KEYSIGHT

eBook

Optimize Your RF Board Design Flow

The competitive proliferation of wireless applications in the commercial and aerospace industries is driving the need for fast turnaround on RF boards. Combining electromagnetic (EM) and circuit simulation in a seamless co-simulation environment is key to meeting performance, reliability, and time-to-market goals. Attention to issues ranging from data management to customization using the open-source Python language will help successfully implement a fully integrated RF Board design flow.

Electronic Design

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Wireless Applications

Wireless and other radio-frequency (RF) applications are proliferating in the commercial and aerospace/defense industries. This competitive proliferation is driving the need for fast turnaround times for the complex, high-performance RF boards that find use in radars, drones, satellites, mobile phones, and other wireless end products as well as the subsystems that go into them.

Further propelling the drive for RF board performance is the need for sub-terahertz (up to 250 GHz) frequencies to support 5G/6G transmission of big-data upload/downloads (Fig 1). These frequencies will be essential to achieve the high wireless data rate throughputs necessary to provide the cloud processing of the massive amounts of user and machine data generated by artificial intelligence (AI) and machine-learning (ML) applications.

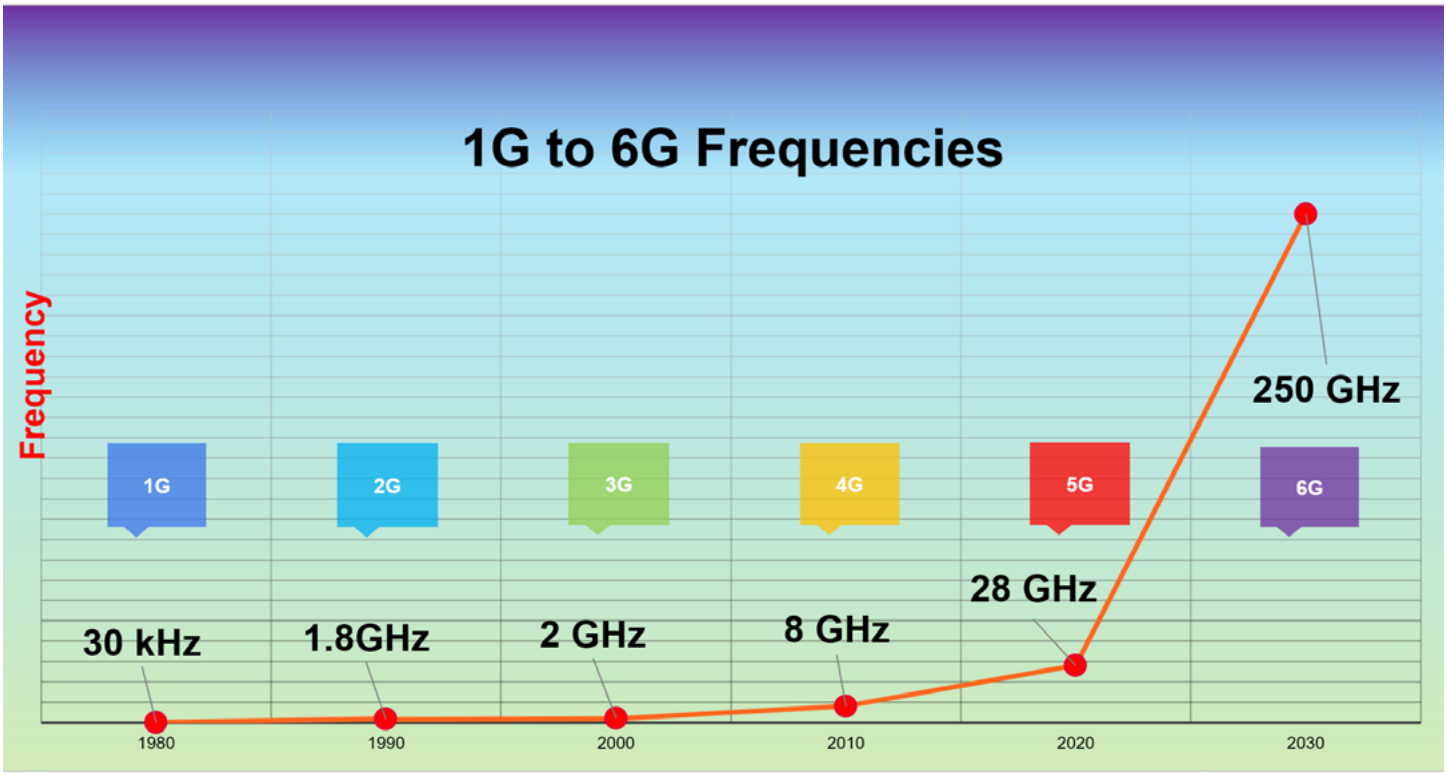


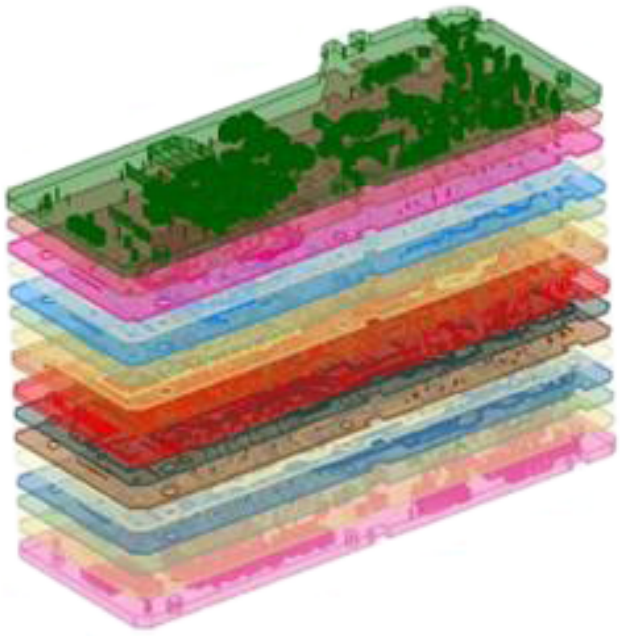
FIGURE 1: Progression of frequencies from 1G to 6G to enable higher data bandwidths.

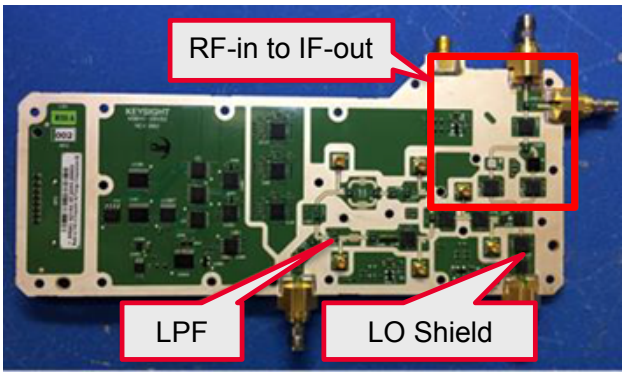
RF Board Design Challenges

RF boards present several challenges related to the multi-technology integration of chips, packaging, modules, and antennas. Boards containing 30 or more integrated circuits (ICs) and associated components and interconnects typically include RF sections that require shielding from non-RF sections. Subcircuits must be impedance-matched to other subcircuits and often to printed antennas on the same board.

