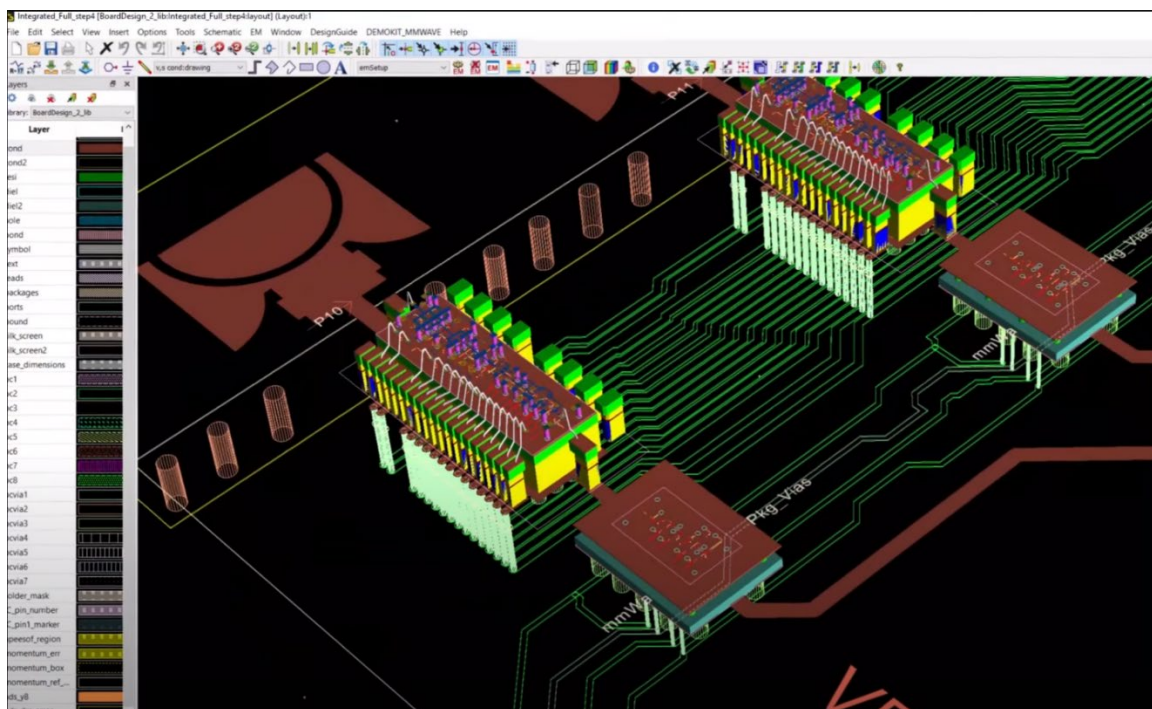


Figure 3. Two 5G phase-shifter and power-amplifier MMICs mounted on a board layout in Keysight PathWave ADS with SmartMount

Everything in the streamlined workflow runs in a single PathWave ADS workspace and uploaded libraries without manual formatting or database conversions. The same steps would be labor-intensive and error-prone without SmartMount technology.

SmartMount facilitates smoother handoffs between designers in the same organization or between organizations in a supply chain, from chip manufacturers to system integrators. With SmartMount, authentic 5G modulation, and on-demand simulation as design tools, teams can insert components into systems more efficiently and accurately capture and analyze their context in detail.

Stability analysis with Winslow probes yields high accuracy

Small structures, high frequencies, and complex 5G modulation make resonance more common. Designers can guess where and how much capacitance to place when stabilizing a 5G PA. Or they can use Winslow probes to modify structures and components for stability analysis.

Winslow probes (or WS-probes) build on non-invasive impedance probes known as S-probes. Ideal sources enable in situ bidirectional S-parameter computation, but where S-probes lose accuracy under feedback, Winslow probes remain accurate. Figure 4 shows Winslow probes inserted using PathWave ADS around a transistor in a power amplifier. Driving point analysis with Winslow probes generalizes to varying loads with rapidly computed results from Kurokawa and other stability methods.

