

## Solving Electromagnetic Densification at the Point of Design



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*Density, both informational and physical, determines complex RF system success or failure. Systems like 5G and Wi-Fi 7 pack more information into precious spectrum on smaller base stations, access points and devices. Finding density-related problems at prototyping, or later in deployment, adds cost and risk. Traditional RF electronic design automation (RF EDA) workflows are falling behind density challenges, analyzing one problem at a time and missing too much. A new approach: solving electromagnetic (EM) densification at the point of design.*

**S**hift left—earlier visibility on designs in virtual space is the fundamental purpose of EDA tools. When modeling and simulation reflect real-world performance, design problems become easier to fix. Still, complex densification problems have many domains with combined interacting effects. Pulling EDA and test and measurement tools together in a workflow knocks out EM problems earlier, before committing to hardware. This article reviews three examples regarding how these workflows are solving EM densification:

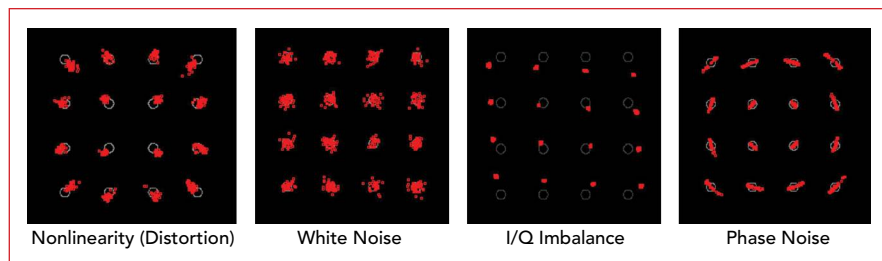
1. Analyzing wideband designs using modulated signals and authentic waveforms<sup>1</sup>
2. Visualizing stability with EM-circuit excitation early in design and physical layout<sup>2</sup>
3. Increasing confidence in EM design integrity through iterative co-simulation.<sup>3</sup>

EM workflows appear across the ecosystem, soon connecting vendors, customers and customers-of-customers through “simulatable datasheets,” which is briefly explained.

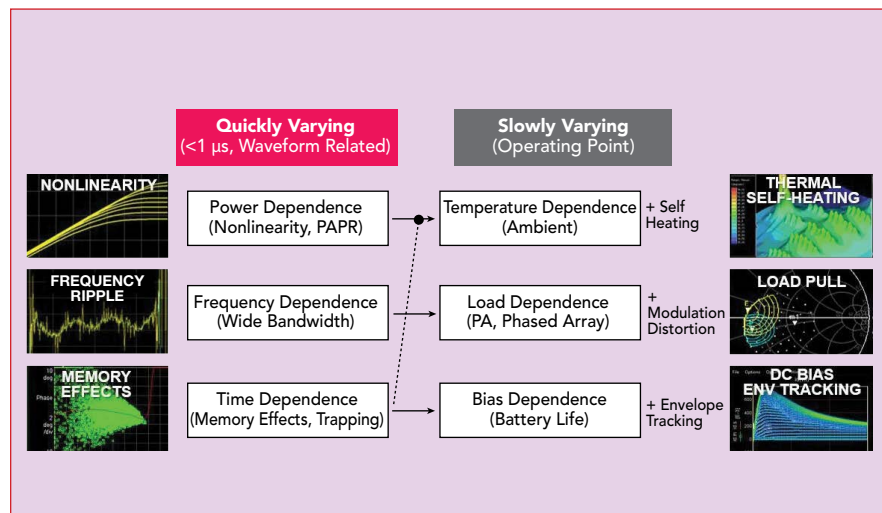
### TAKING ON INFORMATION DENSITY

Wireless systems broke free of some limits, but moving information still has boundaries. When Claude Elwood Shannon explored communication channels, he saw their data capacity maximized by bandwidth, using signals with many noise-like characteristics. Analog systems with inefficient modulation left data-hungry services unsatisfied. Digital systems packed more bits into each transmitted symbol, saving bandwidth, but true to Shannon, complexity rose and specifications tightened.

Today, complex modulations are part and parcel of RF system specifications including 5G and Wi-Fi 7. Digital quadrature amplitude modulation (QAM) arranges data points in a two-dimensional constellation. Higher-order constellations put points closer together, requiring a higher signal-to-noise ratio to keep error rates down. 5G new radio (NR) features 256-QAM modulation delivering eight bits per symbol. Wi-Fi 7 is moving to 4096-QAM modulation for



▲ Fig. 1 EVM impairments and symbol errors in a 16-QAM constellation.