Figure 2 shows one such complex board: a wideband downconverter for Keysight's 50-GHz N9042B UXA signal analyzer. This board measures 8 by 4 inches, has 16 metallization layers and about 250,000 vias, and accommodates about 1,000 surface-mount technology (SMT) components. It will serve as the basis for a design example later in this eBook.

FIGURE 2: Clockwise from top right: the Keysight 50-GHz N9042B UXA signal-analyzer, the analyzer's downconverter board, and a 3D visualization of the board's 16 metallization layers.





Electronic Design Automation (EDA) Trends

Several trends are emerging to address the challenges that such complex RF boards present and to simplify the multi-tool design complexity of traditional design flows. These trends range from the emergence of AI-driven circuit models to fast EM simulation, but they all converge on the goal of a comprehensive, seamless design flow that minimizes iterations and eliminates the manual work needed to stitch together simulation results from multiple EM and circuit simulators.

The new approach overcomes the drawbacks of the traditional design environment. As Figure 3 (left) shows, the traditional unintegrated approach includes multiple iterations of RF layout, circuit simulation, and EM simulation. It involves multiple cycles of cookie-cutter approaches to removing structures and components that cannot be EM-simulated, adding pins to replace stripped-out components, and manually stitching together the results from the EM to circuit-simulation tools. These manual steps are inherently slow and prone to errors. The traditional approach also frequently involves time-consuming custom programming to create script files for many operations, such as data manipulation for interfacing with third-party tools.

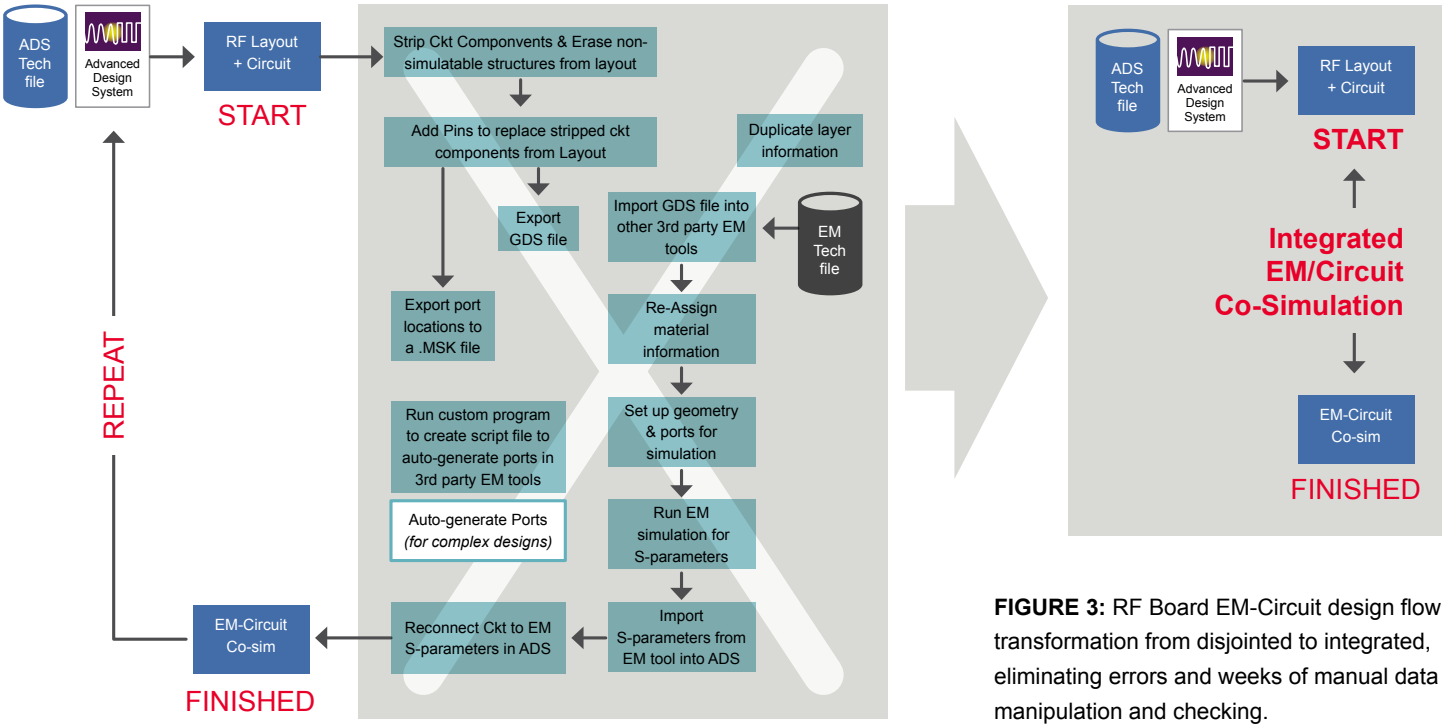


FIGURE 3: RF Board EM-Circuit design flow transformation from disjointed to integrated, eliminating errors and weeks of manual data manipulation and checking.

In contrast, modern tools can achieve a successful one-pass design flow for implementing boards such as the UXA downconverter, providing seamless automated access to circuit and EM co-simulation results (Fig 3). These tools incorporate high-capacity EM solvers with mesh optimization to provide 5x to 15x improvements in speed compared with traditional tools. They also provide the ability to quickly create nonlinear models from measured or simulated data as well as 10x to 100x speed improvements in temperature-aware circuit simulation. Finally, for the occasions when custom programming is necessary, the new tools work seamlessly within open-source automation environments, such as Python, to support the fast and efficient integration into multi-tool networks.

The integrated EM/circuit co-simulation design flow is becoming essential — not only for the interconnected components that make up the circuits but also for the mechanical and physical aspects of the board (including connectors, packaging, and shielding), which can affect its RF, thermal, and electromagnetic interference/compatibility (EMI/EMC) performance. Fast, accurate simulation can eliminate the many iterations and re-spins characteristic of traditional RF board design efforts to achieve optimal competitive RF performance (for example, with regard to sensitivity and interference resistance) with fast time to market.

In addition, an integrated EM/circuit co-simulation environment not only speeds design but also can facilitate production by quickly simulating process variations, helping to produce designs that can tolerate differences in thickness, conductivity, and other parameters that can fluctuate during the manufacturing process — thereby boosting yields.

