

A Next Generation RF Analysis Engine for High-Fidelity Digital Twin Modeling

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Abstract

The growing complexity of 5G-Advanced and emerging 6G systems requires RF simulation platforms that deliver both high fidelity and scalability. Traditional tools often fail to capture real hardware behavior — such as nonlinearities, multi-dimensional dependencies, and measurement-driven effects — creating a gap between simulation and lab results. To address this, SystemVue introduces Spectrasys II, a next-generation RF analysis engine designed for accurate and scalable RF digital twin modeling.

Spectrasys II is built on a modern, extensible architecture and introduces several key innovations: native multi-dimensional modeling (MIPs), polymorphic component representations, and equation-based S-parameter modeling. Most importantly, it enables measurement-driven workflows, including advanced models such as measured intermodulation amplifiers and the VanDyke mixer, implementing a “what you measure is what you get” paradigm. This complements traditional IMT-based approaches by introducing MDIF and peak-table-based modeling workflows that improve accuracy and simplify model creation.

By combining hardware-correlated modeling, multi-dimensional simulation, and seamless data integration, Spectrasys II significantly reduces the gap between simulation and reality. The result is faster design iteration, improved prediction accuracy, and a scalable foundation for next-generation RF system design across wireless, aerospace, and satellite applications.

Introduction

Wireless communication systems have undergone rapid transformation over the past decade, driven by the emergence of technologies such as massive MIMO, Non-Terrestrial Networks (NTN), Integrated Sensing and Communications (ISAC), and millimeter-wave and sub-THz radios. These systems introduce tightly coupled interactions between RF hardware, large-scale antenna arrays, baseband processing, and dynamic propagation environments. As a result, system design has become increasingly complex, requiring simulation platforms capable of accurately predicting end-to-end performance prior to costly and time-consuming hardware implementation.

However, traditional RF system simulation engines are fundamentally limited in their ability to capture the true behavior of modern RF components and subsystems. In practice, RF performance depends on multiple independent variables — including frequency, bias conditions, temperature, and input signal power — as well as nonlinear and memory effects. Conventional modeling approaches often rely on simplified, single-dimensional representations or static behavioral models, which fail to capture these dependencies and lead to discrepancies between simulated and measured results. This gap between simulation and hardware remains a major challenge in RF system design workflows.

To address these limitations, Keysight has introduced Spectrasys II, a next-generation RF analysis engine integrated within the SystemVue environment. Spectrasys II is designed to enable RF digital twin workflows, where system-level models closely replicate real hardware behavior across operating conditions. By incorporating native multi-dimensional modeling, measurement-driven model extraction, and modern, extensible architecture, Spectrasys II provides a robust foundation

for high-fidelity RF system simulation. This enables more accurate performance prediction, improved correlation with laboratory measurements, and accelerated design cycles for advanced wireless, aerospace, and satellite communication systems.

Motivation for Spectrasys II

The development of Spectrasys II was driven by a set of architectural and modeling challenges identified in earlier RF system simulation engines. As wireless systems have grown in complexity, incorporating wideband signals, large antenna arrays, and tightly coupled RF/baseband interactions, the limitations of legacy modeling approaches became increasingly evident. There was a clear need for a scalable, extensible, and high-fidelity modeling framework capable of supporting modern RF system design requirements.

A primary motivation was the need to enable native multi-dimensional modeling of RF components. In practice, the behavior of devices such as amplifiers, mixers, and filters depends simultaneously on multiple independent variables, including frequency, bias conditions, temperature, and input signal power. Conventional approaches typically approximate these dependencies using simplified or single-dimensional models, leading to inaccuracies in system-level predictions. Spectrasys II addresses this limitation by introducing Multi-Independent Parameters (MIPs), allowing device characteristics to be represented as functions of multiple variables within the simulation engine. This enables more realistic modeling of nonlinear and operating-condition-dependent behavior.

Another key motivation was to improve the software architecture, consistency, and maintainability of the modeling framework. Earlier implementations relied on a large collection of RF component models with heterogeneous interfaces and inconsistent symbol representations, making extension and validation difficult. Spectrasys II introduces a standardized model framework that consolidates functionality into a smaller set of core components, while leveraging polymorphism to support multiple model implementations within a unified interface. This architectural approach improves code quality, enhances test coverage, and simplifies future development and integration.

A third important driver was the growing need for hardware-driven modeling workflows. RF system design increasingly relies on measurement data obtained from laboratory instruments to capture real device behavior. Spectrasys II enables direct integration of such data into system-level models, allowing engineers to construct measurement-informed RF digital twins. By bridging the gap between measurement and simulation, this approach improves model accuracy, enhances confidence in design decisions, and reduces the need for iterative hardware prototyping.

Architecture of the Spectrasys II RF Engine

Spectrasys II introduces a redesigned RF simulation architecture within SystemVue, with a strong emphasis on modularity, extensibility, and the ability to model complex device behavior. The architecture is built to support modern RF system requirements, including wideband operation, nonlinear effects, and multi-dimensional dependencies, while maintaining a scalable and maintainable software foundation.