▲ Fig. 2 Factors affecting PA performance and EVM.

12 bits per symbol. Orthogonal frequency division multiplexing bundles dense carrier sets into a narrow bandwidth leading to sudden intense peaks, as much as 10x the average power level, creating dramatic noise-like stresses on radio architectures. Both 5G and Wi-Fi 7 add MIMO antenna technology and spatial multiplexing for increased throughput within a given bandwidth.

In this light, error vector magnitude (EVM) emerges as a critical metric for signal quality and for transceiver and equipment performance. It is an RF designer's proxy for bringing the customer experience forward to the point of design. EVM measures how accurately transmitted symbols match their intended spot in the QAM constellation (see **Figure 1**). Higher-order QAM constellations put points close together to start. Imperfections in a radio shift constellation points off their mark. These effects include non-linearity, noise, loading and channel interference. When points are close together, accurate discrimination between adjacent points becomes harder.

All this leads to an observation. It is not possible to design a 5G NR or Wi-Fi 7 compliant radio without incorporating a higher-order modulation scheme per specification. To prove such a transmitter works, authentic higher-order modulated signals of sufficiently wide bandwidths are required to measure EVM performance at system validation. In fact, every modern digital RF system relies on complex modulation for achieving its desired information density. For these systems, there is no such thing as a choose your own compliance adventure.

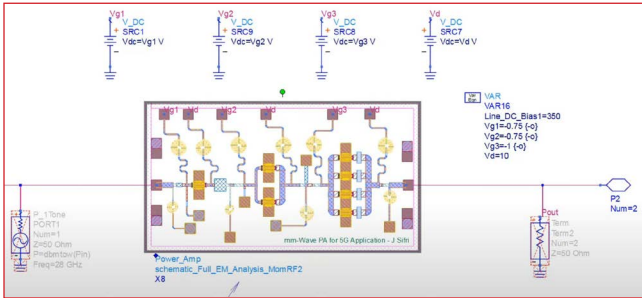
Yet, that is exactly how many designers pursue physical design densification. At the point of design, EDA tools perform schematic capture, physical layout and localized simulations of design choices. Are those choices understood in a system context? Does optimizing one factor have consequences on others? Is it possible to tell what those interrelationships might be? Simulating approximate or incomplete models with simplified signals looking for one problem is an excellent way to miss others.

Those mysteries lead teams to fall back on physical prototypes for observing and troubleshooting RF issues. Hardware re-spins, however, are expensive schedule killers. Anything from functional design errors to hard-to-reproduce interactions under dynamic conditions can trigger a re-spin. Waiting until prototyping to find any lurking issue leaves RF designers at the mercy of higher risks and project costs.

Let us return to the EVM example and look at why modulated signals are important for accurately characterizing power amplifiers (PAs). S-parameters and pure sinusoidal stimuli provide a modeling baseline of raw PA performance. The same PA in a hardware prototype running against complex modulation may fall apart in unexpected ways. Why? Combining physical densification, power, modulated signals and a host of parasitic effects pushes assumptions, exposing various design weaknesses.

Effects factoring into EVM spread across domains in two categories as shown in **Figure 2**. Quickly varying effects are waveform-related and are how information density shows up. Besides power effects, demanding signals bring implications in both frequency and time domains. Slowly varying effects impact a device's operating point and are often byproducts of physical density. Thermal, load and bias dependence reveal issues with stability, coupling, resonances, frequency shifts, matching and package interactions.

These effects are not entirely separable. A complex waveform can set off time-dependent memory effects such as charge trapping and self-heating. Sweeping frequency across a wide bandwidth finds linear impedance mismatches and ripple varying across the band. However, a wide bandwidth waveform excites all factors simultaneously, creating "rogue waves" with infrequent and sudden signal peaks 8 to 13 dB above the average power level. Under extreme peak-to-average power ratio conditions in regulated frequency bands, PA energy efficiency, signal quality and output power become harder to optimize. Modulated



▲ Fig. 3 5G mmWave PA design using PathWave Advanced Design System.

waveforms with accurate carrier dynamics uncover more issues than one-tone and two-tone analyses using harmonic balance.