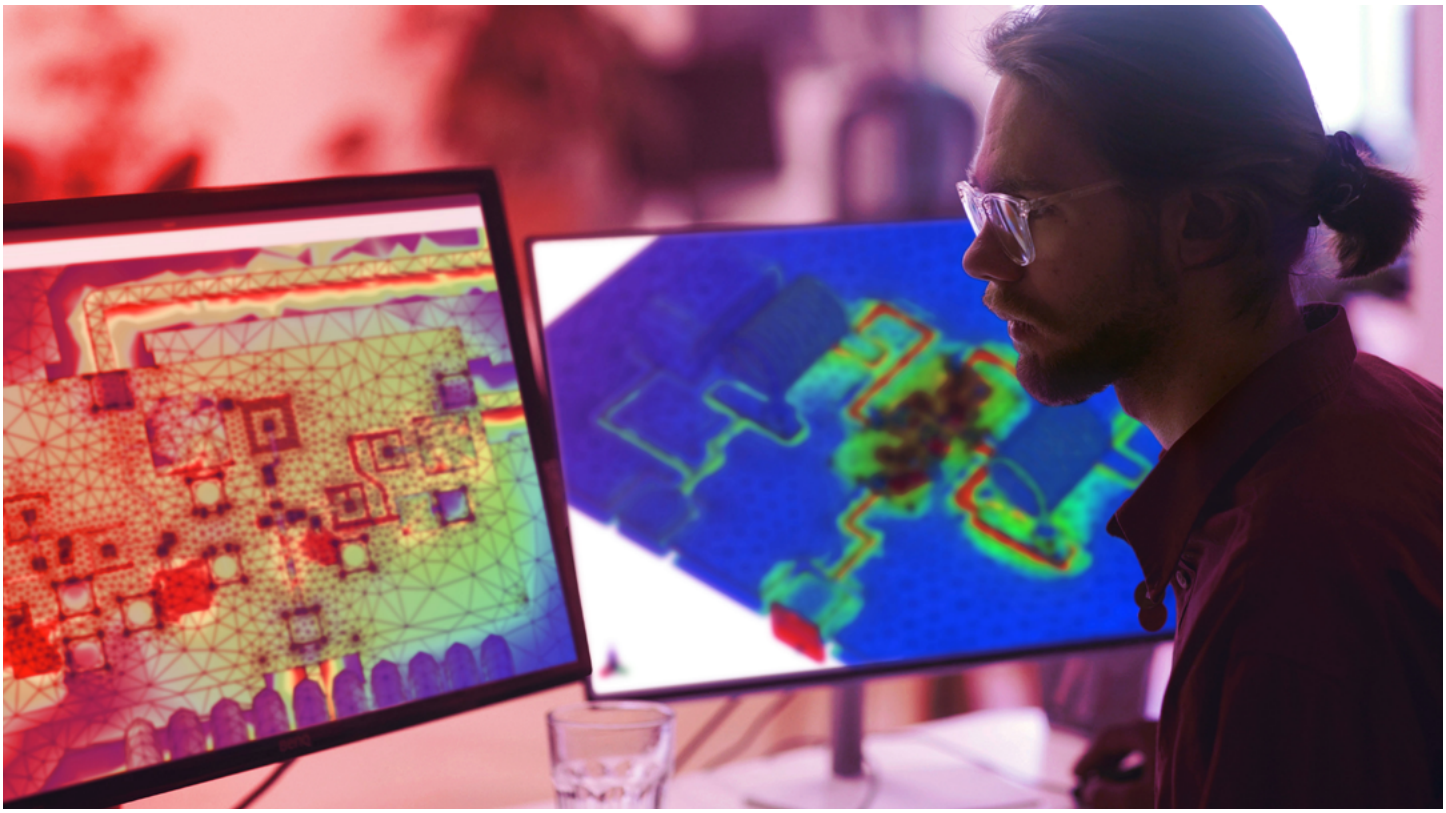
Furthermore, an integrated RF board design flow enables RF component providers to efficiently offer reference designs that can help get you started on competitive design wins for 5G/6G, automotive radar, Wi-Gig networking, and other RF/mmWave applications. Finally, RF board design flows are increasingly supporting open environments. They can import databases from multiple vendors' tools, and they permit customization through open-source languages such as Python.

RF Board Simulation Tools

Available simulation tools for RF boards include 3D finite-element-method (FEM) and finite-difference-time-domain (FDTD) EM simulators; 2½D method-of-moments (MoM) simulators; and nonlinear harmonic-balance, circuit-envelope, transient-convolution, and linear S-parameter circuit simulators. FEM can simulate arbitrary 3D passive structures in the frequency domain. It partitions a complete finite problem space into 3D tetrahedral elements and can solve problems adaptively, with the mesh refined in regions where EM energy and field gradients are greatest.

MoM also works in the frequency domain to solve planar 3D structures more efficiently than FEM, and it can help speed intermediate steps during the design flow before final simulation with FEM. And finally, FDTD simulates arbitrary 3D structures in the time domain and can handle large and complex problems such as the human head next to a mobile phone for safety compliance.

Using many such EM and circuit simulation tools in isolation, however, has presented difficulties — a change in circuit design, for example, might necessitate a change in an



electromechanical shielding design, which in turn might require more changes in the circuit design — essentially, the cure for one problem must be simulated to ensure it does not cause another. The result has been repeated iterations of each of the EM/circuit tools in alternating fashion, requiring the error-prone integration of the data from the multiple tools, resulting in very long design times.

Keysight's recent innovation is RFPro, the next-generation EM simulation platform for RF circuit designers. RFPro is integrated within the company's Advanced Design System (ADS) design and simulation environment, which streamlines the integration of multi-technology circuit-assembly and simulation into a complete design workflow. ADS can import databases from different tools, and it offers data-analysis capabilities that can efficiently process simulation results.

As part of ADS, RFPro combines multiple tools into one simulation environment for EM and circuit co-simulation and optimization. RFPro integrates FEM and MoM EM solvers. To speed the EM simulation operation — to enable fast process-variation analysis, for example — Keysight's implementation of MoM, called Momentum, employs precomputed Green's functions and matrix compression techniques to provide significantly faster EM simulations than full 3D simulators can achieve.

RFPro optimizes 3D and 2½D EM simulation for RF circuit designers to automate EM-circuit co-simulation, ensuring design integrity by making layout cookie-cutting unnecessary. In addition to performing accurate circuit simulation in ADS, RFPro takes into account EM and impedance effects of packaging, 3D interconnects, arbitrary metal shapes, antennas, material electrical characteristics, and size differences caused by process variations. These variations can include etch bias, which allows you to quickly analyze the effect of over/under-etching (which alters the electrical performance) with automatic mesh morphing without the need to develop separate parameterized layouts.

RFPro also can simulate thickness bias, with thickness variations specified in percent or absolute values (for example, 4 µm), and registration bias, which permits analysis of the effects of mask misalignment. It can also simulate conductivity bias and permittivity bias process variations for conductors and semiconductors. Because the simulation is so fast, designers can readily optimize their designs with respect to physical characteristics as well as electrical parameters.

In addition to eliminating the cookie-cutter approaches, the tools support state-of-the-art data analysis, including pre-layout analysis to help identify RF critical nets. They also enable engineers to visualize results on familiar instrument-like Smith charts or rectangular plots and to study 3D surface current flows or antenna beamforming radiation patterns — all before building any hardware so that design flaws can be fixed upstream.

