

Microwaves & RF®



Simulating & Optimizing RF Circuits in 3D Advanced Packaging

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 **KEYSIGHT**



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Introduction:

Advanced wireless technology is pervasive, with wireless functionality appearing in aerospace-defense systems, communication-networking systems, vehicles, and countless other applications. Such applications require the advanced packaging of wireless capability into RF modules using 3D heterogeneous integration (3DHI) techniques, presenting significant 3D assembly, simulation, and optimization challenges for 5G, 6G, and millimeter-wave design engineers. An effective 3DHI module design (*Figure 1*) requires an open workflow that includes multiple electronic design-automation (EDA) platforms for on-chip and off-chip designs, and

engineers require accurate, traceable multidomain simulations and optimizations to avoid costly, time-consuming respins, with co-optimization required across chips, interconnects, interposers, boards, and other structures.

The integration of a 3DHI workflow across multiple platforms requires an open, customizable, and automatable architecture. Such architecture would leverage artificial intelligence (AI) to capture design intent for reuse, to orchestrate functional expansion with Python scripting and AI agents, and to accelerate simulation speed.

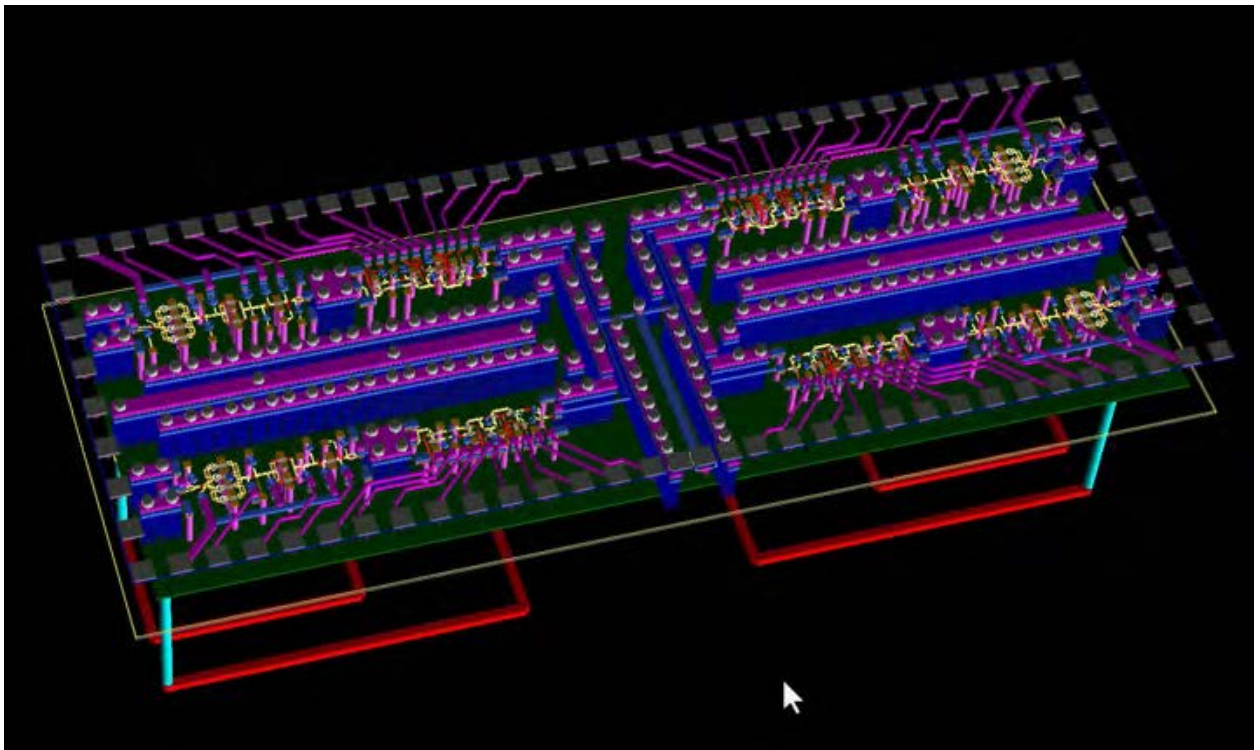


Figure 1: A 3DHI RF module can integrate chips, packaging, interconnects, interposers, boards, and antennas.