This highlights the risk of waiting until hardware prototyping before fully exercising RF designs. Staging physical effects in combination may also be exceedingly difficult, which leads to latent problems cropping up in system deployment. In virtual space, simulators can sweep combinations of parameters in the presence of authentic wideband signals; but higher bandwidth signals also force more data collection, slowing the characterization process.

For increased test coverage of parametric scans, intelligent test and measurement trade-offs on signal complexity reduce measurement time with techniques like signal compaction and modulation distortion (or distortion EVM). These same techniques can apply to simulations, along with intelligent trade-offs for accelerating RF characterization without sacrificing fidelity. An example is fast circuit envelope technology in EM co-simulations, capturing linear frequency responses, loading, power dynamics and bias effects and even

memory effects in a run-time, on-the-fly modeling step.

Figure 3 shows a mmWave PA design and Table 1 shows the PA simulation results from 50,000 points of a 5G modulated source. Applying both compact test signals and fast envelope tech-

niques improves simulation time by 44x with little change in EVM accuracy. This increase in speed is critical to gaining design insights. It is the difference between simulating an EVM test case once at verification versus simulating EVM contours against a parametric scan and making incremental design improvements.

This two-way workflow between RF EDA and test and measurement algorithms enables designers to probe deeper much earlier, handle changes at the point of design and achieve consistency with measured results. Dense systems can be created, simulated, adjusted and re-simulated with authentic signals and combinations of effects modeled. Margins against system-level metrics are no longer a guess.

Modulated signals also enable the system experience to travel up and down the ecosystem. Understanding performance in a customer's environment is key to achieving information density goals. Next is a look at a deeper example where physical density sets up complex EM interactions.

ONE-PASS STABILITY ANALYSIS

Amplifier instability occurs when gain and feedback mix. With fre-

quencies, bandwidths, complexity and physical density rising, resonances are now common. Bypass capacitors may be a fix. Compact packaging makes placing capacitors hard, and where and how much capacitance to use is unclear.

Simulations have hundreds of stability analysis techniques to choose from, most focused on one issue and some difficult to apply. A classic method is the Rollett stability factor, or K-factor, which produces valid results for a known-stable network when ideally terminated. Its two-port linear network assumptions degrade at higher frequencies with complex modulation. Tone-based (harmonic balance) frequency domain simulations might falsely converge for some frequencies, leaving instability undetected.

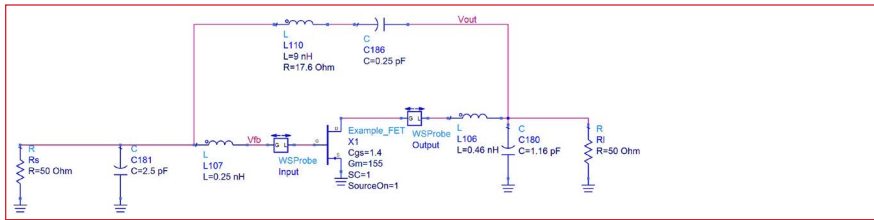
A broader technique is the Normalized Determinant Function (NDF), which also requires a known-stable network. For normalization, NDF needs access to every source in the network. It creates a passive network by setting all active sources to constant “off” values—removing them from the response. Estimating the off values can be error prone, and black-box models can prevent source access entirely. Large transistor networks make for huge matrices and lengthy simulations. Required frequency sweeps beyond operating ranges add more time and complexity.

Non-invasive impedance probes hold more promise. The S-Probe uses ideal sources for “in-situ” bi-directional S-parameter computation but struggles with feedback around the probe, losing accuracy. Since feedback factors into stability, the S-Probe by itself is ineffective for stability analysis. The WS-Probe (also known as the Winslow Probe, for its inventor Dr. Thomas Winslow) builds on the S-Probe, providing accurate results in the presence of feedback.

WS-Probes enable comprehensive stability analysis techniques. Output processing can generate an admittance matrix for high impedance termination conditions, like NDF. K-factor can also be derived.