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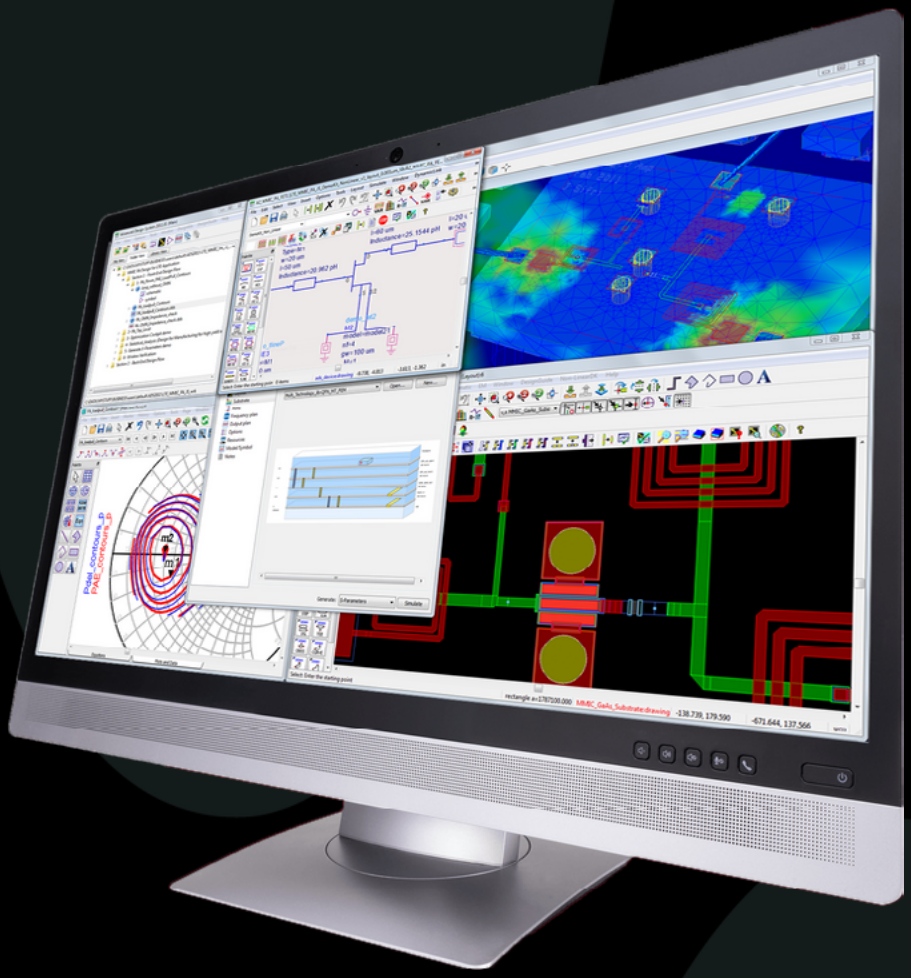


Automate Your RF Board Design Flow with RFPro

Achieve error-free design integrity and accelerate time to market with a seamless EM / circuit co-simulation environment.

Show me how

Co-Simulation Design Flow

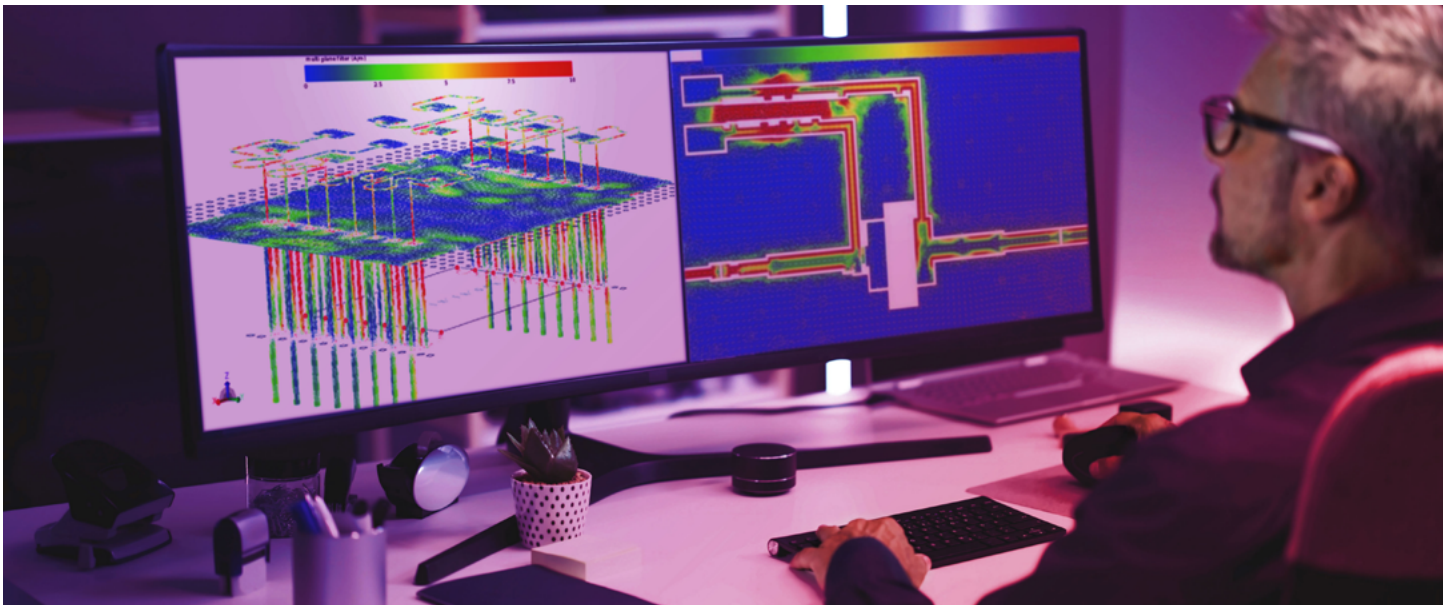
In the co-simulation environment, the typical RF-board design flow proceeds as follows:

- Read in board data as an industry-standard ODB++ or another file format. Edit as appropriate — for example, add RF shields, 3D connectors, 3D SMT components, and input/output ports. Then, specify material properties such as the dielectric constant and loss.
- Select what structure to simulate with EM or circuit simulation.
- Perform the 3D, 2½D, and circuit co-simulation in one environment for spec compliance.
- Check for manufacturing tolerances, and optimize for tolerance robustness.
- Obtain sign-off for the hardware prototype and measurements before volume production.

As a design example, Keysight's instruments R&D team used RFPro in ADS to design the 50-GHz signal analyzer's wideband downconverter board. RFPro's advanced EM tools with intuitive automated expert settings enabled the design team to quickly optimize the board's 250,000 vias, RF shielding, RF routing, and packaging structures; **it also** supported fast dedicated analyses for board impairments before production.

The UXA downconverter board takes the main RF input, downconverts it to an intermediate frequency (IF), and feeds the IF signal to sister boards. The key challenge is to obtain accurate high-frequency performance with minimal noise and interference. The design flow included several steps.