6G Implications

6G has significant design implications compared with earlier cellular generations. 6G pushes frequencies even higher than the mmWave frequencies introduced with 5G, taking advantage of sub-terahertz (100 to 300 GHz) frequencies. 6G equipment operating at these frequencies can boost data rates to 50 times those of 5G to meet consumer and industrial demands for ever higher throughput wireless data.

Operating at these frequencies presents challenges, however. Sub-terahertz wavelengths are comparable in size to the dimensions of 3DHI components, and designers must therefore contend with the resulting parasitics that can degrade performance. In addition, because of the short transmission distances of sub-terahertz waves, 6G requires dense base-station deployments, each with a large number of front end modules with integrated beam-forming antennas. Because of the sub-terahertz frequencies, this can be more compact than 6 GHz or even mmWave versions.



3DHI Challenges for RF Circuit-Design Engineers

To contend with the challenges, 6G and advanced 5G applications are driving the demand for complex, optimized RF modules. The complexity, in turn, requires module design workflows that can co-optimize chips, off-chip packaging, printed-circuit boards, and integrated antennas.

When designing mmWave circuits, RFICs, and RF 3DHI modules, engineers rely on EDA simulation software for efficient and accurate design, simulation,

and optimization. These tools must be able to correctly assemble 3DHI structures and accurately simulate and optimize all aspects of RF module designs to ensure they meet multiple specification performance requirements simultaneously. The tools must also allow engineers to detect and compensate for performance degradation caused by nonideal electromagnetic and dynamic electrothermal effects arising from the circuit's dense 3D physical layout and packaging before building hardware.



Traditional RF Design Methodology Limits

In the past, technology dictated the design flow, with separate, rigid, siloed, technology-locked tools handling GaN or GaAs design, silicon IC design, and laminate design, followed by assembly and verification, as well as tape out and manufacturing. These tools have all operated in isolation.

However, the chips do not work in isolation. They need to be put in a 3DHI package that may combine silicon ICs and III-V semiconductors (devices formed from elements in groups III and V of the periodic table), such as gallium nitride (GaN) and gallium arsenide (GaAs) ICs, and the package may even integrate beam forming antenna arrays. Typically, silicon ICs implement the baseband, and III-V ICs form the power amplifiers. The module combining multiple technologies must meet specific specifications to comply with system wireless standards such as Wi-Fi 7 or 5G/6G. Using the traditional rigid, siloed, technology-locked tools, it has been challenging, if not impossible, to link the various tools in a way that permits thorough evaluation of chip, package, and antenna interactions within a complex module.

In *Figure 2*, for example, the siloed Tool 1 handles the GaAs development, including process-design-kit (PDK) selection, physical design, and electronic and electromagnetic (EM) simulations. Similarly, siloed Tool 2 and Tool 3 handle silicon and laminate design, respectively, each in isolation, followed by assembly, verification, tape-out, and manufacturing.

The number of separate tools used in modern RF designs can become overwhelming, requiring a variety of tedious, error-prone operations to

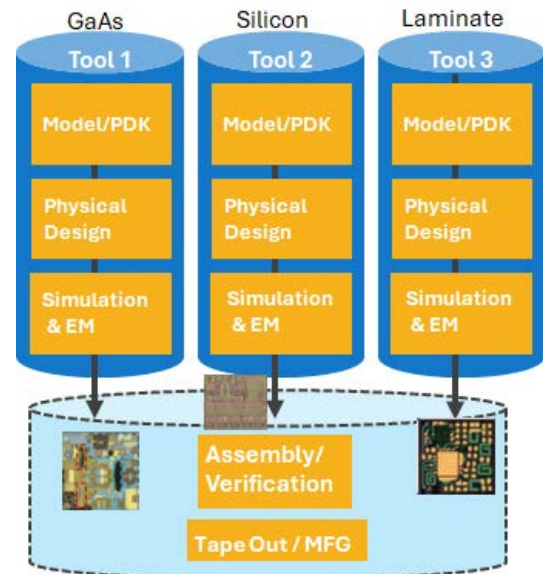


Figure 2. Traditionally, technology has dictated the design flow.

translate between them. According to a 2018 survey conducted by Keysight Technologies, “The time it takes designers to switch between software tools can be significant. The process often involves importing and exporting files, reconnecting ports, and rechecking netlists. Designers also spend a great deal of time correcting errors resulting from the tool switch.”