A key architectural enhancement is the separation of model code from the simulation engine. This decoupled design allows new device models to be developed, integrated, and validated independently of the core engine, significantly improving flexibility and long-term maintainability. As a result, RF libraries can be extended without impacting engine stability, enabling faster innovation and easier adoption of new modeling techniques.

Spectrasys II also introduces a standardized component framework, including a unified symbol library with consistent sizing, pin alignment compatible with SystemVue dataflow blocks, and visually distinct representations for RF components. This standardization improves usability and reduces ambiguity during schematic creation, leading to more efficient system design and easier interpretation of complex RF architectures.

In addition, architecture leverages polymorphism and part consolidation to simplify the modeling environment. Rather than maintaining many specialized components, Spectrasys II reduces the library to a smaller set of core parts, where each symbol can represent multiple model implementations. For example, a single filter component can be configured to realize different responses — such as Chebyshev or Butterworth — through parameter selection, without altering the system topology. This approach significantly reduces library complexity while increasing modeling flexibility.

These architectural improvements collectively result in a more streamlined and scalable modeling framework. Engineers can rapidly switch between model implementations, reuse components across designs, and focus on system-level analysis rather than library management. The standardized and extensible architecture also facilitates collaboration across teams and supports integration with future technologies. Ultimately, Spectrasys II enables faster model development, improved code quality, and more efficient RF system design workflows, making it well-suited for large-scale and multi-domain applications.

Multi-Dimensional RF Device Modeling

One of the most significant innovations in Spectrasys II is its native support for multi-dimensional device modeling. Traditional RF system simulators typically represent component behavior as a function of a single variable, most commonly frequency — leading to simplified models that fail to capture real operating conditions. In practice, RF device performance depends simultaneously on multiple independent variables, including frequency, bias voltage, temperature, and input signal power, as well as nonlinear interactions between them. Figure 1 illustrates the multi-dimensional data structure used in the new RF_Amp model, enabling simultaneous dependency on multiple operating parameters.

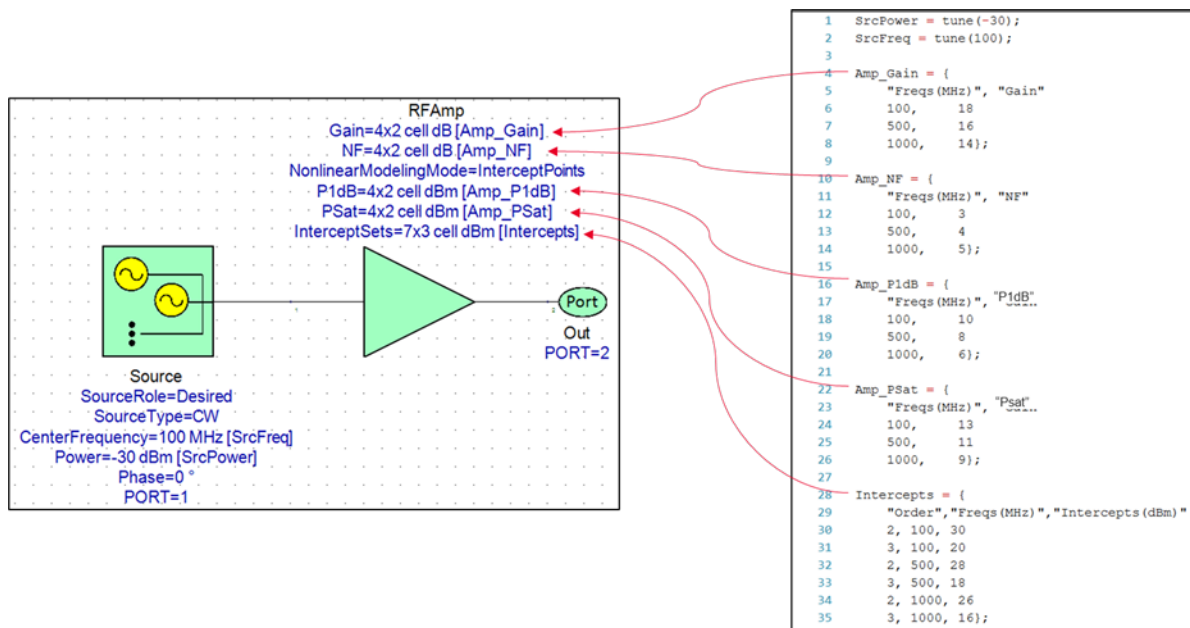


Figure 1. Example of a new RF_Amp model multi-dimensional data format.

To address this limitation, Spectrasys II introduces Multi-Independent Parameters (MIPs), enabling device characteristics to be defined as functions of multiple variables within the simulation engine. For example, gain, noise figure, and compression behavior can be expressed as:

$$\text{Gain} = f(\text{frequency}, \text{input power}, \text{bias voltage})$$

$$\text{Noise figure} = g(\text{frequency}, \text{control voltage})$$

$$\text{Compression point} = u(\text{frequency}, \text{temperature})$$

These relationships can be implemented using either multi-dimensional tabular data or analytical equations, providing flexibility in how models are constructed. Measured or simulated datasets can be efficiently represented using MDIF (Multi-Dimensional Interchange Format) files, which support multiple independent axes and allow direct integration of real device data into system-level simulations. Figure 2 shows an example of modeling a commercial variable gain amplifier using multi-dimensional parameterization within Spectrasys II.