Figure 4 shows WS-Probes in a simple amplifier-feedback configuration and Figure 5 simulates its

| TABLE 1                                          |                     |         |           |            |                 |
|--------------------------------------------------|---------------------|---------|-----------|------------|-----------------|
| SIMULATION TIME VS. SIGNAL TYPE                  |                     |         |           |            |                 |
|                                                  | Simulation Time (s) | EVM (%) | Pin (dBm) | Pout (dBm) | Power Gain (dB) |
| Envelope (3255 $\mu$ s)                          | 1371                | 4.87    | -15.4     | 19.8       | 35.2            |
| Compact Signal (1000 $\mu$ s)                    | 386                 | 4.67    | -15.4     | 19.8       | 35.3            |
| Fast Envelope (Level 1)                          | 93                  | 4.87    | -16.2     | 19.0       | 35.2            |
| Compact Signal (1000 $\mu$ s) with Fast Envelope | 31                  | 4.68    | -15.4     | 19.8       | 35.3            |



▲ Fig. 4 WS-Probes inserted in a simple feedback amplifier circuit.

loop gain in manual test benches versus WS-Probes—producing exact matches.

One simulation in Figure 5 with the WS-Probe covers the same metrics as 16 different manual test bench simulations. Coverage grows larger with circuit complexity. **Figure 6** shows more metrics including Bode's Return Difference (internal), NDF (external), Driving Point Admittance and Ohtomo loop gain, again with exact matches between manual test benches and WS-Probe results.

There are two other benefits from simulating with WS-Probes. They can aid in a virtual load-pull, examining load-dependent stability by extending results from Driving Point Admittance with Kurokawa stability criteria. They also apply equally well in both small signal

and large signal analysis, avoiding staging difficulties inherent with large signals.

The upshot for densification is more powerful EM-circuit excitation techniques via simulation at the point of design and layout. Using nodal voltages and currents to stimulate an EM structure, circuit plus physical layout attributes, produces a visualization of current density and radiation patterns. Instabilities move around the structure as frequencies vary. **Figure 7** shows a simple amplifier structure at three different frequencies, highlighting a bias feedback problem and a ground plane feedback problem.

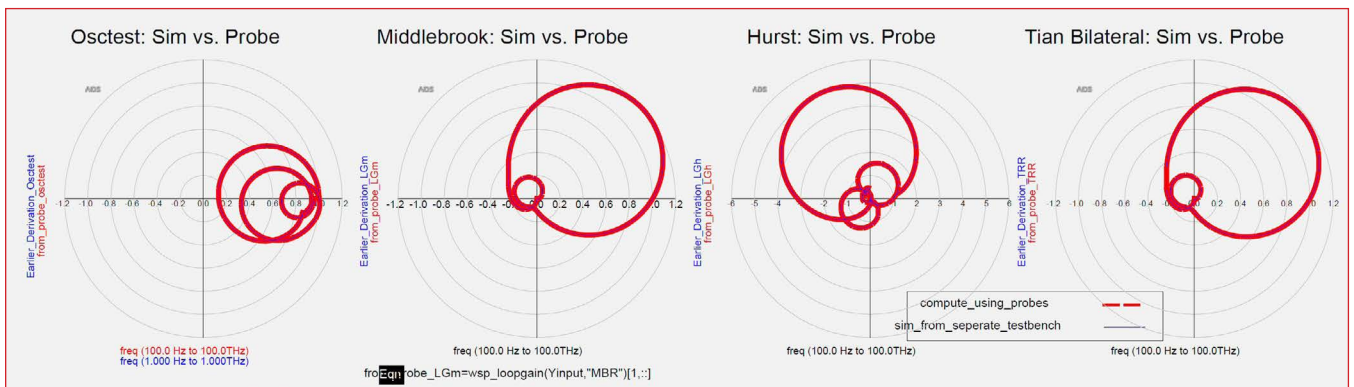
These coupling problems would be near impossible to spot in the lab but are laid open at simulation with non-invasive probes and

“in-situ” analysis. Straight-forward layout changes (pushing bias lines apart and adding vias to the ground plane) improve stability across the frequency range. Extend this example to more complex circuits and larger dense structures, and the power of an RF EDA workflow merging design, layout and simulation is evident. Next is a look at this workflow in more detail.