RF engineers may develop custom in-house synthesis and automation algorithms and other tools to assist with these tasks, but such tools may be developed by senior engineers and may not be well documented. The application of or even existence of these tools may be difficult for junior team members to comprehend, and many of the tools can be challenging to easily integrate across closed platforms, thereby lengthening engineering design cycles.

3DHI Emerging RF Design Workflow

Now, however, the technology is no longer able to dictate the workflow, and it is the flow that dictates the technology. The complexity of a 3DHI RF module design is beginning to require that the RF design tools evolve to enable a workflow that effectively addresses all aspects of the design requirements, with the flow consisting of several steps:

- Multi-technology selection from internal or third-party IP
- IC design and circuit simulation
- Physical and packaging design
- Thermal and EM simulation
- DHI assembly, including thermal floor planning
- System analysis
- Multi-domain co-optimization of on-chip and off-chip components
- Performance and physical validation
- Tape-out and manufacturing
- Documentation

Figure 3 outlines the steps involved in a composable, interchangeable, workflow-driven approach that enables the chip, package, interposers, interconnects, boards, and antennas to be designed, simulated, and optimized together. Throughout the processes of initial planning, schematic capture, device modeling, passive design, tolerance analysis, and final layout, an integrated workflow can save designers 40% of the time previously spent on rote tasks, freeing them up for more constructive design explorations.

EDA tools that can fit within such a flow include Keysight Advanced Design System (ADS), Cadence Virtuoso, and Synopsys Custom Compiler. Together they address analog, mixed-signal, silicon RFIC, and

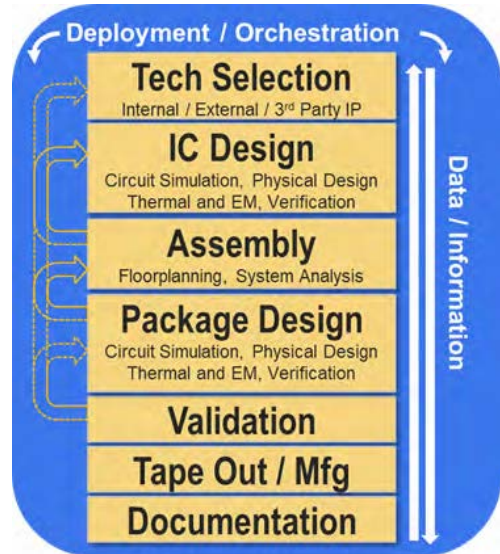


Figure 3. Design is evolving toward a composable, interchangeable methodology where the flow dictates the technology.

III-V MMIC designs. In addition, Keysight's Advanced Design System (ADS) enables the 3D assembly of these technologies into 3DHI modules that include off-chip packaging, antennas, and PCBs for multi-domain simulation and co-optimization with Keysight RF Circuit Simulation Professional (Nexus).

Traditionally, these tools have operated in the previously described siloed fashion, with all the attendant problems related to importing and exporting files in various formats, reconnecting EM ports to circuit nodes, performing layout-vs-schematic (LVS) and layout-vs-layout (LVL) verification, performing a design-rule check (DRC), and correcting errors.

To meet the need for a workflow where chips, packages, interposers, interconnects, boards, and antennas can be designed, simulated, and optimized

together while reducing time-consuming manual rote tasks, Keysight embarked on a major tool optimization project to architect ADS to be an integration platform for assembling heterogeneous technologies into 3DHI modules. The goal was to simulate any selected RF path through the modules using multidomain circuit, EM, and electrothermal simulators.

One result of this effort is Keysight Nexus, a circuit simulation tool that operates identically across Virtuoso, Custom Compiler, and ADS to simulate RF paths traversing a 3DHI structure across technology boundaries and design hierarchies. Together with Keysight RFPPro, the companion cross-platform EM simulation tool, the combined tools enable chips, off-chip packaging, and boards to be circuit- and EM co-simulated to account for and compensate for parasitics, which can save several costly and time-consuming design respins.

The tools can simulate the entire combination using an open Python-automatable workflow-driven approach, with traceable design data moving in both directions across an integrated workflow. Keysight Nexus orchestrates complex multi-domain simulation and optimization by capturing and unifying workflows among ADS, Virtuoso, and

Custom Compiler, addressing silicon and non-silicon RFIC, MMIC, and small-scale package design and optimization (*Figure 4*). ADS also addresses the drag-and-drop integration and assembly of ICs, packages, interposers, passives, boards, and phased-array antenna elements. The entire unified workflow provides native simulator integration as well as a consistent cross-platform user interface.