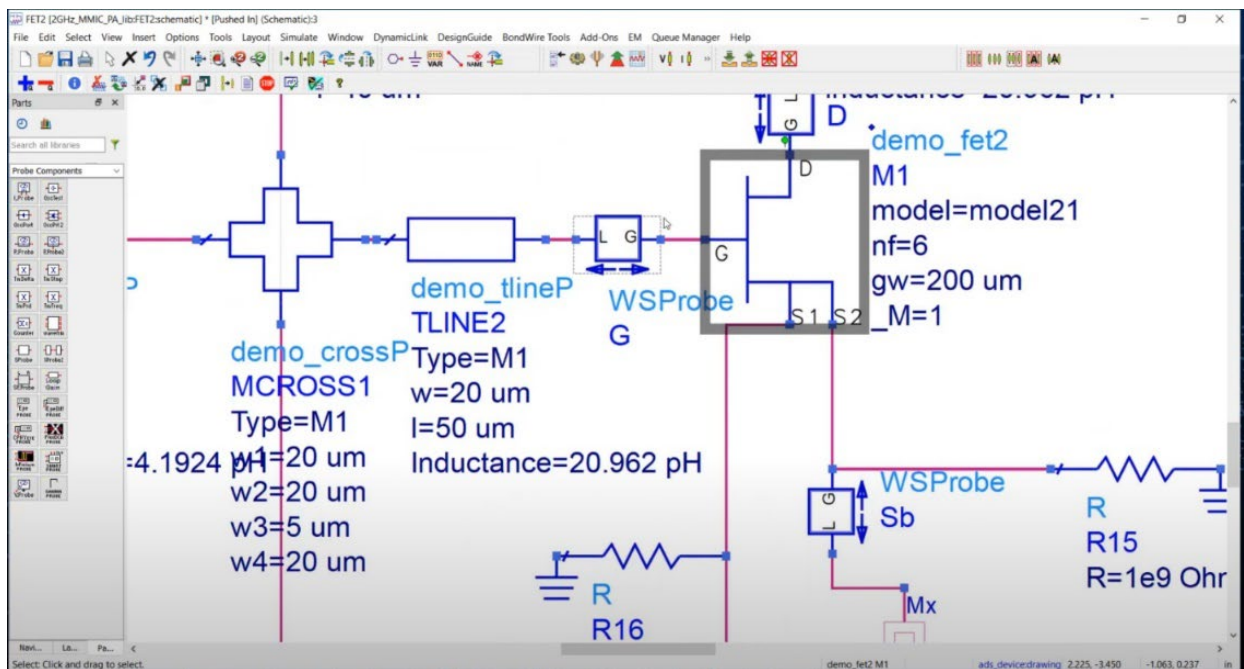


Figure 4. Winslow probes inserted in PathWave ADS on a gate and source of a transistor in a power amplifier

Load-pull analysis with Python-generated contours covers more scenarios

After achieving stability, load-pull analysis sweeps simulations with a range of impedance loading on a PA, looking for power delivery changes. In PathWave ADS, precalculated EVM and adjacent channel power ratio (ACPR) contours generated by Python expressions simplify accurate analysis. Python also enhances data post-processing. Designers can control data displayed in PathWave ADS, with one example shown in Figure 5.

