

Boosting Phased Array Models: Power Amplifier Load Pull and Active Impedance

Behavioral simulation captures power amplifier load pull and array active impedance effects on beamforming

Unlocking Phased Array Design Potential

After proving their mettle in applications like radar and 5G base stations, Phased Arrays are now unlocking their potential in more diverse applications. From miniaturized phased arrays in 5G mobile handsets to defense radar and electronic warfare, these arrays offer size and reliability improvements over mechanically scanned antennas, with higher element count arrays offering simultaneous shaping and delivery of multiple beams.

Phased arrays are growing steadily in defense radar, electronic warfare, and communication applications. However, intense interest now focuses on phased arrays for commercial satellite communication platforms. This shift is driven by the emergence of The New Space Economy, a new era in space exploration and utilization featuring cost-effective, quick-turnaround launch vehicles with mass-deployment capability for smaller payloads of low-earth orbit (LEO) satellites. LEO-based networks, enabled by phased arrays, provide coverage for underserved geographic areas and offer rapid deployment capability and network resilience for conflict zone and disaster response roles.

The phased array design segment is experiencing a surge in demand, fueled by the COVID pandemic and the emergence of new opportunities. Market estimates place its value at an impressive \$3.6B in 2021, with analysts projecting it to reach a staggering \$10.7B by 2031, indicating a compound annual growth rate (CAGR) of 11.5%. These figures underscore the immense potential and exciting future of phased array design.¹ New projects' rapid pace and scale pose significant challenges for design teams that rely heavily on physical prototyping and testing. In many instances, conducting physical tests to replicate real-world conditions is simply not feasible, highlighting the need for alternative design approaches.

If the modeling fidelity for a design is high enough, system-level behavioral simulation of phased array designs can substantially reduce risk and speed up design cycles. Load pull analysis, a crucial part of this process, allows for accurate prediction of array element behavior before fabricating physical arrays. This not only reduces the risk of design flaws but also ensures a faster and more efficient design cycle. Figure 1 shows a layout of a 4x8 array in Keysight Advanced Design System (ADS) for EM simulation with RFPro.

¹ "Phased Array Antenna Market Size, Share, Growth, And Industry Analysis By Type (Radar Phased Array, Communication Phased Array) By Application (Military, Satellite Communications, 5G, Other) Regional Forecast By 2031", Business Research Insights, February 2024, <https://www.businessresearchinsights.com/market-reports/phased-array-antenna-market-102544>