To meet the multi-specification performance goal of RF modules, users can invoke comprehensive multi-domain simulation and optimization with respect to a variety of parameters, including nonlinear stability margin, which indicates how close to instability an amplifier is operating. The tools can also optimize circuit specifications such as error vector magnitude (EVM) and power-amplifier digital predistortion (DPD). The tools also evaluate electrothermal and EM performance. The combination enables tape-out with full confidence, eliminating costly and time-consuming respins and resulting in fast time to market. The tools share trusted algorithms with Keysight's RF instruments, helping to ensure full compliance with standards such as Wi-Fi 7 and 5G/6G. Keysight has found that the optimized integrated workflow cuts the number of design turns by 2 to 3 times and reduces prototyping costs by 60%.

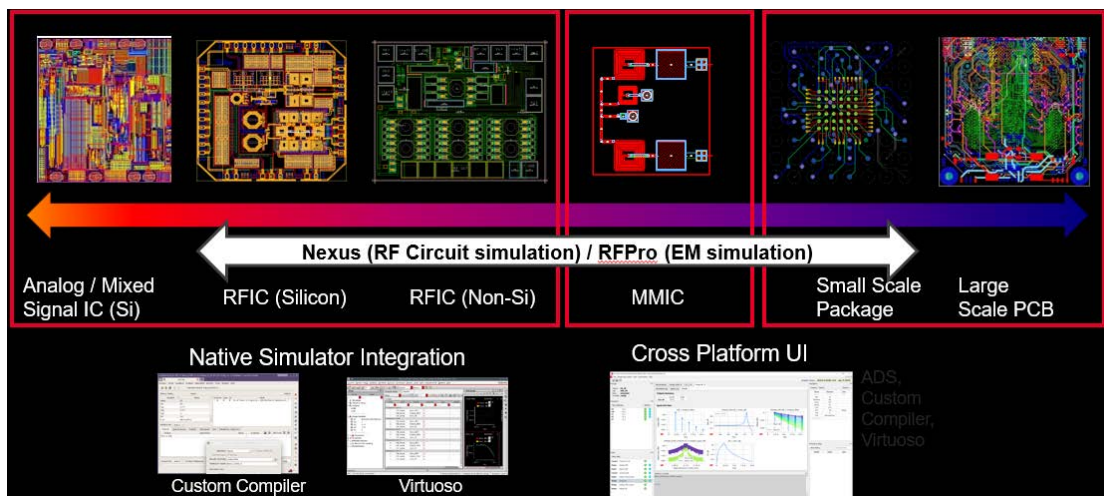


Figure 4. Nexus and RFPPro unify circuit and EM simulation workflows from silicon RFICs to small-scale packages.

Co-Simulation and Co-Optimization

In a complex 3DHI RF module, the chips, packages, interposers, interconnects, boards, and antennas cannot be optimized independently. A design tweak that optimizes an interposer, for example, may require an offsetting change to the performance of a GaAs power amplifier. Consequently, all design elements must be designed, simulated, and optimized together.

In an integrated workflow, the optimization must consider physical properties, such as the geometry of an antenna, as well as electrical specs, such as the error vector magnitude of a power amplifier. Optimization of a specific circuit within a module must take place in a way that meets the total system requirements. Therefore, both EM optimization and circuit optimization must be included in the system optimization loop in a process called co-optimization. In addition, the co-optimization loop may need

to run thousands of times to find the optimum balance of all electrical and geometrical design aspects that meet overall system specifications. Consequently, the co-optimization loop must run quickly, accelerated by advanced algorithms and massively parallel processors, including graphics processing units (GPUs).