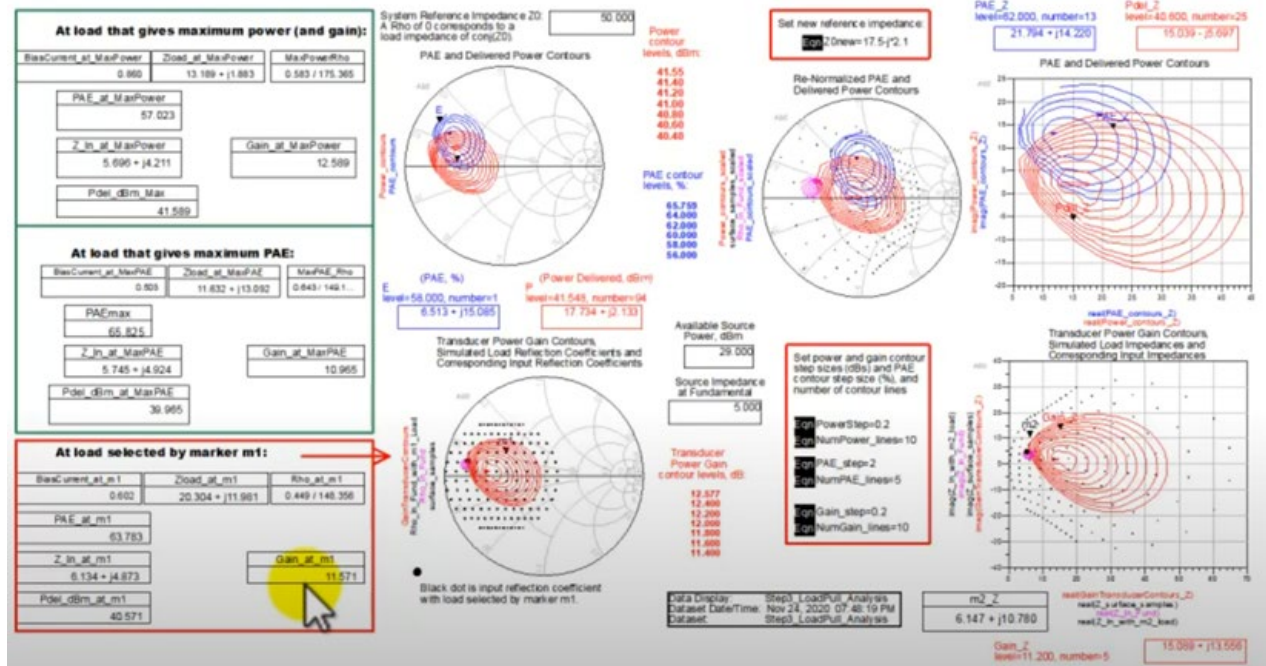


Figure 5. Load-pull simulation in PathWave ADS showing power-added efficiency and delivered power contours

Exploring Working Designs for Weak Points

Stability and load-pull analyses increase confidence a 5G PA design works as intended under benign conditions and can point to efficiency and power delivery optimizations. But toss in unexpected thermal loads and coupling, noise, distortion, spiking waveforms, process variations, and more real-world effects, and design weaknesses appear. In a 5G context where margins are already thin, overdesigning may seem easier than testing for those weaknesses. Without more analysis, overdesign may add costs.

An essential element of PathWave ADS is a seamless transition between layout and various simulations without manual reformatting steps. Freedom to explore deeply and more often with iterative simulation uncovers issues that would likely escape physical testing or an end-of-project simulation run for verification.

Electrothermal simulation looks in and around structures

Densification presents unique thermal challenges. Thermal coupling between structures becomes a more significant problem than self-heating. Small changes in layouts and packaging can introduce or alleviate coupling. Finding potentially destructive hazards requires thermal simulation in time and frequency domains, along with a complete understanding of materials and their thermal properties.

Developed from innovative Keysight HeatWave thermal solver technology for high-transistor-count digital microprocessor designs, the PathWave ADS electrothermal simulator provides a 3D visualization of dynamic thermal behavior (Figure 6). It incorporates power dissipation from PathWave ADS circuit simulation, structure locations from PathWave ADS layout, material thermal properties from process design kits, and multi-technology stack information from Smart Mount in detailed analysis.