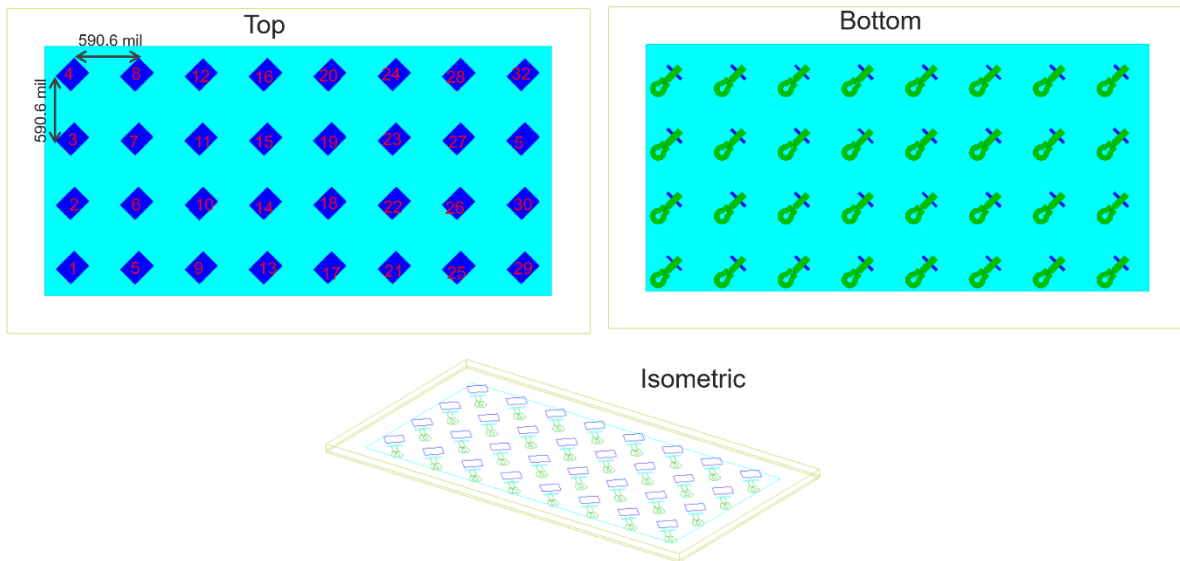
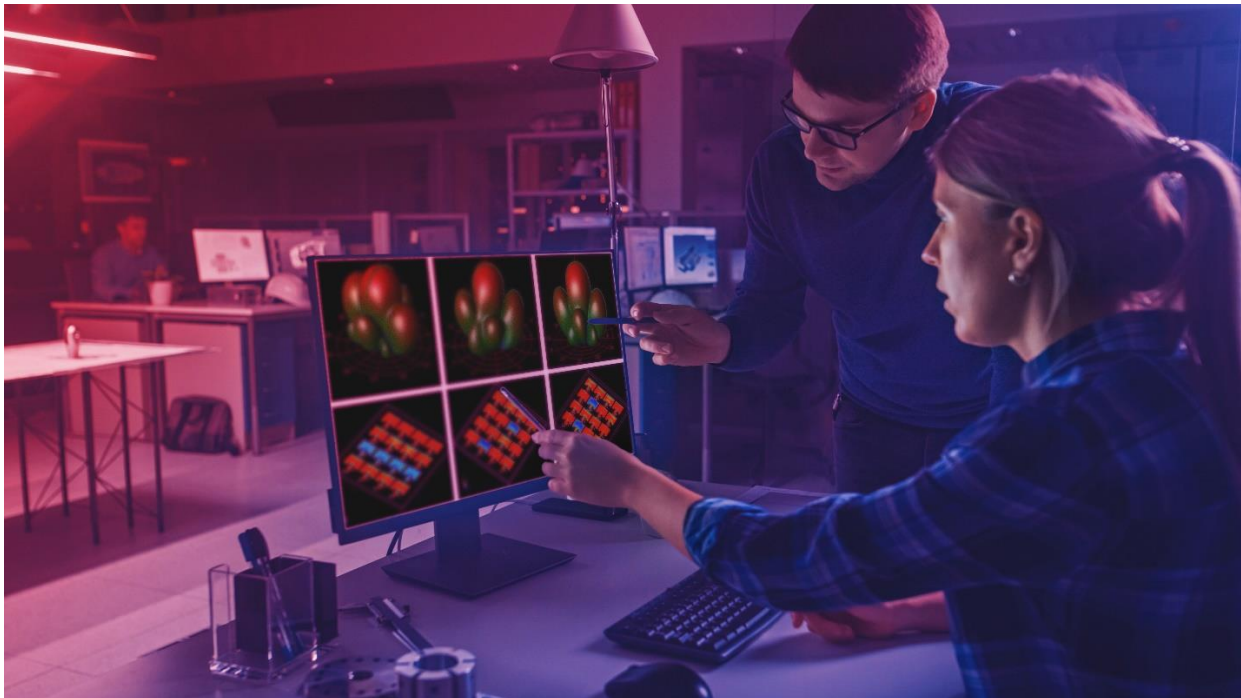


Figure 1. 4x8 antenna array layout with top, bottom, and isometric views in ADS

RFPPro simulation produces an embedded element pattern (.ffio file) by automatically exciting the entire array one element at a time with all other element ports terminated, capturing the pattern of every element in its position in the array. Element patterns differ depending on metalization, structural details, and position of the element in the array. Elements also exhibit EM coupling, where energy radiated from one element is picked up by others – modeling this mutual coupling is essential to predict far-field patterns of an array accurately. The simulation also produces an S-parameter element coupling matrix, which is useful for system-level behavioral simulation.