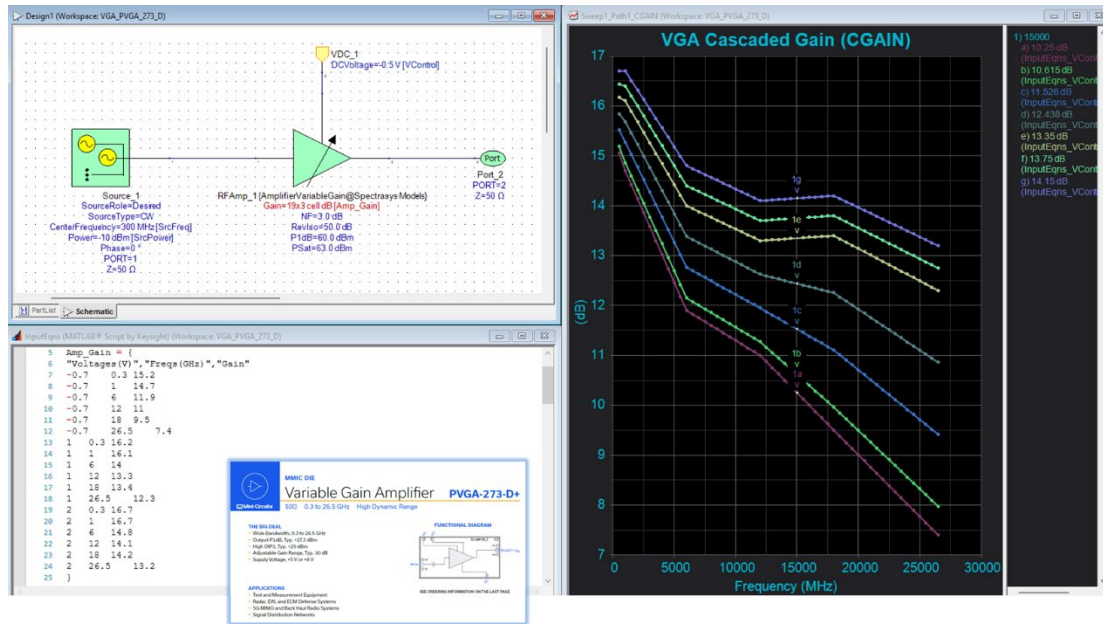


Figure 2. Example modeling of a commercial variable gain amplifier.

By making multi-dimensional physics a native capability of the simulation engine, Spectrasys II eliminates the need for ad hoc approximations and workarounds commonly used in legacy tools. The platform supports multi-dimensional tabular datasets with interpolation across supported independent parameters, enabling continuous modeling across operating conditions. This enables realistic representation of device behavior across the full operating envelope, rather than at isolated operating points.

A key advantage of this approach is its ability to support multi-parameter analysis, design exploration, and optimization. Engineers can perform parametric sweeps across multiple variables simultaneously, enabling efficient evaluation of trade-offs and sensitivities. This is particularly critical for advanced RF systems — such as phased arrays, satellite payloads, and wideband communication links — where performance metrics like gain, noise figure, linearity, and efficiency are strongly interdependent and vary dynamically with operating conditions.

In practical applications, multi-dimensional modeling enables accurate representation of real components and subsystems, including amplifiers with power- and frequency-dependent behavior or variable gain devices controlled by bias settings. By directly incorporating measurement-based data into these models, Spectrasys II allows designers to build high-fidelity RF digital twins that closely match hardware performance. This results in improved prediction accuracy, reduced reliance on simplified assumptions, and greater confidence in system-level design decisions.

Polymorphic Component Modeling

Spectrasys II introduces polymorphism within the RF component library, enabling a single schematic symbol to represent multiple underlying device models without requiring changes to circuit connectivity. In this approach, the functional behavior of a component is determined by its selected model implementation, while the external interface — ports, parameters, and connectivity — remains consistent. This abstraction decouples model selection from system topology, allowing engineers to modify device behavior without restructuring the design.

For example, a single filter component can be configured to realize different responses, such as a Chebyshev band-pass filter, a Butterworth low-pass filter, or a Butterworth band-pass filter, through parameter selection. This capability significantly simplifies design exploration by enabling rapid comparison of alternative implementations within the same system architecture. Engineers can evaluate trade-offs in performance metrics — such as insertion loss, selectivity, or bandwidth — without modifying the schematic structure. Figure 3 demonstrates polymorphic modeling, where a single schematic symbol can represent multiple RF model implementations.