Nexus co-optimizes multi-spec performance across multiple frequency bands, evaluating device fast-slow-typical statistical corners and across technology boundaries and design hierarchies. It can also evaluate electrothermal behavior, EM near- and far-field behavior, and wireless system specs compliance. Nexus performs parallel optimization, which is a scalable way to speed up the time-consuming iterative process to fine-tune multi-performance objectives to meet system requirements. Parallel optimization can provide at least 10 times the speed improvements, enabling

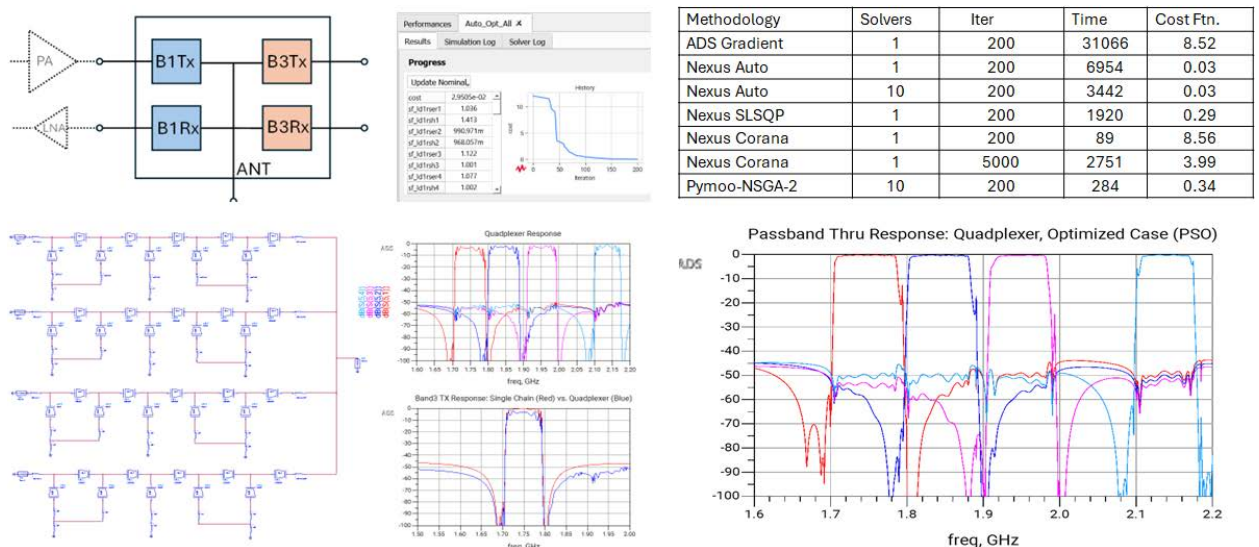


Figure 5. This 5G quadplexer design example involves more than 200 parameters and 45 design goals.

rapid convergence on large-scale problems with advanced algorithms, such as AI Reinforcement Learning. *Figure 5* illustrates the parallel co-optimization of a 5G cellular bulk-acoustic-wave (BAW) quadplexer with more than 200 parameters and 45 design goals. Nexus converged on an optimized solution more than 100x faster than a traditional ADS gradient optimizer.

To speed up EM and circuit co-simulation and co-optimization, Nexus, with its companion RFPro EM simulator, can also perform intelligent

RF path selection for any path containing active and passive components through a 3DHI module that traverses technology boundaries or design hierarchies. The simulation employs a technique called mesh domain optimization (MDO), in which only the selected path and structures near it are meshed, while structures away from the selected path are ignored (*Figure 6*). MDO eliminates the traditional time-consuming, error-prone, and nontraceable cookie-cutter approach of manually editing the physical design to extract a selected RF path for simulation.