The other fundamental piece of a phased array design is the RF signal processing behind each element. In a digital beamforming architecture, signal processing consists of power amplifiers (PAs), attenuators, phase shifters, splitters, and mixed-signal components, as depicted conceptually in Figure 2. Component behaviors developed from circuit/EM co-simulation techniques are valuable for system-level simulation.

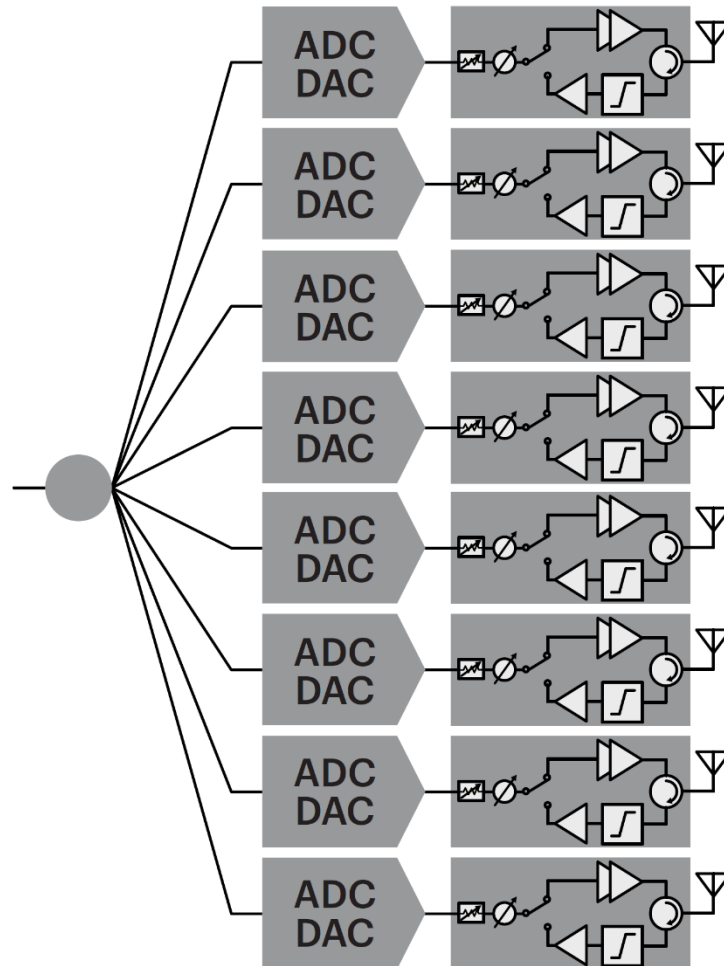


Figure 2. Conceptual view of a digital beamforming architecture for eight array elements

Functionally, an architectural representation of an array and the signal processing might appear to be all that is needed. However, designers will soon realize that real-world interactions present two challenges that combine to produce undesirable system-level results. Additionally, using EM simulation for detailed full-array characterization leads to uncomfortably long simulation times for array sizes with 100 elements or more.

Challenge: Load Pull Shifts PA Performance

RF PA design is an excellent example of how multi-variable optimization becomes necessary. Designers look at gain, peak, average power delivery and efficiency, distortion, linearity, noise, and other performance metrics across a given bandwidth. Changing any feature of a power amplifier typically affects several metrics. Circuit/EM co-simulations can sweep a set of parameters simultaneously, and optimization techniques can explore a multi-dimensional surface, looking for the best results.

Low-frequency PAs usually define a fixed resistive termination as the load, such as 50 or 75 ohms, creating an operating point for optimization versus other variables. In phased array designs with higher frequencies and dynamic impedance, presented by each element as beam shapes change, load pull becomes an issue. Changing drive impedance – the load the amplifier sees – pulls each PA away from its intended operating point, often unpredictably with cross-domain interactions.