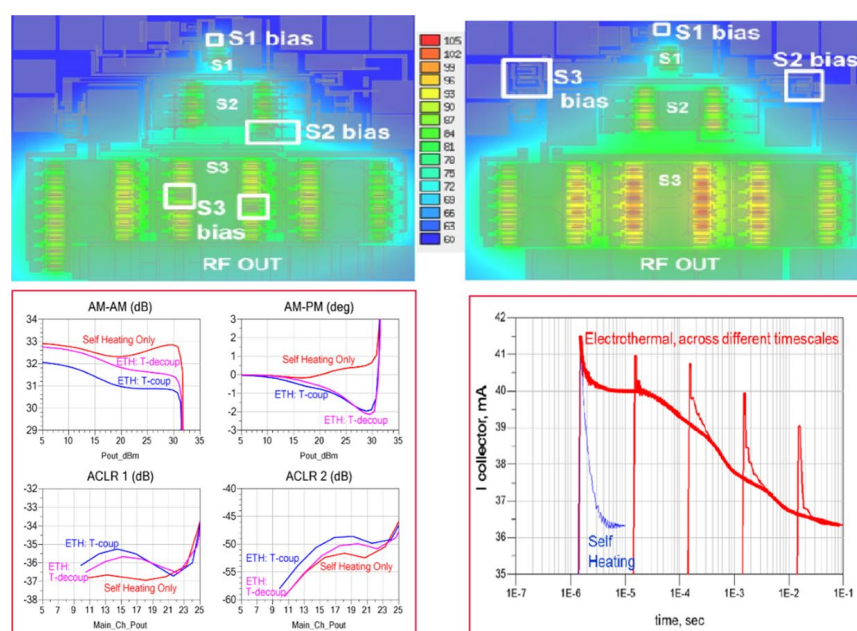


Figure 6. The PathWave ADS electrothermal simulator delivers a 3D visualization of circuit hot spots plus time-varying behavior

Virtual test benches provide authentic waveforms

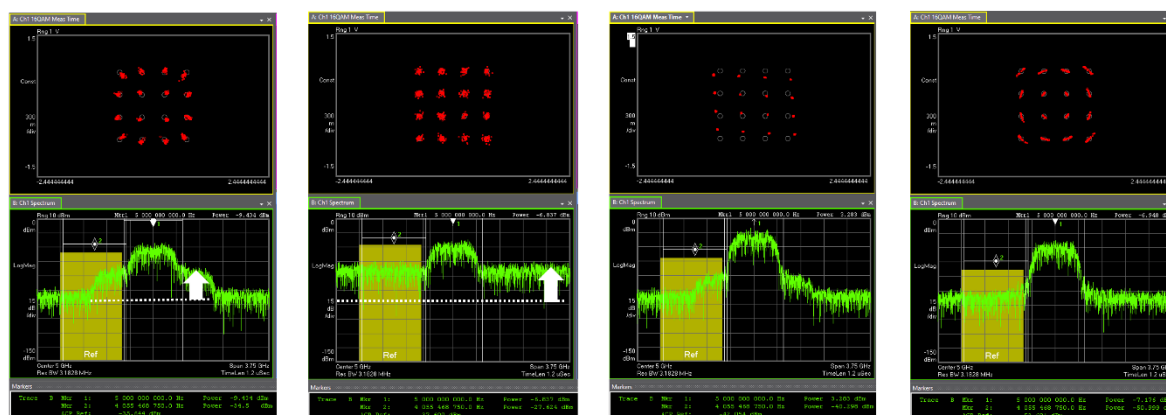
Keysight VTBs move modulation to the point of design, which is essential for 5G PA suppliers to establish a proper context for testing and characterizing components. 5G waveforms are complex yet well-known from 3rd Generation Partnership Project 5G specifications. VTBs in PathWave ADS provide specification-compliant 5G waveforms as a starting point.

VTB waveforms work equally well in both virtual and physical space, a requirement to achieve similar results from simulation and measurements. The same waveform used for simulation in PathWave ADS can also drive waveform generation in Keysight test and measurement instruments. VTBs can sweep parameters, just as a physical waveform generator would. Adding real-world effects like measured channel impairments can make VTB waveforms highly accurate.

EVM analysis enhanced for faster iterative design use

EVM represents the customer's experience inside a 5G design, whether seen by a 5G UE or gNodeB designer, a system integrator, or an end user with a 5G device. If EVM falls out of specification, throughput or data quality suffers, and the user experience degrades. Figure 7 shows a simple 16-point example; zero EVM would have uniformly shaped, equally spaced red dots in a perfect square pattern.

Real-world stress on a 5G design is only possible using an authentic 5G waveform with modulation complexity and bandwidth. However, full-length waveforms also increase the demands on simulation. Time spent in a single simulation multiplies with each iteration. Complex signals and wide bandwidths produce volumes of simulation data for review. Slow runtimes and tedious reviews can discourage teams from taking full advantage of simulation as a design exploration tool for evaluating options and increasing first-pass success when moving to hardware.



Non-linearity (distortion)

White Noise

IQ imbalance

Phase noise

Figure 7. EVM degradation in a 16 QAM constellation under various impairments

EVM is a complicated measurement, especially with hundreds or thousands of points in the modulation constellation. A pure 5G waveform passing through a 5G PA undistorted has zero EVM, but some distortion usually exists. The Keysight PNA-X network analyzer team made a powerful observation: directly isolating the distortion in a known modulated signal speeds up EVM measurements.