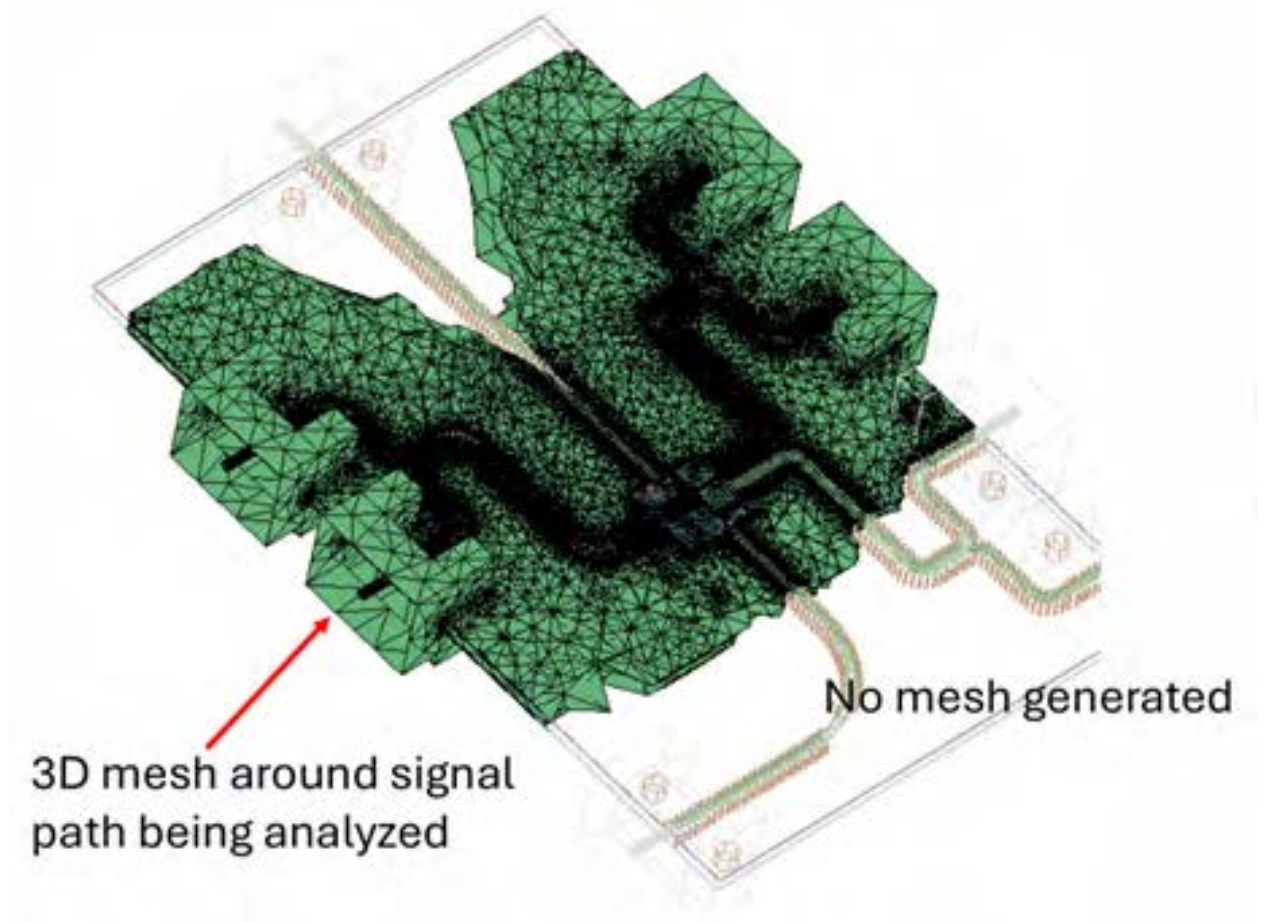


Figure 6. MDO meshes the selected signal path and nearby structures while ignoring other structures.

Traceability

Customers that have mixed environments that combine ADS and Virtuoso or ADS and Custom Compiler platforms may employ multiple teams, which might handle silicon IC and III-V IC design as well as packaging and interconnect designs. When combined, the complete system design might not work without tweaks, and individual design changes by any member of any team can compromise the entire design database.

Consequently, as designs become more complex, design engineers require repeatable, traceable control over multi-domain simulation, optimization, and design-parameter settings to facilitate multiple design explorations by multiple team members, who will select the candidate that offers the optimal trade-offs among often competing multi-domain performance objectives.

To ensure error-free collaboration between RFIC and module designers, the traceability of design iterations across multiple tools, technology boundaries, and hierarchies in a densely integrated 3DHI structure becomes a necessity. Traceability ensures that all edits to any structure within a 3DHI

module are automatically updated within the design database to eliminate errors in the simulation setup and the downstream manufacturing output.

Nexus makes it easy for RF design engineers to implement traceability by keeping track of who changed what. It works across all three platforms, so each state in which a design was simulated can be reproduced without spending time determining which engineer performed a given change. Nexus also supports edit-in-place, with layers and libraries updating automatically across IC, packaging, PCB, and antenna designs. Edit-in-place enables co-design of assembled 3DHI technologies directly, with one click to call up the original editing environment. Nexus automatically updates layers and libraries while preserving the traceability of all edits.

Traceability extends well beyond traditional version control, which lets one person save multiple versions of a file. In contrast, with traceability, Nexus remembers the actions of multiple engineers. Traceability can result in 60% savings in prototyping costs by eliminating manual errors.