Figure 3 shows a load pull analysis for a simple one-amplifier schematic in ADS. Harmonic balance simulation uses a single tone plus harmonics with swept input power and different load impedances at harmonic frequencies. The simulation exposes PA distortion and non-linearity while capturing gain, output power, and power-added efficiency (PAE) at each load impedance. Also plotted is a Smith chart with a contour indicating shifts in the PA's S-parameters as the load changes.

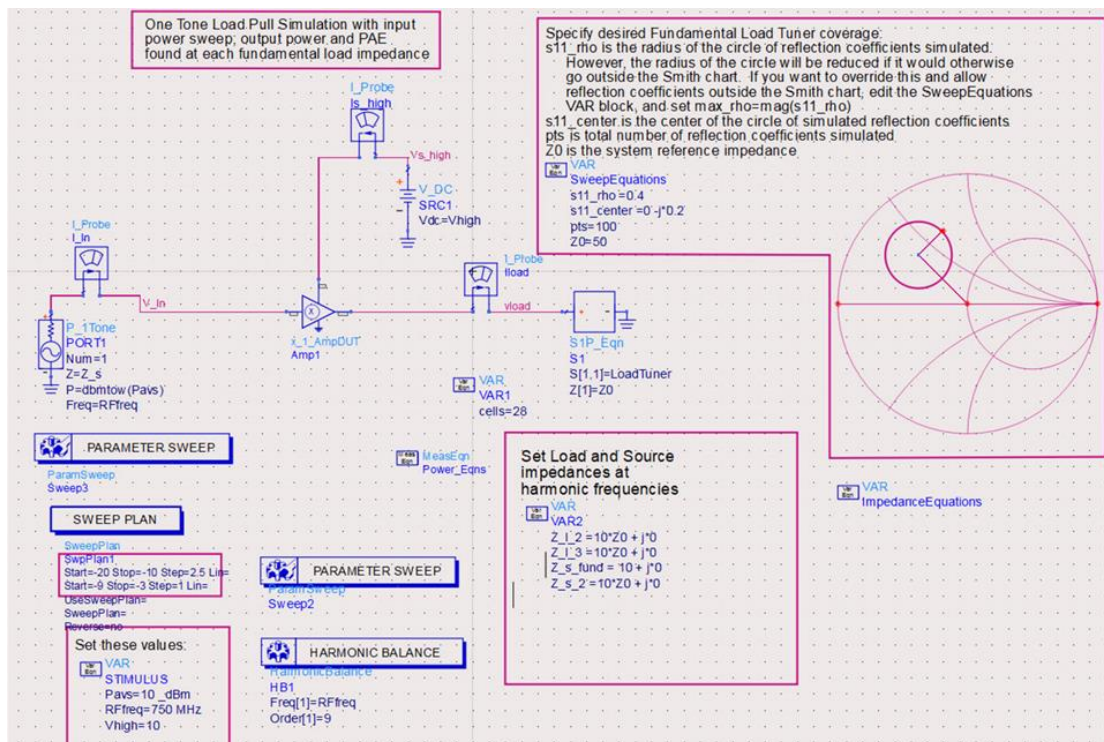


Figure 3. Load pull analysis for a power amplifier using a harmonic balance simulation in Keysight ADS

Load pull analysis with circuit/EM simulation in ADS results in changes to the PA's X-parameter matrix that describe its behavior more accurately – extracting parameters faster and just as accurately as measurements with a network analyzer such as the Keysight PNA-X, which uses similar measurement science. In the solution described shortly, the new PA X-parameter matrix feeds into Keysight System Design along with a modified array coupling model for a more realistic representation.

Challenge: Quantifying Array Active Impedance

Phased arrays have one fundamental purpose: beamforming, steering, and shaping a beam for its context. In radar systems, a wide beam offers faster detection, with narrower beams used to track one or more targets after acquisition. In 5G and 6G systems, beamforming at the base station and mobile device creates massive MIMO connections for optimum data throughput. Satellite communication systems apply beamforming to improve link margin and overcome channel interference.