The technique, known as distortion EVM, pulls out the linear component of a signal, leaving a distortion component remaining. Time domain EVM analysis carries Fourier equivalence to frequency domain computations, according to Parseval's theorem (Figure 8). Interestingly, the time and frequency domain analysis agreement improves as power increases. Furthermore, distortion EVM applied in the frequency domain has a higher dynamic range. This advantage can reveal performance details of 5G PAs previously masked by noise.

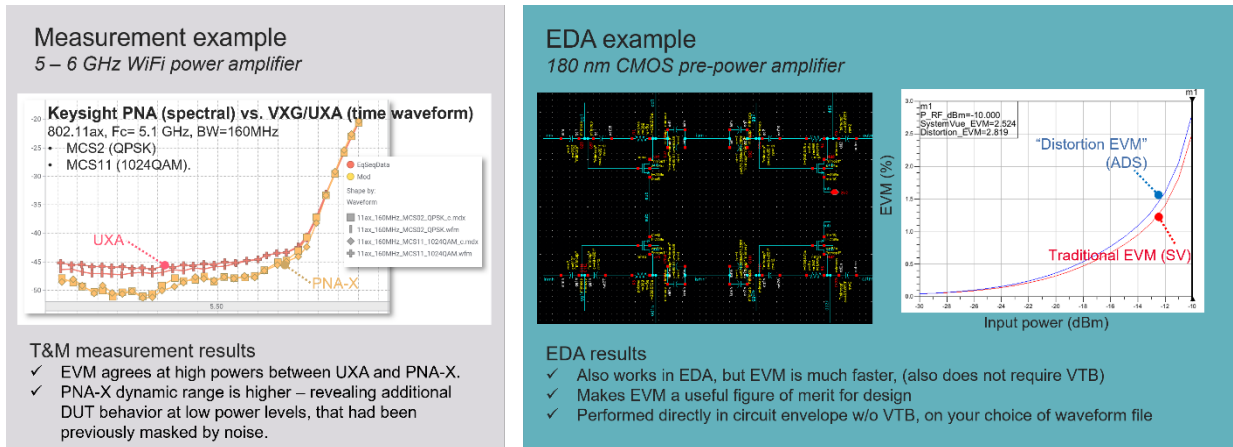


Figure 8. Fourier equivalence leads to matching distortion EVM simulation compared with traditional EVM algorithms

In simulations, not reanalyzing the “clean” linear signal during measurements dramatically cuts the analysis time, again with minimal impact on EVM results. Figure 9 also shows a strong match between distortion EVM calculations in PathWave ADS compared with a traditional EVM algorithm.

Digital predistortion analysis using DPD Explorer

Distortion is a crucial criterion for 5G PAs but is challenging to balance with high power delivery and wide bandwidth. DPD techniques adjust distortion and optimize EVM and ACPR with an inverse function input to the PA, analyzed through simulation in PathWave ADS and a companion tool, DPD Explorer. The spectrum power plot in Figure 9 shows a 5G PA response before DPD (blue) and after DPD (magenta).