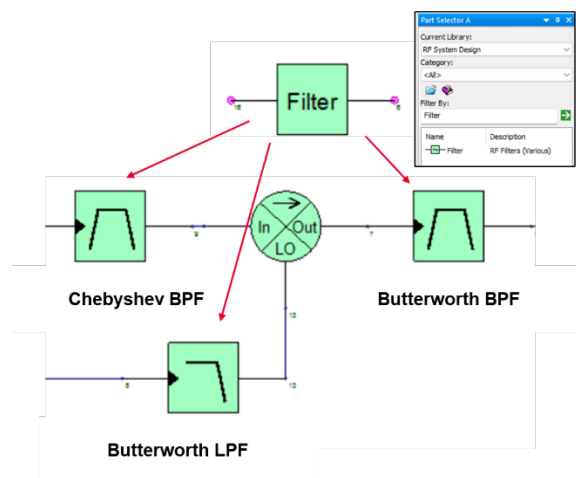


Figure 3. Polymorphism: A single design symbol can map to multiple models.

Polymorphism also streamlines library management and model scalability by reducing the number of distinct component symbols required in the simulation environment. Instead of maintaining an ample collection of specialized parts, Spectrasys II consolidates functionality into a smaller set of flexible components. This reduces complexity, improves usability, and enhances consistency across designs, while also facilitating easier extension of the library as new models and technologies are introduced.

Hardware-Driven Modeling Workflows

Spectrasys II emphasizes hardware-driven modeling, enabling engineers to construct simulation models directly from measurement data. Three notable examples are the new measured intermodulation amplifier model, dynamic gain model, and the VanDyke mixer model.

Measured Intermodulation Amplifier Model

Amplifier nonlinearity is a dominant factor in determining overall RF system performance, particularly in modern communication systems employing wideband and high peak-to-average power ratio (PAPR) modulation schemes. Accurately capturing nonlinear distortion and compression behavior is therefore essential for reliable system-level simulation. Spectrasys II addresses this need by introducing a measurement-based amplifier modeling mode derived directly from two-tone intermodulation characterization.

In this workflow, two-tone intermodulation measurements are performed across a range of input power levels to capture the nonlinear response of the device under test. The resulting spectral components, including fundamental tones and intermodulation products, are extracted and stored as peak tables representing the measured output spectrum. These datasets are then imported into SystemVue — typically via MDIF format — and mapped into a model representation using multi-dimensional parameterization. The model generation process leverages this measurement data to construct a behavioral amplifier model that reflects the device's actual nonlinear characteristics. Figure 4 presents measurement-derived amplifier data used to construct a high-fidelity nonlinear behavioral model.

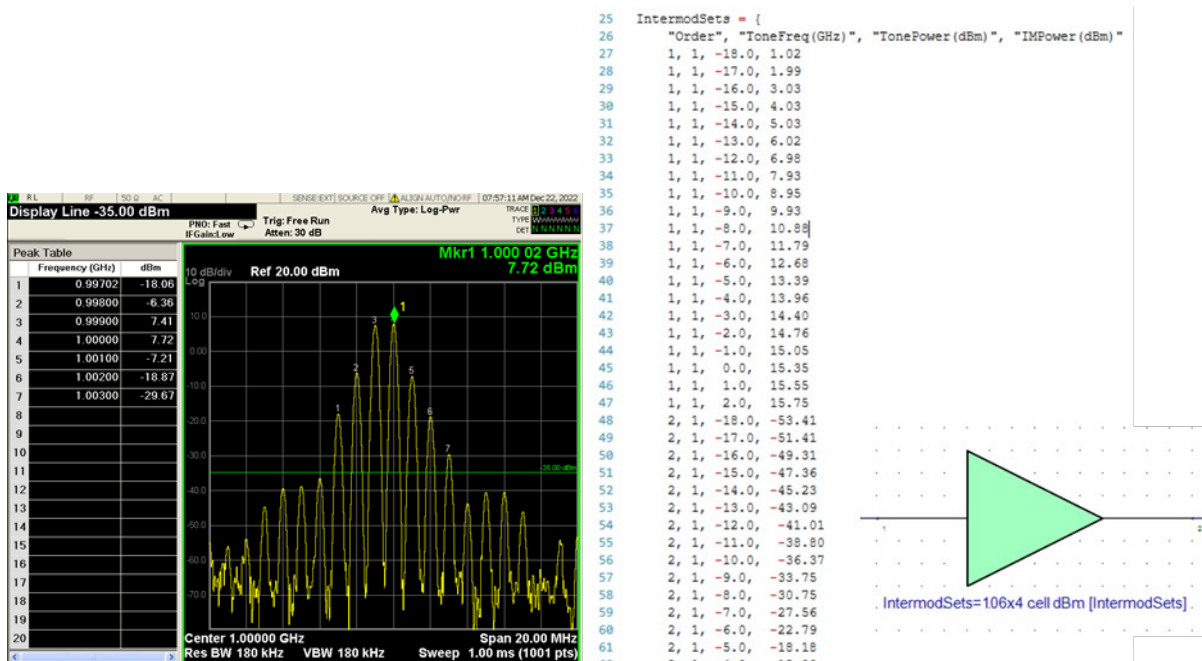


Figure 4. Example data generated directly from measurements ensuring model behavior matches reality.