Beamforming uses a phased array, or one or more subsets of its elements, to create beams with specific directions and shapes. Due to layout and structural issues, the weights (complex amplitudes), steering angles, and phase shifts applied to the array (or subarray) elements combine with the raw electromagnetic coupling between elements. This combination results in each element presenting an active impedance.

Array active impedance is complex to predict in physical space, even with detailed measurements. Detailed models from frequency-domain simulations do not capture time-domain variations observed as beamforming stimuli change and the active impedance varies.

A logical step is performing time-domain analysis, but a challenge arises considering the model in Figure 4. PA load impedance values depend on antenna port reflection coefficients, which are unknown initially, making a conventional sequential analysis for B_2 and Γ_L impossible. The result is that a time-domain simulation fails to converge with broadband stimulus and unknown reflection coefficients.

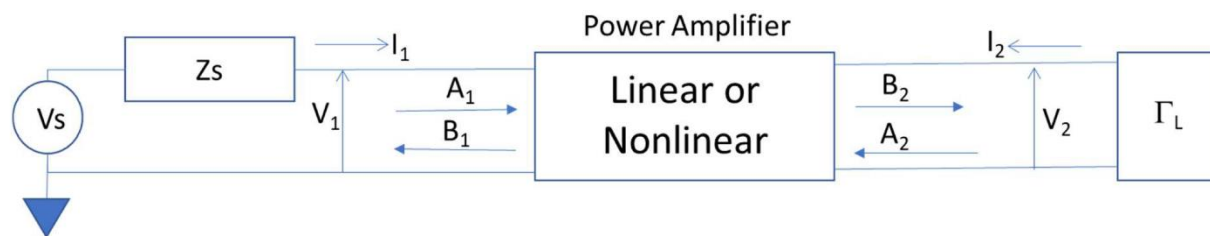


Figure 4. Non-linear S-parameter model for a PA with a single channel input and a variable load impedance

Furthermore, calculating Γ_i for a phased array depends on coupling effects between neighboring elements. Methods neglecting this coupling cannot produce accurate models of array active impedance. However, when coupling is appropriately recognized, many iterative calculations in quantifying array active impedance drive simulation times much higher as the array size grows.

The combined effects of array active impedance and load pull, more complex than found in the separate simplified analyses of the elements and PAs, alter a beam's intended direction and shape. The outcome is measurable with test equipment, but understanding which design parameters must change to correct the beam orientation is only possible with modeling and simulation.

Figure 5 shows an example of a beam intended for a 30° angle with a specific shape. Using time-domain simulation and an imported X-parameter model for PA load pull, the beam orientation is as expected (top). Adding imports of the antenna element patterns and the element coupling matrix and enabling active impedance calculations in data flow time-domain simulation in System Design results in a 2° shift in the beam angle and significant sidelobe variation (bottom). This orientation shift would likely go undetected without array active impedance simulation until physical measurements and would almost certainly be detrimental to system-level performance.