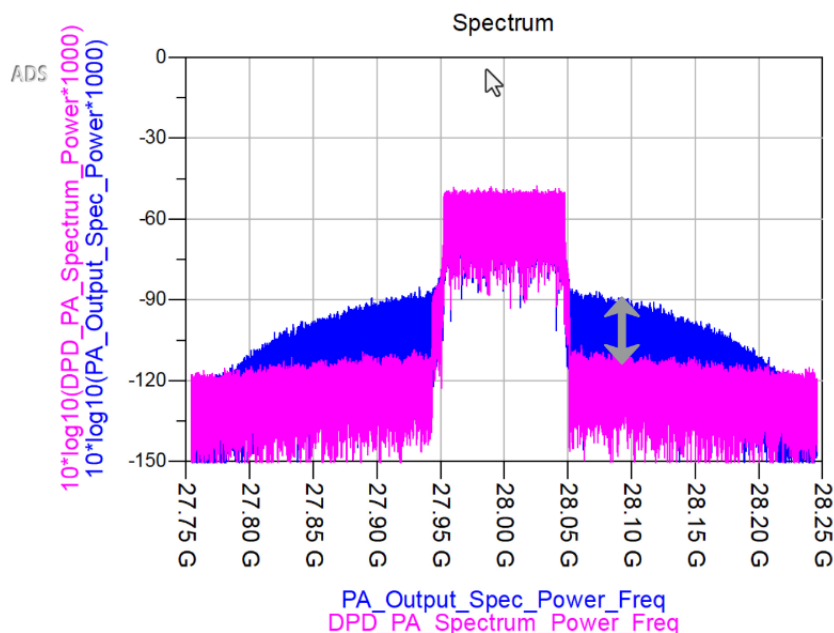


Figure 9. Keysight PathWave DPD Explorer compensates for 5G PA distortion, resulting in a significant EVM improvement

DPD encapsulates the benefits of shift left in 5G PA design processes. Creating adequate DPD compensation requires a thorough understanding of structures surrounding a 5G PA and authentic modulation supplied to it. While many DPD techniques use FPGAs to shape the compensation response, allowing for some adjustment after measurements, a virtual exploration of structures around the 5G PA may provide insight into layout or component changes that would offer more performance improvement. Revisions made while the design is still in virtual space are inexpensive and quick.

Simulating Faster with Statistical Methods

All this deeper analysis in PathWave ADS fits into a 5G PA workflow with faster simulation. More modeling detail, complex modulation, and wider bandwidths would typically drive simulation times up or push users onto more powerful simulation platforms. Decades of experience in RF EDA and test and measurement equipment put Keysight in a unique position in the industry, fostering innovation to reduce simulation processing. Three statistical methods, developed in parallel between hardware and software teams, deliver accurate simulations in dramatically shortened time.

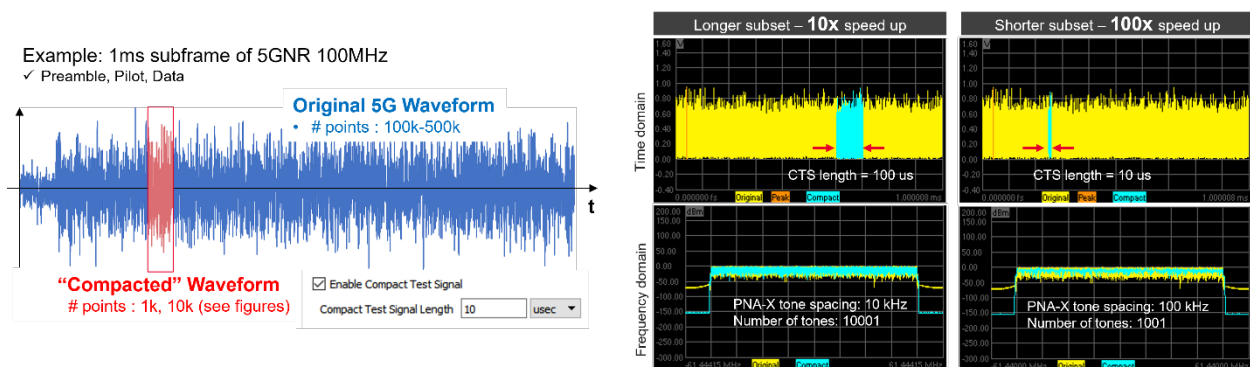


Figure 10. Compact test signals create a statistically relevant subset of a 5G waveform with fewer points