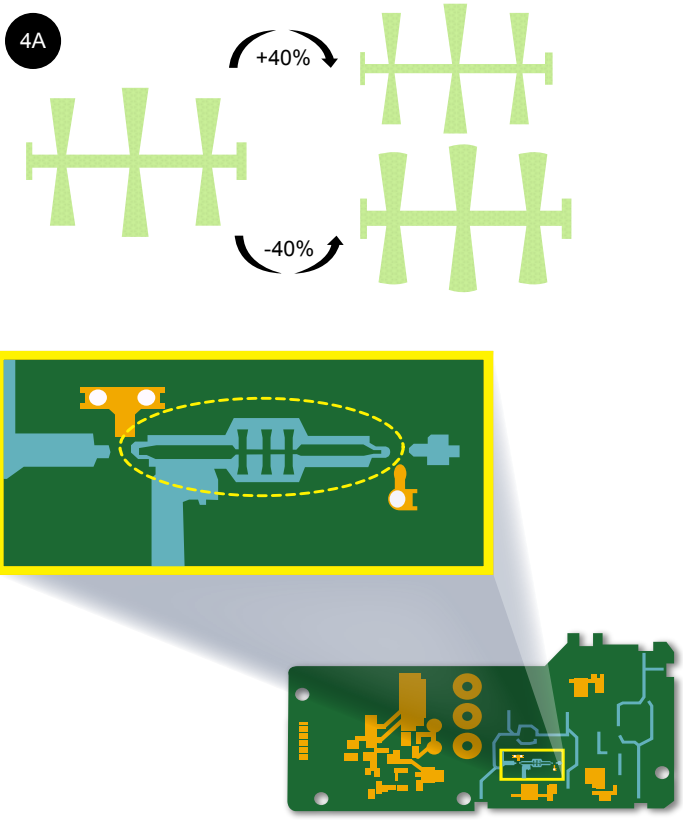
The first step was to analyze the tolerance sensitivity of the board's low-pass-filter. To do that,



the team viewed the board in ADS and selected only the filter and ground as the parts of interest. With ADS, a mesh optimization process can identify such a region of interest without explicit cookie-cutting that can cause erroneous simulated resonances.

The R&D team also examined the effect of etch bias (expressed as a percentage of layer thickness), in which the physical realized metallization differs from the ideal because of process variations, as shown in Figure 4A. With RFPro, a mesh morphing technique eliminates the need for time-consuming manual geometry parameterization. The team compared MoM and FEM simulation results with actual measurement results (Fig 4B) and concluded that the impact of an etch bias from -40% to +40% was acceptable (Fig 4C), indicating that the design could tolerate a wide range of manufacturing variations and thereby enable high production yields.

FIGURE 4: Low-pass filter +/-40% process variation sensitivity analysis showing S-parameter vs. frequency tolerance response. Confirmed with measurements.



In addition to investigating etch bias, the R&D team analyzed the local oscillator shielding to identify shield resonances (Fig 5). ADS permits investigation of such resonances using a simplified model to save time before a final full simulation. For the UXA board, the simplified model ran in about two minutes, versus 25 minutes for the full model (running on a laptop with an Intel Core i7 processor). The simulations showed that the UXA board's local-oscillator (LO) shield required a poly-metal absorber, which reduced resonance Q factors by at least three orders without adding any new resonances. The full simulation verified the results obtained using the simplified model.

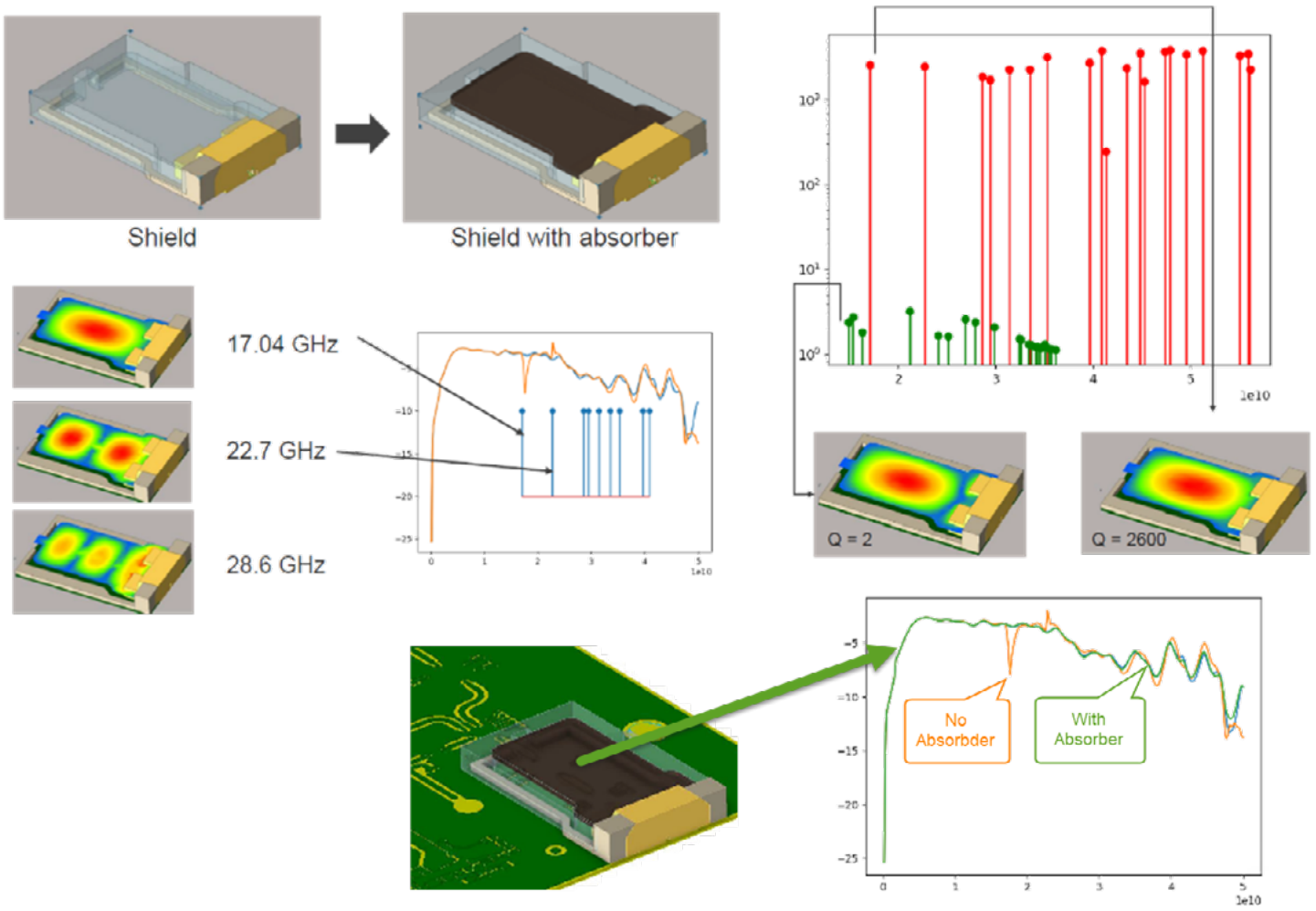


FIGURE 5: Identification of cavity resonance and simulation of a shield with and without a poly-metal absorber to mitigate cavity resonances.