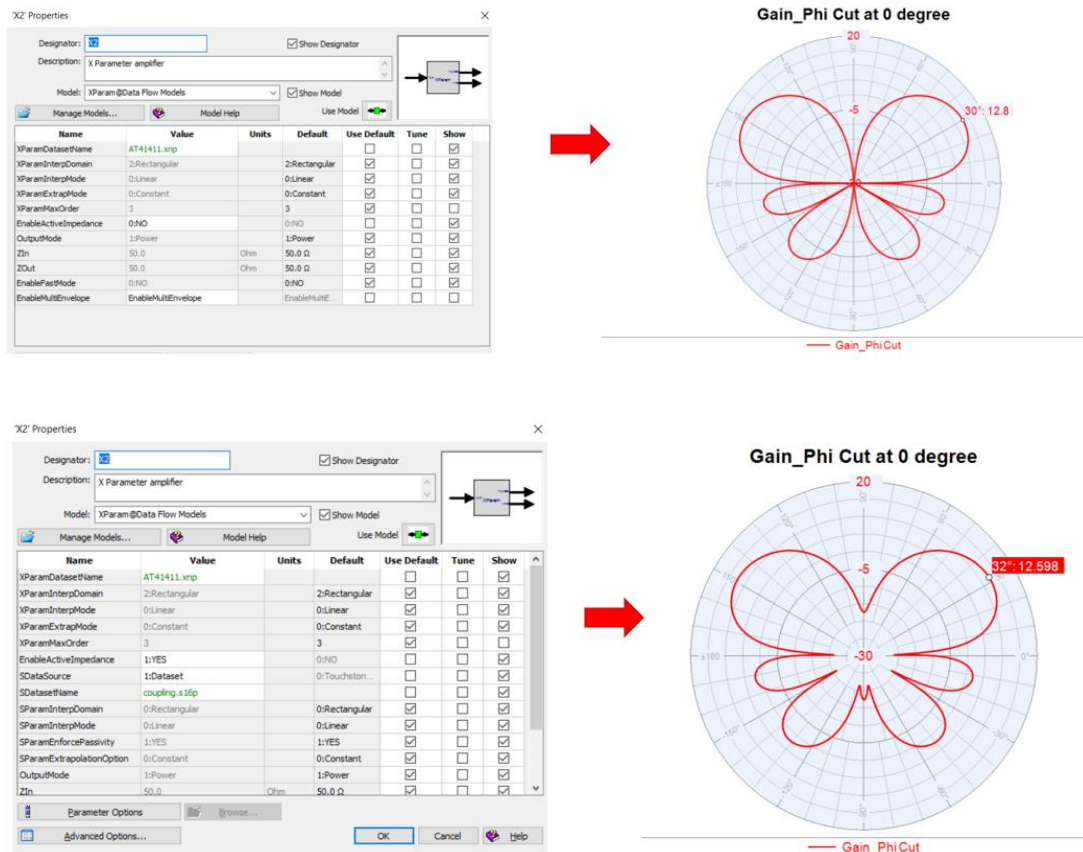


Figure 5. Beam deformation due to active array impedance effects captured in behavioral simulation.

Although behavioral simulation in System Design offers faster simulation times than EM simulation in ADS while retaining model fidelity, larger arrays expand S-parameter matrices and lengthen times. The solution described next simplifies the array representation, reducing simulation complexity and enabling simulations of much larger phased arrays.

Solution: Behavioral Simulation Efficiency

Phased array teams can move into a workflow with **Keysight System Design and W4503E Phased Array Simulation (W4503E)** element as an efficient, accurate system-level design and simulation platform. Three high-fidelity models, developed by antenna and circuit engineers from EM simulation with ADS (assumed in this discussion), physical anechoic chamber measurements, or EM simulation with third-party tools, set the stage for behavioral simulation by system architects:

- An embedded element pattern for the array,
- An S-parameter coupling matrix for the array,
- An X-parameter matrix for PAs with load-pull behavior modeled.

A System Design model of an array starts with an antenna configuration preserving the exact mapping of numbered element locations corresponding to the ADS layout. Then, the embedded element pattern and the S-parameter coupling matrix are imported. Figure 6 shows a simple schematic for a 4x8 array and import dialogs to complete the configuration.