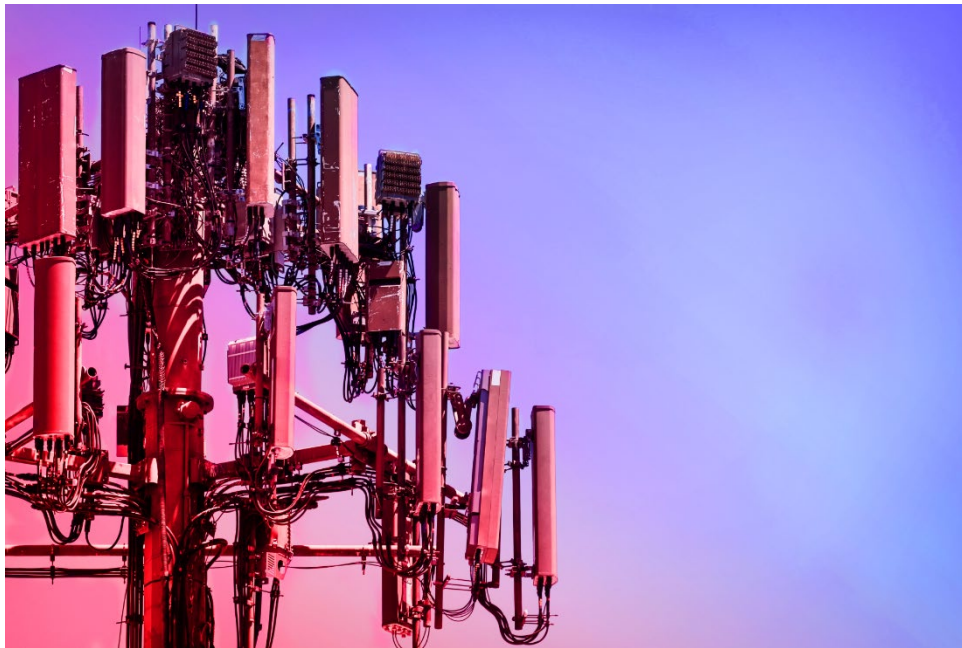
Compact test signals are an example of Keysight's unified measurement science. A handful of frequency points across a wide bandwidth are insufficient for contextual testing or simulation, but using too many points across that same bandwidth sends simulation times spiraling. A complex 5G waveform with real-world impairments added might contain as many as 500K points. Keysight's PNA-X network analyzer team set out to create a solution. Using statistical metrics, the team observed that a few milliseconds of a 5G waveform (Figure 10) with similar bandwidth excursions and amplitude distribution (applying complementary cumulative distribution functions) could substitute for the entire waveform with minimal impact on EVM results.

Using the same technology in PathWave ADS, teams can control the length of the compact test signals for simulation. They can reduce 5G waveforms with 100K – 500K points down to compact representations ranging from 1K – 10K points. Since the only adjustment is to the waveform, accuracy remains intact with modeling and simulation algorithms at full fidelity. The corresponding time savings in a simulation is one or two orders of magnitude, making iterative EVM checking in a routine PathWave ADS design workflow for 5G PAs attractive.

Convolution provides complex signal representations. Most EM solvers use only polynomial approximations for faster simulation. While quick to compute, polynomials can sacrifice accuracy, depending on the time step, and sometimes fail to converge properly, leaving signals with offsets and ringing. As bandwidth increases, such as in 5G, the fidelity of representing frequency-dependent components becomes increasingly essential for accurate EM simulations. Convolution helps capture dynamic behaviors in structures and packaging, delivering a higher-fidelity analysis.

Circuit envelope techniques also help PathWave ADS automatically localize some composite behavioral models of transistors and structures on the fly, creating precalculated surfaces to simulate against. These surfaces consider frequency-dependent 5G modulation details across the bandwidth, including signal amplitude and memory effects. They can speed up simulation by two orders of magnitude compared with using the complete solver on discrete models. The impacts of fast envelope equivalents on analysis accuracy are minimal.

Keysight continues its research into measurement science, continuously updating modeling and algorithms in PathWave ADS and companion tools for 5G mmWave designers. As each new software release launches, PathWave ADS users can keep pace with these advances.



Comprehensive 5G PA Design Solutions

Simulating 5G PA designs at the component and system levels with authentic modulation and high-fidelity behavioral models increases predictability, lowers risk, and shrinks schedules. PathWave ADS enables multi-technology layout and multi-domain analysis, evaluating the impacts of 5G PA design choices while delivering accurate results in a single virtual workspace.

Deeper analysis in PathWave ADS helps designers understand how a PA performs in their 5G mmWave context, preventing underdesign and overdesign. Information sharing across the supply chain using modeling and simulation with authentic modulation promises to create more opportunities in the fierce competition for 5G design wins. Moving into a Keysight RF EDA workflow and mastering cutting-edge 5G PA design practices should be a priority for teams at 5G PA manufacturers, device designers, and system integrators.

For more information on these Keysight RF EDA solutions, please visit the following links:

[What's New in RF and Microwave Design? | Keysight](#)

[PathWave Advanced Design System \(ADS\)](#)

[PathWave RFPro](#)

[ADS Electrothermal Simulator](#)

[PathWave DPD Explorer for ADS](#)

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