The resulting model accurately reproduces intermodulation distortion, gain compression, and power-dependent behavior across operating conditions. By directly incorporating measured data, this approach ensures strong correlation between simulated and measured output spectra, enabling a “what you measure is what you get” modeling paradigm. This significantly improves prediction accuracy for key system metrics such as spectral regrowth, Adjacent Channel Power Ratio (ACPR), and Error Vector Magnitude (EVM), while reducing reliance on simplified analytical models and minimizing the gap between simulation and hardware validation.

Dynamic Gain Model (DGM) in Spectrasys II

A key capability in Spectrasys II is the Dynamic Gain Model (DGM), a high-fidelity behavioral modeling framework for nonlinear RF components, particularly Power Amplifiers (PAs) and other nonlinear RF components. Unlike conventional static models that characterize gain or compression at a single operating point, DGM captures the dynamic, signal-dependent behavior of devices under realistic modulated excitations. This includes amplitude and phase nonlinearities (AM–AM and AM–PM), as well as memory effects arising from bias networks, thermal dynamics, and frequency-dependent impedance interactions.

At its core, DGM provides a high-fidelity behavioral representation of nonlinear RF device behavior under complex modulated signal excitation, including memory effects and dynamic nonlinearities. Instantaneous behavior is described through amplitude-dependent gain and phase mappings, while dynamic effects are incorporated by modeling the device response as a function of both the current input and its temporal evolution. This behavioral formulation captures signal-dependent nonlinear interactions and memory effects relevant to wideband RF systems.

To capture memory effects, DGM introduces dynamic filtering mechanisms or kernel functions that operate on the signal envelope, reflecting physical processes such as electrical memory, thermal effects, and impedance dispersion. These dynamic terms modulate the instantaneous nonlinear response, allowing the model to reproduce key phenomena such as spectral regrowth, intermodulation distortion, and phase dispersion in wideband signals. Model parameters are typically extracted from measurement data and can be extended to include multi-dimensional dependencies on frequency, input power, bias, and temperature. Figure 5 compares measured PA output spectra with DGM-predicted results, illustrating strong correlation between hardware and simulation.