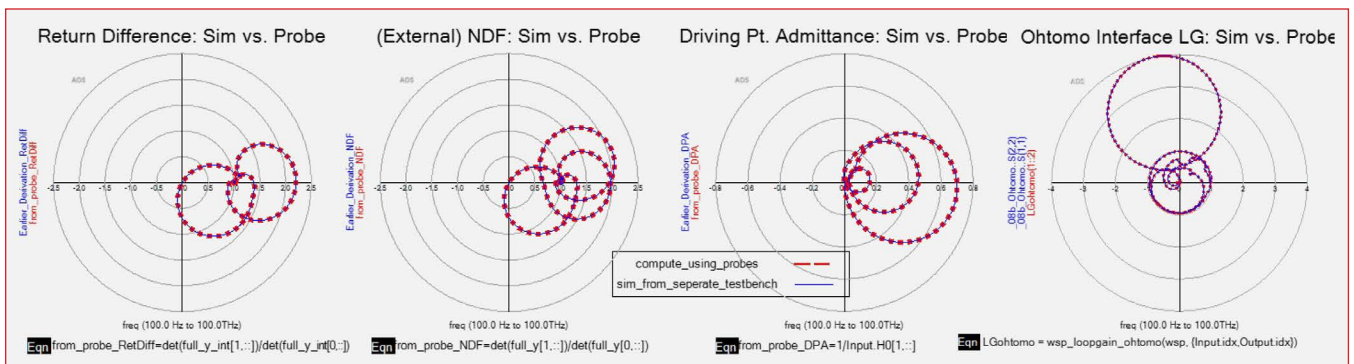
## ITERATIVE EM-CIRCUIT CO-SIMULATION

In complex RF systems, frequencies and integration density are rising, and 3D multi-technology assembly is everywhere. Parasitic effects from packaging, physical routing and interconnects and interactions between components degrade system performance. Some symptoms are frequency shifts, resonances, instability, mismatches, power losses and poor isolation from interference. Design integrity faces major risks; an uncaught mistake costs a hardware re-spin, a design win is undone or a market window is missed.

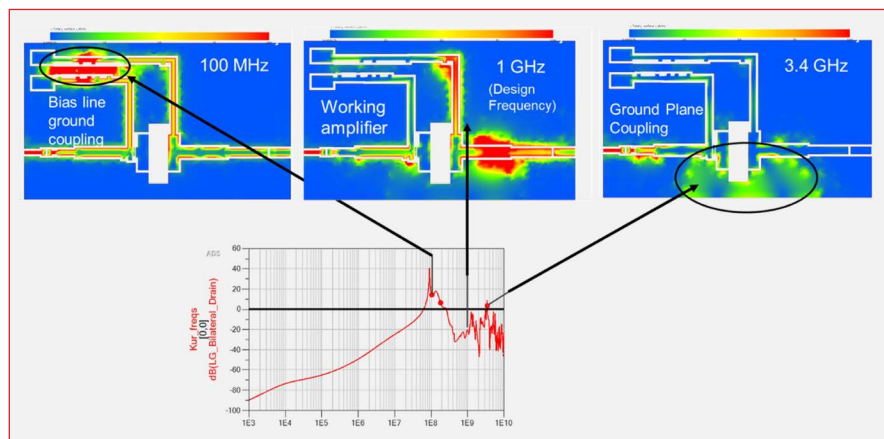
Circuit simulation is familiar territory for most EDA users, it is un-



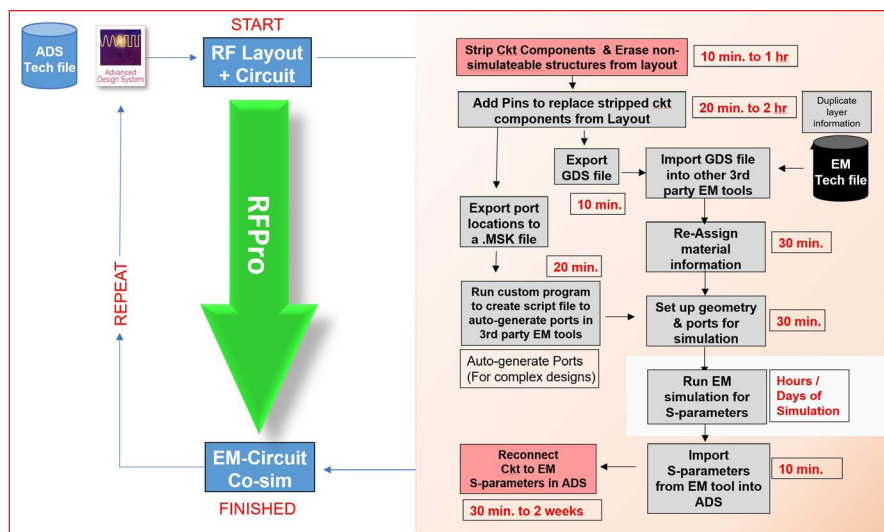
▲ Fig. 5 Oscstest, Middlebrook, Hurst and Tian Bilateral loop gain, comparing test benches with WS-Probe simulations.