Next Generation Multi-domain RF Circuit Simulation & Optimization

Transform Your RF Design with AI and
Accelerate Time-to-Result

Show me how ►

Transforming RF design with AI: capture, orchestrate, accelerate

AI is constantly in the news, but it has not always been immediately clear how it can be applied to RF design. Keysight has been exploring the topic to gain insights into designing RF components for its RF instrumentation. The company has learned that an effective strategy involves three recursive steps: capture, orchestrate, and accelerate.

The first step is to capture designs in Python, converting RF design workflows into Python AI agents. Any schematic or layout design in ADS can be represented as a Python script. An engineering team can capture existing design knowledge into flowcharts and export them in Python, and an individual engineer can macro-capture a specific design action.

With the engineers' design represented as a Python script, they can parameterize it as the first step in creating an RF design workflow. Subsequently, AI agents can reuse and manipulate the script as part of a more complex workflow. Python scripts can be used to create parameterized functions that connect to larger workflows, serving as a common language for AI tools.

To support collaboration among engineering team members, a tool called Nexus Connect captures design, simulation, and optimization decision trees and converts the entire design methodology into an executable whiteboard flow chart. Nexus Connect automatically generates a Python script representing each design block to facilitate simulation, optimization, decision trees, and parameter settings, freeing the designers from tedious documentation tasks and helping them defend their designs in a design review. AI agents or other engineers can reuse the Python scripts for subsequent complex projects without the need to reinvent the wheel each time. The captured scripts

can be used to create parameterized functions that can be plugged into a new design workflow. Nexus Connect can also help capture institutional knowledge, which can be lost when senior engineers transfer to other positions or retire.

The second step in a successful RF design strategy, orchestration, is the process of automating ADS or Nexus by running captured Python scripts through their Model Context Protocol (MCP) interfaces. This approach opens the door to dialogs like the following, an edited one between a user and the GitHub CoPilot coding assistant regarding a Butterworth design:

User: Connect to the ADS MCP server.

**CoPilot: Let me ping it to verify connectivity...
...Connected! The ADS MCP server is live and responding.**

User: Use the "design_filter" prompt to design a Butterworth N=5 lowpass filter at 2 GHz.

CoPilot: ...the "design_filter" prompt...might be a specific prompt/skill defined in the MCP server or workspace.

...I can see that there's a "design_filter" prompt defined in the MCP server.

...Actually, the prompt is a template that renders instructions for an AI agent to follow when invoked by "prompt/get" ...I should execute this as a general-purpose agent with the full prompt and context.

CoPilot proceeds to do so. The agent then computes the Butterworth N=5 values and physical L/C values; builds the schematic, simulates S-parameters; validates the passband, cutoff, and rolloff frequencies; and reports the results with an inline plot, as shown in *Figure 7*.

A similar approach can be used to orchestrate the design of an amplifier previously captured as an

executable flowchart. In one class J amplifier design example, the orchestrated automation can execute 90 pages of manual steps in about 30 seconds.

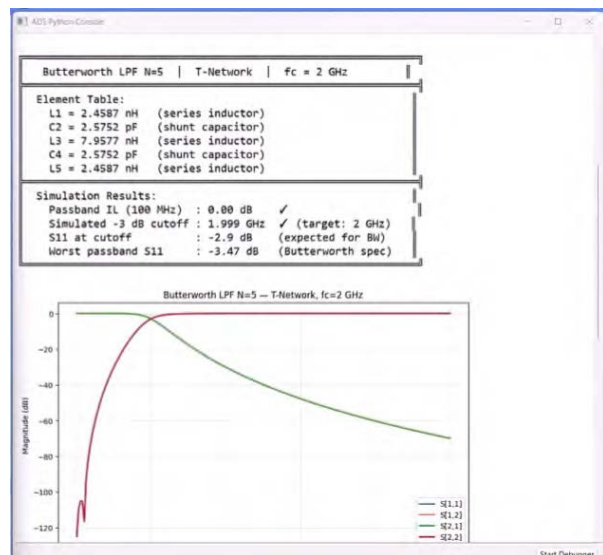


Figure 7. In response to a natural-language prompt, GitHub CoPilot invokes an AI agent to compute Butterworth N=5 values and physical L/C values and to generate an inline plot.

The final step in effectively applying AI to RF design is acceleration, which can be achieved by using parallel solvers, AI algorithms, or new reinforcement learning—all of which can combine to boost optimization speeds by 10x.