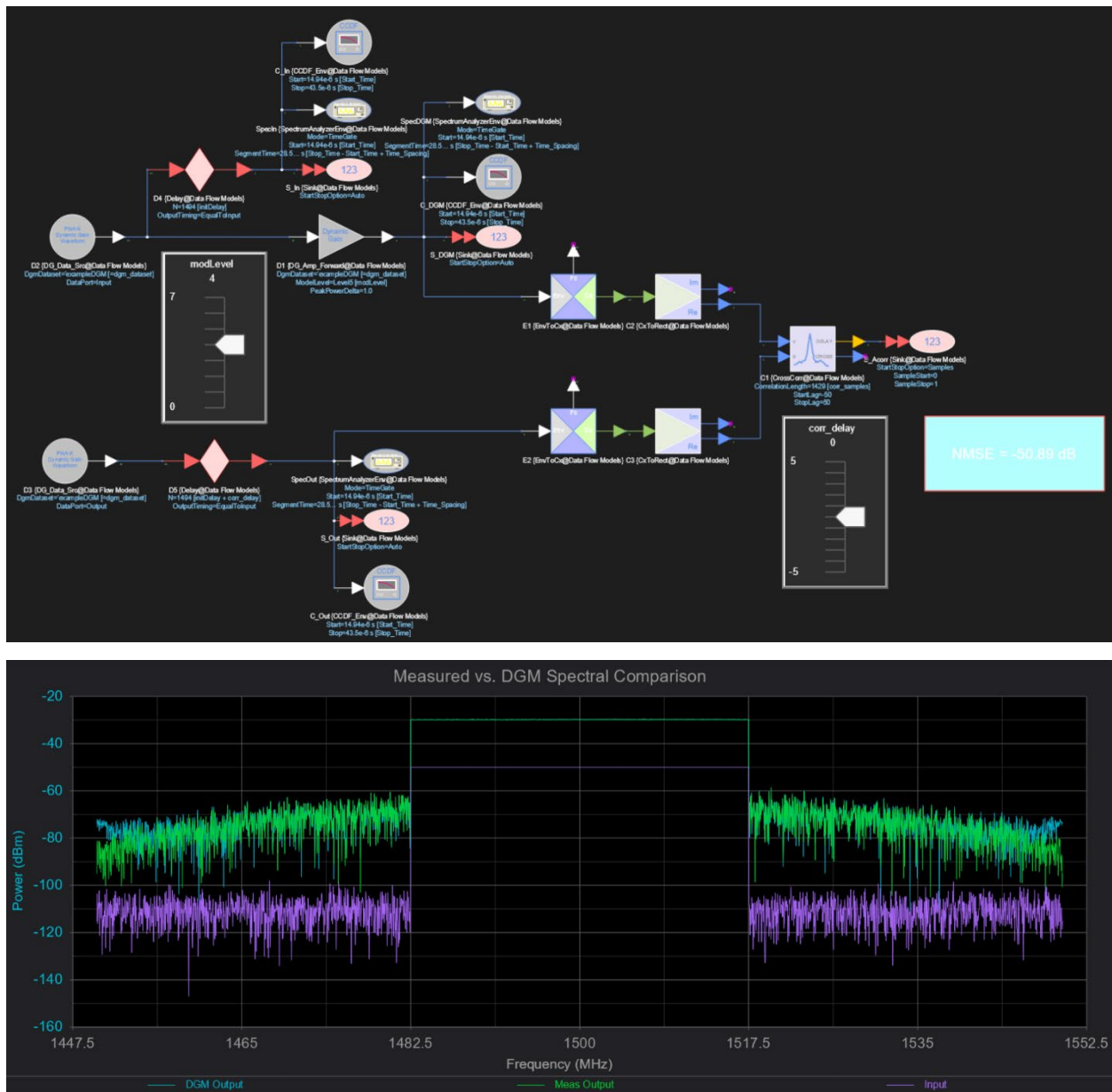


Figure 5. Example comparison of measured output vs DGM predicted output of a power amplifier and the corresponding SystemVue schematic.

DGM integrates seamlessly with Spectrasys II's multi-dimensional modeling infrastructure, enabling measurement-informed models that remain valid across the full operating envelope of the device. This capability is particularly critical for modern wireless systems, including 5G-Advanced and emerging 6G, where wideband signals, high Peak-to-Average Power Ratios (PAPR), and carrier aggregation demand high modeling accuracy. By providing a compact yet physically meaningful representation of nonlinear behavior, DGM enables reliable prediction of system-level metrics such as EVM, ACPR, and spectral compliance, and supports advanced applications including digital predistortion (DPD), linearity optimization, and interference analysis.

Overall, the Dynamic Gain Model forms a critical foundation for high-fidelity RF digital twin modeling, bridging the gap between device-level characterization and system-level performance evaluation while maintaining computational efficiency suitable for large-scale simulations.

VanDyke Mixer Model

Mixers are critical RF components whose nonlinear and frequency-conversion behavior is inherently difficult to model accurately using traditional techniques. Conventional approaches, such as intermodulation table (IMT) models, represent spurious responses using static, index-based matrices of relative power levels. While useful for basic analysis, these methods are limited in their ability to capture real-world behavior under varying operating conditions and often require extensive, error-prone data preparation. To address these limitations, Spectrasys II introduces the VanDyke mixer model, a next-generation behavioral modeling approach derived directly from measured data. Figure 6 shows validation of the VanDyke mixer model through comparison of measured and simulated mixer spur behavior.

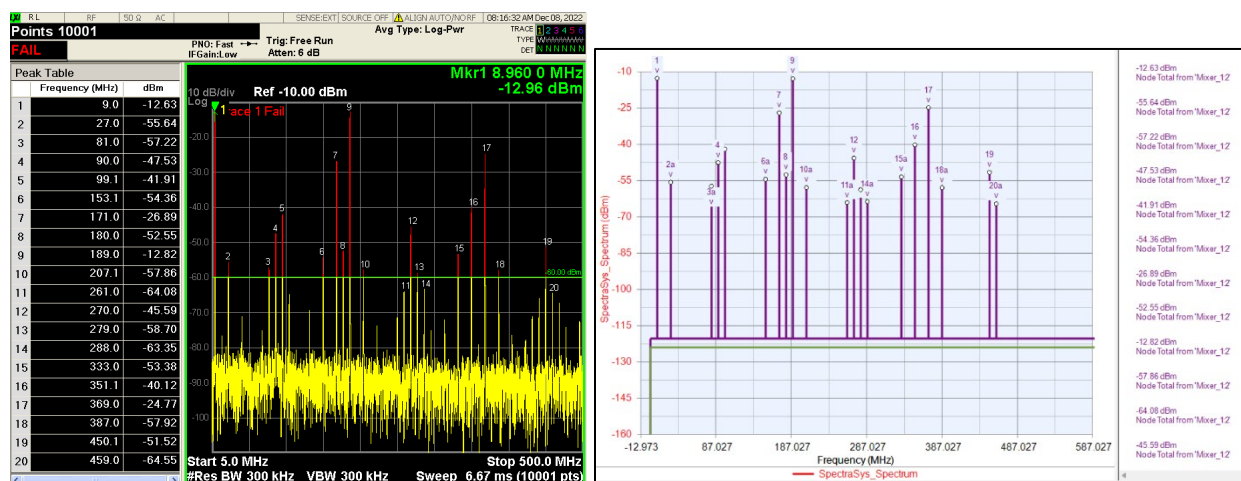


Figure 6. Validating hardware accurate modeling with the new VanDyke mixer (measurement vs model output)

The VanDyke mixer is based on a hardware-driven workflow that directly maps the measured spectral data into simulation models. In this process, mixer spur measurements are first captured using a spectrum analyzer, and the resulting peak data is stored in MDIF (Multi-Dimensional Interchange Format). Spectrasys II uses the measured peak-table data to construct behavioral mixer models that represent spur behavior as functions of RF and LO operating conditions. Each spur is characterized by its frequency relationship and measured power level, forming a structured and physically meaningful model. This approach is summarized by the principle “What You Measure Is What You Get,” ensuring strong correlation between simulated and measured spectra.