Yet another step the R&D team performed was to investigate how the signal is down-mixed from the board's RF input and high and low LO inputs to the IF output. The team was able to easily select the RF/LO to IF signal path and develop a simulation that applied a broadband nonlinear excitation to the RF and LO inputs (Fig 6A) while measuring the signal spectrum at the IF output.

This approach automated the EM extraction, including parasitics, using FEM, without requiring any time-consuming and error-prone manual cookie-cutting to isolate the signal path. The automated process also preserved design integrity and enhanced traceability. For the UXA board, the FEM extraction took four hours and 30 minutes and 120 GB of memory to evaluate 25 million unknowns. Figure 6B shows the measured and simulated IF results. Both indicate that flatness remains within acceptable minimum and maximum limits.

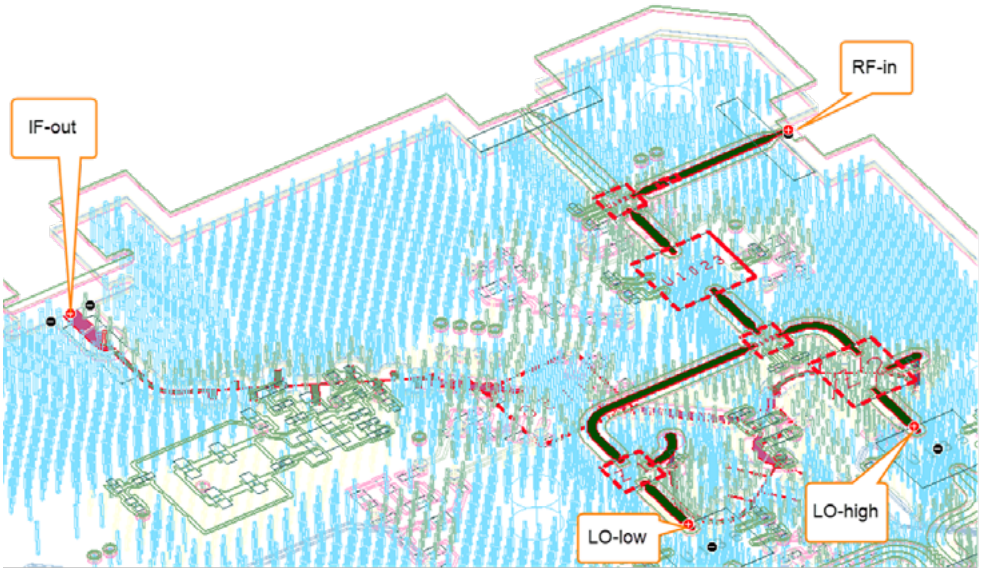


FIGURE 6A: Nonlinear excitation (top right) of RF and LO inputs to obtain IF output.

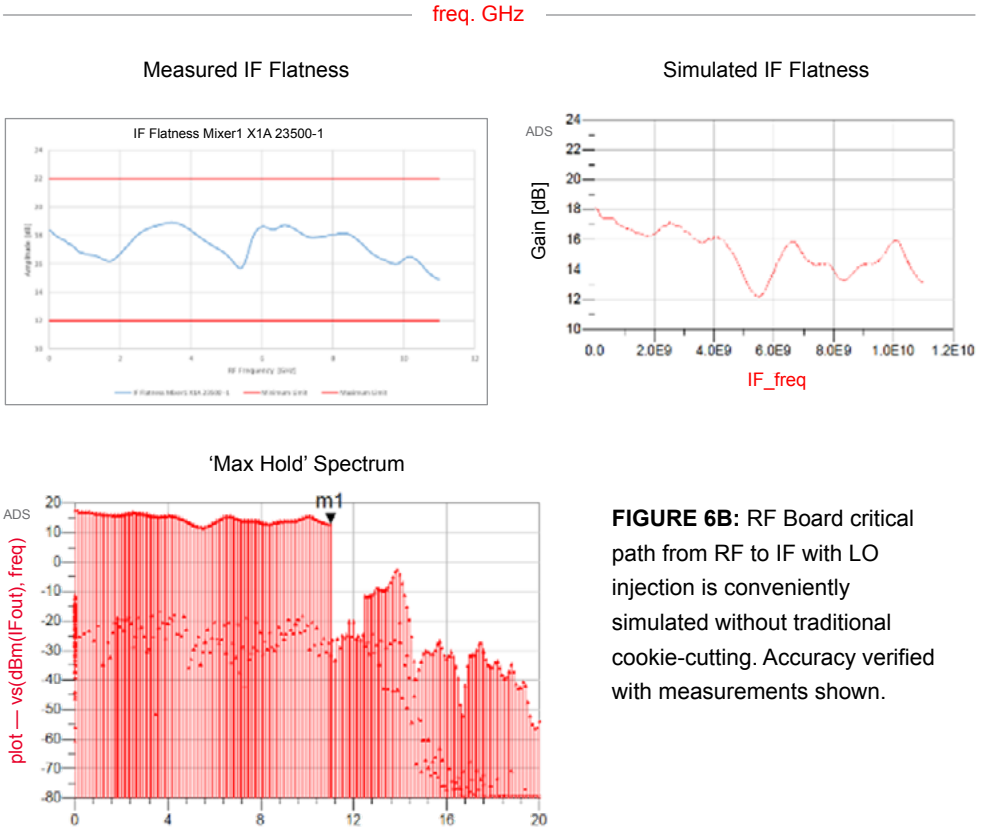


FIGURE 6B: RF Board critical path from RF to IF with LO injection is conveniently simulated without traditional cookie-cutting. Accuracy verified with measurements shown.

Component and Packaging Simulation

It is becoming increasingly important that 3D components such as SMT inductors and connectors be simulated accurately for first-pass success to eliminate iterations. Software applicable to this process includes Keysight's EMPro FEM and FDTD 3D EM simulation and modeling environment, which can be used in conjunction with ADS RFPro for EM and circuit co-simulation. RFPro provides instant EM simulation access during design with automatic expert settings, making the tool easy to use for circuit designers — not just highly experienced EM engineers.

RFPro's enhanced FEM engine easily handles mixed board-packaging technologies, and it enables interactive EM simulation and EM-circuit co-simulation to analyze coupling effects between technologies. In addition, statistical EM simulation can help produce tolerance-insensitive designs to boost production yields. Parameters such as temperature, as well as process and material property variations, can be swept during simulations.

Simulations can run locally or in an accelerated high-performance-computing (HPC) environment. Keysight offers cost-effective HPC accelerator licenses that can be incrementally added to the base simulation tools to achieve desired time savings. The hardware and memory to run the parallelized HPC simulations can be hosted through cloud services or on-premises compute clusters.