AI-generated surrogate models play a key role in acceleration. Surrogate models are particularly useful in optimizing distributed EM structures such as spiral inductors or matching networks (Figure 8). They provide reinforcement learning for the optimization of functions that previously had been difficult to optimize.

Surrogate models are fast, compact neural-network models trained on a set of measurement data or EM and circuit pre-simulation data. These models replace slow, computationally expensive EM simulations, running in milliseconds rather than hours, and teams can use automated AI/ML techniques to build them at very low engineering

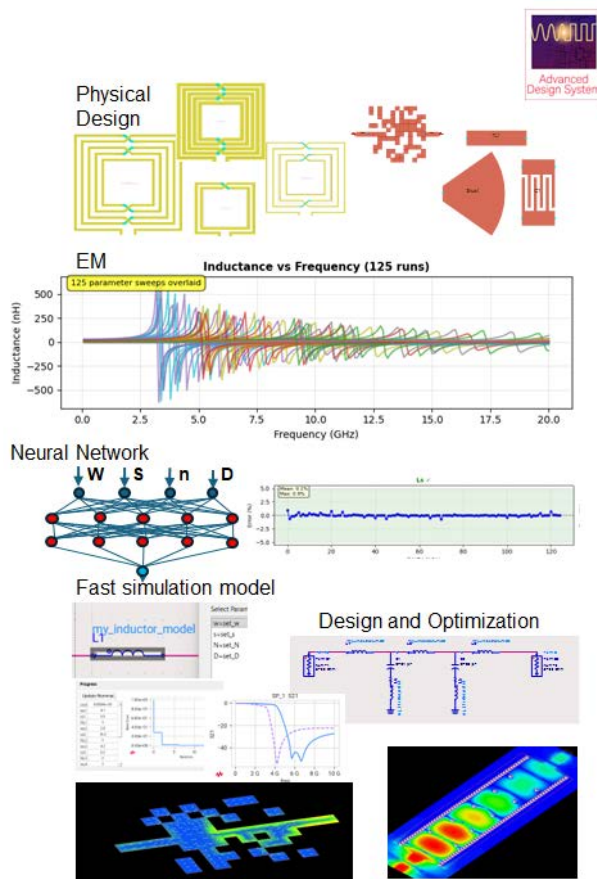


Figure 8. In these examples of spiral inductor, pixelated filter/matching network and Substrate Integrated Waveguide (SIW) filter, fast compact neural-network surrogate model replaces slow EM simulation for design tuning and optimization.

cost. The Keysight platform also supports a “Bring Your Own” (BYO) capability that lets engineers use their own pretrained, trusted physical models or their own optimizers to facilitate the creation of flexible synthesis solutions.

Finally, it is important to note that AI complements RF design engineers but does not take over their responsibilities. With AI, engineers can engage in design explorations that were not previously possible by making use of surrogate models and AI optimizers. However, the engineers will need to sharpen their AI skills to effectively capture their designs, orchestrate the execution of Python scripts, and accelerate RF design workflows to ensure optimum time to result.

Conclusion

The Keysight next-generation RF circuit simulation and optimization open ADS software platform supports the design of mmWave circuits, MMICs, RFICs, and 3DHI modules while working seamlessly with the Cadence Virtuoso and Synopsys Custom Compiler platforms. Keysight's ADS, Nexus, and RFPro software goes deep into the multi-domain application-specific workflows where multi-physics interactions decide complex system performance. In addition, the software unifies design, simulation, validation, and optimization through an end-to-end workflow with traceability and AI augmentation to ensure productivity and trustworthiness. Because AI-driven workflows can evaluate a design in milliseconds, engineers can explore thousands of candidates, with reinforcement learning agents searching the design space to unlock new approaches to multi-objective co-optimization.

Resources to Learn More:

- **Solution Brief:** RF 3DHI Modules and RF Chiplet Designs Crucial to 6G RF Systems
- **White Paper:** The Next-Generation of Circuit Simulation in RF EDA | Keysight
- **Webinar:** Designing 3DHI Modules in Phased Array Systems
- **Bootcamp:** Designing 3D Heterogenous Integration (3D HI) RF Modules
- **White Paper:** Planning Your AI Design Journey in RF EDA
- **How-To-Video:** Connect AI to Keysight ADS for RF Designs | Keysight
- **How-To-Video:** Getting Started with GitHub Copilot for RF EDA | Keysight

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