A key advantage of the VanDyke mixer model is its ability to capture realistic nonlinear and multi-dimensional behavior. Unlike traditional IMT models, it inherently accounts for dependencies on input power, LO power, and frequency, and supports interpolation across operating conditions. The model accurately represents both forward and reverse spurious responses, distinguishes between sum and difference mixing products, and incorporates higher-order nonlinear effects. It

can also accommodate multi-tone excitations and model behavior in compression regions, making it well-suited for modern wideband and high-dynamic-range RF systems.

More broadly, the VanDyke mixer exemplifies the hardware-driven modeling paradigm introduced in Spectrasys II, where system-level behavioral models are derived from measurement-informed data, improving correlation with real hardware behavior. This paradigm significantly simplifies the modeling process by eliminating the need for complex IMT table generation and manual data manipulation. By focusing on relevant, measured spectral components and automating the conversion to simulation models, Spectrasys II enables a more intuitive workflow and reduces the potential for user error.

As a result, the VanDyke mixer model provides higher accuracy, improved usability, and faster model development compared to legacy approaches. Simulation results generated using this model closely match measured hardware performance, enabling reliable prediction of system behavior. This capability is essential for building high-fidelity RF digital twins and supports advanced applications in wireless communications, aerospace, and satellite systems, where accurate modeling of nonlinear and spurious effects is critical.

Custom RF Modeling and Extensibility

Spectrasys II introduces support for equation-based S-parameter modeling, enabling users to define custom linear RF component behavior directly within the simulation engine. This capability allows engineers to construct analytical or data-driven representations of S-parameters without relying solely on external files, providing greater flexibility in model development. As a result, users can implement proprietary component models, create equation-based representations of measured or synthesized S-parameter data, and extend the simulation library without modifying the core engine architecture. This extensibility is particularly valuable for research environments and advanced system design teams that require customized and rapidly evolving modeling capabilities. Spectrasys II now allows equation-based S-matrix definition, similar to Advanced Design System (ADS) SnP_Eqn utility. The user can build fully custom linear RF models directly inside the RF system simulator (see Figure 7).

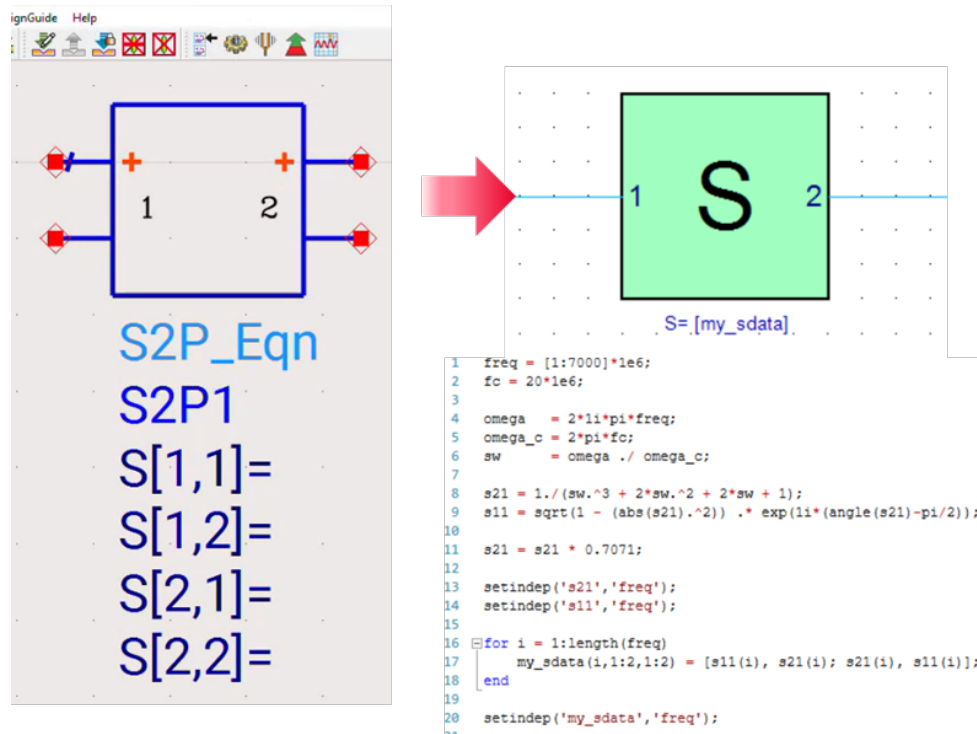


Figure 7. Illustration of an equation-based S-matrix definition in ADS and SystemVue.