Python Customization

In any design flow, engineers tend to need some customization. The integration of the popular open-source Python language is effective in automating the design flow and creating AI models for use in simulation. Keysight offers four key features to support Python:

- ADS now supports expanded APIs that allow deeper access to functions inside the platform with an emphasis on Python.
- Visual Studio now offers professional code development support for Python.
- ADS allows teams to follow the traditional route for deployment or to use Python to create new deployment models to invoke ADS functions from outside the platform, including from stand-alone apps.
- ADS enables teams to run Python code interactively from the new Python console command-line interface.

With these capabilities, designers can create a schematic from scratch; add terminations, grounds, and components; set component values; and wire components together.

Two examples demonstrate the benefits of Python automation in ADS. The first involves linking test equipment to the design environment. Keysight offers standard modulated source waveform models in ADS, but designers may need a custom waveform for a power-amplifier (PA) design, for example. They can write a Python script that connects Keysight's PathWave vector signal analyzer (VSA) software together with ADS.

The script grabs a live instrument-generated modulated IQ waveform and brings it into ADS. In turn, ADS generates an output dataset that can be brought back into the VSA software for demodulation (Fig 7). Essentially, ADS can use the same waveform, with the same error vector magnitude (EVM), in the design environment as is used in the test environment. This hardware-and software-in-the-loop technique represents a powerful tool enhancement for emerging technologies, and it serves as an introduction to digital twinning.

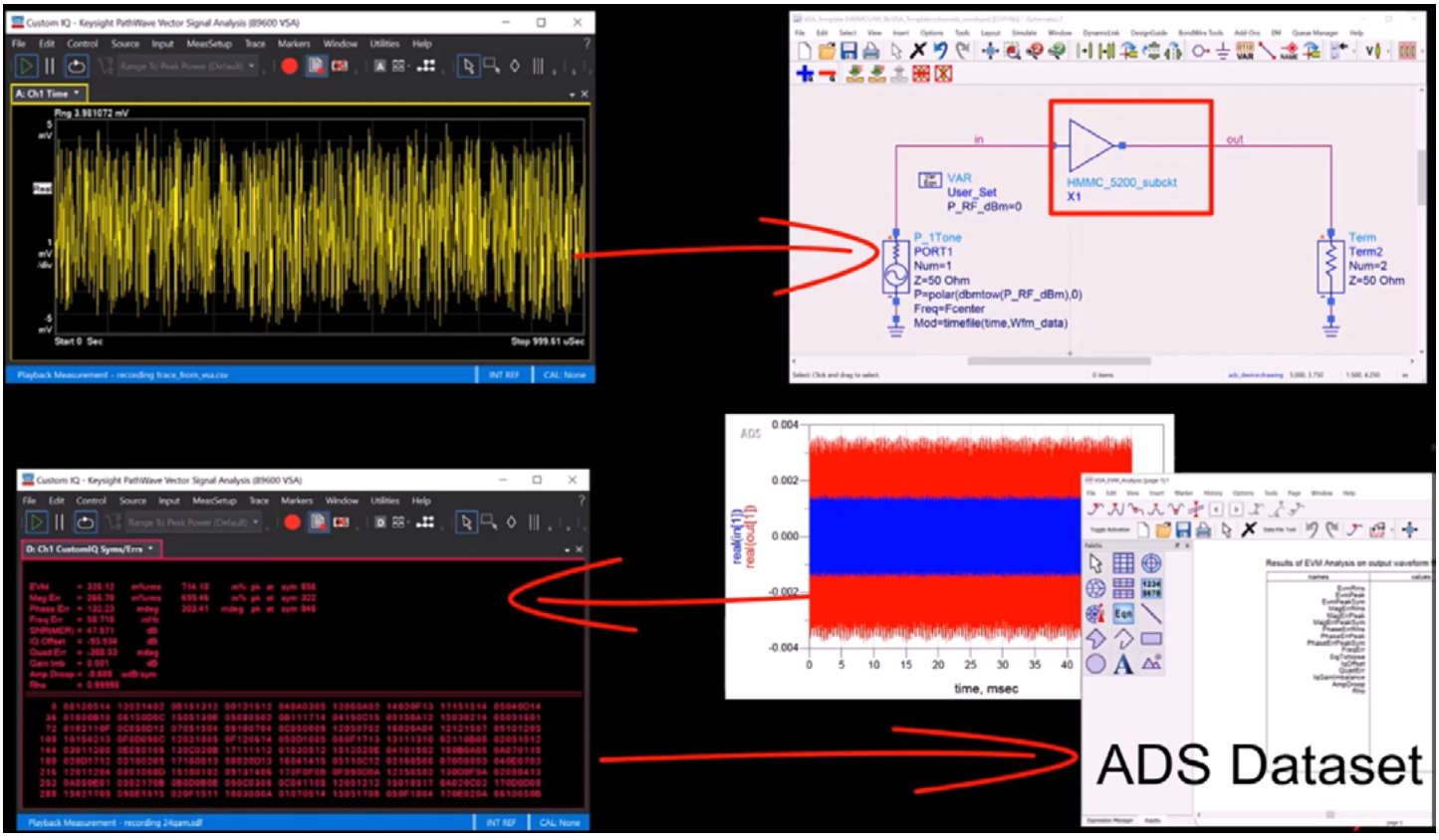


FIGURE 7: Hardware and software in the loop using Python automation.

The second Python example elaborates on the digital twins concept by applying artificial neural nets (ANNs) as a modeling tool. ANNs can take sparse or irregularly spaced data and allow smooth interpolation to derive waveforms with well-behaved derivatives. With ANNs, designers can take static measurement datasets that they have on hand and turn them into executable simulation models (Fig 8). In addition, they can take a published data-sheet curve and turn it into a PA behavioral model. The new Python hooks in ADS make it easy to use ANNs for all types of multivariate data to apply to AI and ML applications in ADS.

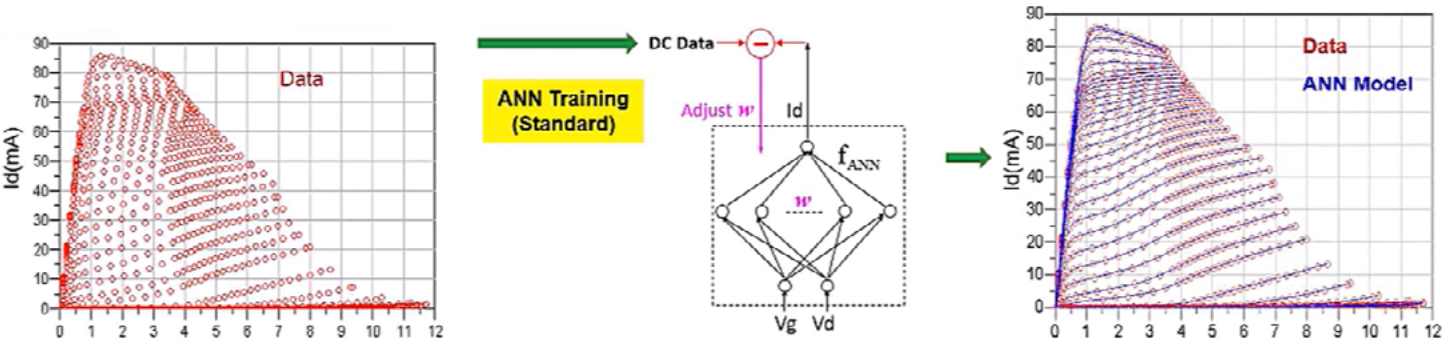


FIGURE 8: Using Python automation and ANNs to create models from datasets.