▲ Fig. 6 Return Difference, NDF, Driving Point Admittance and Ohtomo loop gain, comparing test benches with WS-Probe simulations.



▲ Fig. 7 EM simulation of an amplifier in PathWave RFPPro, showing instability locations at several frequencies.



▲ Fig. 8 In-situ analysis using PathWave RFPPro streamlines EM simulation workflow.

thinkable not to take advantage of it. Toss in EM structures and effects, and accurate simulation gets more challenging. As previously shown, there are now innovative and effective EM simulation techniques for densification problems. The question becomes how to fit these techniques into RF design workflows.

One reason teams may be treading carefully is that there are different, disjointed EDA tools for different jobs in the workflow. Becoming proficient with each tool requires a learning curve, and once a tool is in a workflow it is tough to part with it even if it lacks some features. On the plus side, circuit design capture, circuit simulation and physical layout tools have already merged. Most package assembly and EM simulation tools, however, still add extra steps, especially if bad results send teams back to the drawing board.

Those extra steps can chew up weeks at a time. The right side of **Figure 8** shows data from 10 years of EDA user interviews. It is the process to get a circuit design into a format ready for EM simulation in a third party tool. Some steps are manual, some scripted. Excess components and structures are stripped, EM simulations extract S-parameters and those are then meticulously reconnected back to the original circuit nodes. In every step, especially the first and last ones, there is a chance for an oversight or error.

The left side of Figure 8 shows “in-situ” 3DEM analysis streamlined with PathWave RFPPro. It starts with the original circuit file, extracts and reconnects S-parameters, inserts non-invasive probing automatically and jumps to EM-circuit co-simulation within minutes. Be-

cause RFPPro reads data through an OpenAccess API, it integrates with Keysight EDA platforms or in a mixed-vendor EDA workflow.

One RFPPro customer was able to run only three or four EM simulation runs per week using a third party tool—that customer is now able to do 30. It is more than a productivity improvement, however. Bringing EM-circuit co-simulation into an EDA workflow moves simulation from a limited-use verification sign-off tool to an iterative problem-solving tool at the point of design. Analyzing EM effects becomes routine, like analyzing circuit functionality, and fixes can happen on the spot. Teams can efficiently develop predictable designs with critical EM effects fully assessed before hardware prototyping or deployment. Confidence in design integrity goes up, surprises go down.

These changes point to bigger possibilities in the future for the RF design ecosystem. Vendors design parts, those parts integrate into equipment manufacturer modules and boards, and those fit into larger end-customer systems. Vendor design wins rely on designers at the next level correctly stringing together pieces from different vendors. Aligning data from printed data sheets may produce a fit or it may not.

System-level EM simulation with transportable data and models in simulatable datasheets is the next frontier. Simulatable datasheets for parts will drop into system-level models for virtual performance evaluation. Knowledge about how a part works in an application will flow easily from vendor to customers to customers-of-customers, and back. Teams will not spend time sorting out specifications, but instead will focus on anticipating deployment scenarios at the point of design to achieve design wins.

## DENSIFICATION AS AN OPPORTUNITY

Densification drives stress for teams, designs and processes and it drives opportunity. EM analysis at the point of the design means that when teams find something, they can do something about it. Three areas were discussed:

# TechnicalFeature

1. Information density shows up in far more complex waveforms. Systems demand modulated signals, and so should RF design teams. Seeing, understanding and preserving signal details must be part of the RF design workflow, not an afterthought in verification. RF EDA and measurement science are strongly connected.
2. Physical density, including 3D multi-technology assembly, is spawning more interactions between domains. Interference, crosstalk and parasitic effects can no longer be estimates. Packaging details must be known early. Resonance, thermal and stability concerns need full attention. Finding an issue in hardware is too late and adding EM simulation to workflows is urgent.
3. Shift left will be a competitive advantage. Design in context, in a workflow providing time savings and virtual accuracy using modulated signals and in-situ EM analysis, leads to design wins. If others find issues first, business may be lost. Models and results need to be transportable, ready to connect with other design processes, vendors, customers and environments.

Digital transformation is solving EM densification at the point of design. More versatile analysis engines, behavioral models, tools and IP help designers and their customers create and apply innovative designs in more applications with greater success. ■

## References

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