In addition, Spectrasys II provides a flexible and unified framework for integrating measured and custom models into system-level simulations. Engineers can import multiple MDIF datasets, perform interpolation across operating conditions, and leverage context-based modeling to dynamically link parameters to simulation variables such as frequency, bias, or temperature. This enables seamless incorporation of vendor components, measurement data, and proprietary models within a single environment. By combining equation-based modeling with measurement-driven data integration, Spectrasys II supports a continuous workflow from component characterization to system-level analysis. This not only improves model accuracy and consistency but also enables efficient design exploration across a wide range of applications, from component-level validation to full RF system architecture design.

Applications in RF Digital Twin Design

The capabilities introduced in Spectrasys II enable a new class of RF digital twin workflows, where system-level models closely replicate the behavior of physical hardware across realistic operating conditions. An RF digital twin is a virtual representation of an RF system that integrates device-level nonlinearities, antenna effects, and propagation environments into a unified simulation framework. By combining multi-dimensional modeling, measurement-driven model extraction, and scalable system simulation, Spectrasys II allows engineers to predict performance with high confidence prior to hardware realization, thereby reducing design risk and accelerating development cycles.

A key enabler of this capability is the tight integration of measurement-informed models and multi-domain simulation. Components such as amplifiers and mixers can be modeled directly from measured data, capturing nonlinearities, spurious emissions, and power-dependent behavior with high fidelity. These models are then combined with antenna array representations, beamforming algorithms, and channel models to form an end-to-end system simulation. This approach allows designers to evaluate critical performance metrics — such as EVM, ACPR, SINR, and link margin — under realistic conditions, bridging the gap between laboratory measurements and system-level behavior.

In wireless infrastructure applications, including massive MIMO and phased-array base stations, Spectrasys II enables accurate modeling of RF impairments, mutual coupling, beamforming strategies, and multi-user interference. By incorporating realistic amplifier behavior and antenna interactions, engineers can analyze the impact of hardware non-idealities on system capacity, coverage, and energy efficiency. This is particularly important for 5G-Advanced and emerging 6G systems, where performance is tightly coupled to both RF hardware and signal processing algorithms.

For satellite and Non-Terrestrial Network (NTN) systems, SystemVue, using Spectrasys II for RF analysis, supports modeling of RF payload chains together with dynamic propagation and channel environments. These systems introduce challenges such as large Doppler shifts, long propagation delays, atmospheric effects, and beam steering across wide coverage areas. By integrating RF front-end models with channel and orbital dynamics, Spectrasys II enables accurate evaluation of link budgets, coverage maps, and system performance for GEO, MEO, and LEO constellations.

In radar and aerospace applications, Spectrasys II provides high-fidelity modeling of RF front-end components, phased-array antennas, and waveform interactions within SystemVue's radar design framework. This enables analysis of detection performance, interference, and system robustness under realistic conditions, including hardware impairments and environmental variations. The ability to model both transmit and receive chains in a unified environment is critical for advanced radar systems and Integrated Sensing and Communication (ISAC) applications.

Overall, SystemVue, powered by the Spectrasys II RF analysis engine, provides a comprehensive framework for RF digital twin modeling that integrates device-level physics, system-level architecture, and environmental effects. By enabling accurate, measurement-correlated simulation across domains, it supports faster design iteration, improved performance prediction, and more reliable system validation for next-generation wireless, aerospace, and satellite systems.

Conclusion

The increasing complexity of modern wireless and aerospace systems demands simulation platforms capable of accurately capturing real RF hardware behavior across operating conditions. Spectrasys II represents a significant advancement in RF system simulation by introducing native multi-dimensional modeling, polymorphic component representations, and measurement-driven workflows within a unified and extensible architecture. These capabilities address key limitations of traditional approaches and enable a more realistic and scalable modeling paradigm.

By integrating these innovations into the SystemVue environment, Spectrasys II enables the creation of high-fidelity RF digital twins that closely correlate with measured hardware performance. This is essential for the design and validation of next-generation systems, including 5G-Advanced, emerging 6G technologies, satellite and non-terrestrial networks, and advanced radar platforms. The ability to accurately model nonlinearities, multi-domain interactions, and real operating conditions significantly improves confidence in system-level predictions and reduces the gap between simulation and implementation.

In addition to improving accuracy, Spectrasys II enhances engineering productivity by streamlining modeling workflows and automating key processes, including model generation, data integration, and validation. Engineers can rapidly explore design alternatives, perform multi-parameter optimization, and evaluate performance using measurement-informed models. This enables faster iteration cycles and more informed design decisions, particularly in complex, multi-domain environments.

These improvements translate directly into reduced development time, lower cost, and minimized design risk. By enabling earlier and more reliable validation through digital twins, Spectrasys II reduces the need for repeated hardware prototyping and accelerates time-to-market. As RF systems continue to grow in complexity, Spectrasys II provides a robust and scalable foundation for bridging the gap between theoretical design and real-world performance, making it a critical enabler for next-generation wireless, aerospace, and defense applications.

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