Data Management and Version Control

Design data management (DM) and version control are also critical concerns in complex multiple iteration designs. An effective approach to version control and DM avoids data loss and allows designers to revert to a previous design from any date, saving the time that would otherwise be needed to recreate a previously discarded version. Keysight's Cliosoft SOS tool supports several key capabilities, including reuse, design data management, collaboration, and analysis.

For example, Cliosoft SOS supports reuse through an IP catalog with the ability to propagate fixes and releases. In addition, it manages RF design data, RTL and digital design data, and analog and custom design data as well as test plans, test processes, and test data during simulation and test. It also includes a web-based interface to facilitate the management of design documents.

Cliosoft SOS also optimizes network disk usage and storage. Instead of requiring users to store full physical copies of design files in each user work area, it establishes design files in each user work area as symlinks, except for files being edited (Fig 9).

In addition, Cliosoft SOS enhances collaboration through remote cache servers, provides auto synchronization, ensures secure and efficient data transfer, and facilitates design-change handoff. It also can generate design-audit reports, identify hierarchical schematic/layout differences, and track changes between releases and over time.

Version control in ADS enables designers to revert back to earlier versions of a design with full traceability of what changed because they are never deleted, and all versions are maintained.

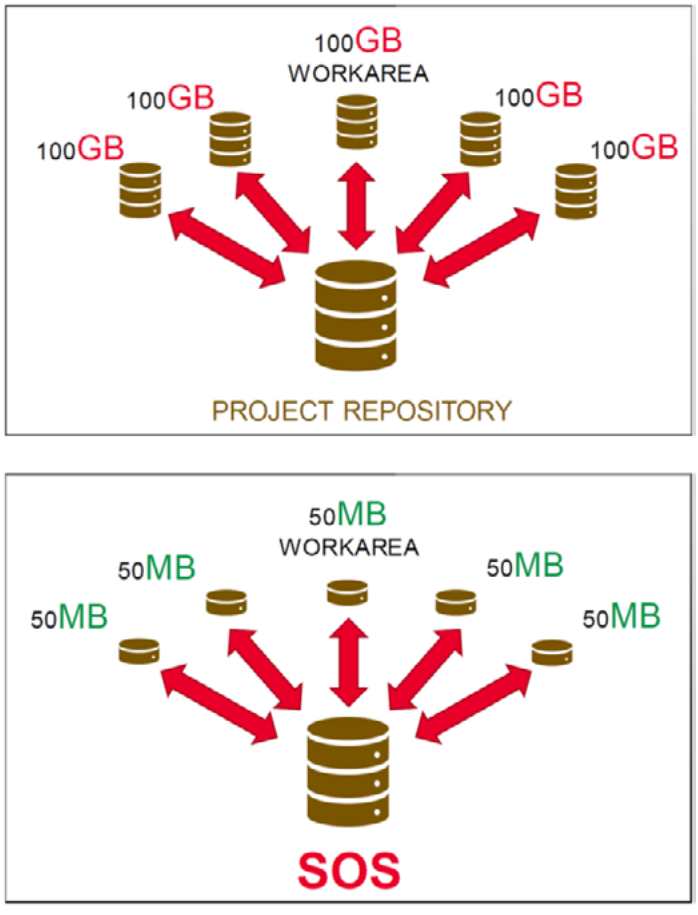


Figure 9. Traditional (top) and SOS (bottom) storage approaches.

Summary

- The growing wireless industry is driving competition for profit in the RF board market.
- Unlike traditional PCB boards, producing RF boards to compete for tight market windows requires circuit and EM simulation before building hardware to eliminate wasteful rework.
- RF board Electronic Design Automation (EDA) software now enables RF Boards to be easily imported in industry-standard formats such as ODB++ for accurate simulation of only the RF paths, without the need for tedious error-prone manual cutting and extraction.
- RF paths include RF metal traces, surface mount devices (SMD), packaging, printed antennas, and connectors. Accurate simulation requires both circuit and EM analyses together, called EM-circuit co-simulation.
- RF board EM-circuit co-simulation design flow is now automated to replace traditional separate circuit and EM analyses, followed by manual connection of simulated results. This reduces days and weeks of manual data connection and checking to minutes while preserving error-free design integrity for subsequent sign off to production.
- Automated EM-circuit co-simulation enables production process variations, such as over/under etching, to be easily analyzed to ensure high production yields despite manufacturing tolerances.
- RF Board EDA software must include Python automation to enable powerful AI/Machine Learning capabilities and other PCB tools to be efficiently integrated into your design flow to speed product development for winning in the competitive RF board market.
- IP reuse, prevention of IP and design database corruption from malicious attacks, or benign mixing of outdated or erroneous data are often overlooked but are critical requirements in your RF board design flow to prevent crippling data loss.

Resources

Staying up-to-date with the latest RF board design trends is essential to remain competitive in the rapidly evolving RF market. Did you realize there may be product updates and new technology that could make your design task easier, or help you keep pace with industry changes?

Start today by accessing the resources listed below to see deeper insights into the issues and techniques discussed in this eBook. Check them regularly for the latest updates!

HOW-TO VIDEOS

- What's New in RF and Microwave Design

LEARNING COURSES

- RF Board Design Flow Educational Bootcamp
- The Importance of RF Simulation
- How to Design an RF Power Amplifier
- Ensure your RF Power Amplifier Doesn't Become an Oscillator
- Identify RF coupling issues early with EM/Circuit Co-Simulation
- How to Integrate Multi-Technology RF Assemblies
- Designing with 5G Modulated Signals
- Designing for Modulation with Keysight EDA Video Asset Page
- Designing for Digital Pre-Distortion in Power Amplifiers
- Using Electro-Thermal Simulation in Your Next IC Design

APPLICATION NOTES

- Bringing Beamforming and mmWave to 5G UEs PDF Asset Page
- Designing Robust 5G Power Amplifiers for the Real World
- Designing for Stability in High Frequency Circuits
- How to Generate and Simulate a Dynamic Gain Model in PathWave Advanced Design System (ADS)

EBOOKS

- Four Secrets to Mastering Millimeter-Wave Communications Circuit Design
- Four Real-World Applications for Electromagnetic Simulation

CASE STUDIES

- Driving Innovation Shortens Design Cycle by 65% for First-to-Market MEMS RF Switch

KEYSIGHT

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Keysight (NYSE: KEYS) inspires and empowers innovators to bring world-changing technologies to life. As an S&P 500 company, we're delivering market-leading design, emulation, and test solutions to help engineers develop and deploy faster, with less risk, throughout the entire product life cycle. We're a global innovation partner enabling customers in communications, industrial automation, aerospace and defense, automotive, semiconductor, and general electronics markets to accelerate innovation to connect and secure the world.

Learn more at www.keysight.com

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