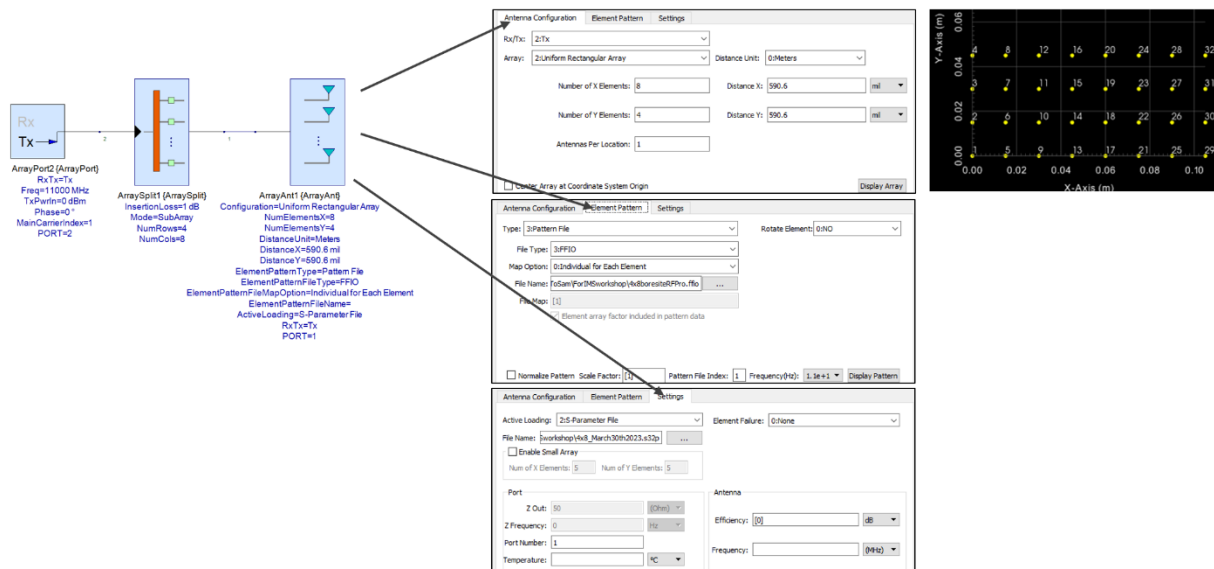


Figure 6. 4x8 antenna array System Design schematic, importing the element pattern and S-parameter coupling matrix

Next, System Design imports the load-pull enabled PA X-parameter matrix emitted from ADS to build its behavioral model. One optimized RF signal processing chain with PAs and other components needs replication to match the number of elements in the array. Smart models in W4503E help condense a set of these chains into a single line – Figure 7 shows the entire one-line architectural model for an 8x8 phased array. W4503E also provides an X-parameter block for array active impedance in the data flow time-domain simulation, shown in Figure 8.

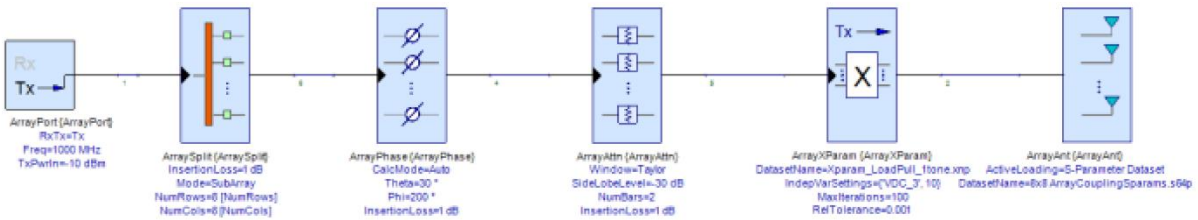


Figure 7. Architectural view of an RF signal processing chain for an 8x8 phased array in System Design

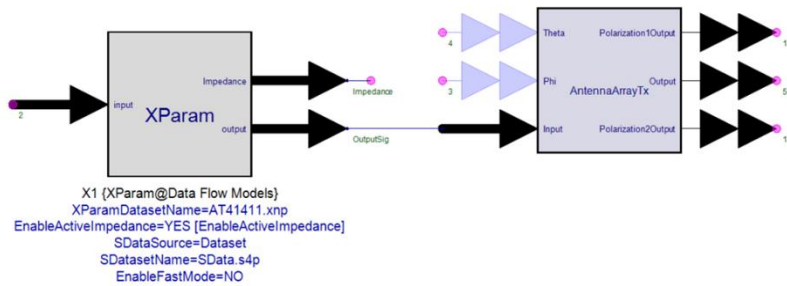


Figure 8. Architectural view of an X-parameter model for array active impedance

A closer look at the time-domain data flow simulation in Figure 9 reveals a yes/no switch for enabling array active impedance in the W4503E user interface. Behind the scenes are the simulation iterations to converge incident and scattered voltage waves into and out of the PAs and the element reflection coefficients, followed by the calculation of impedance seen by each of the PAs, including load pull and element coupling effects.

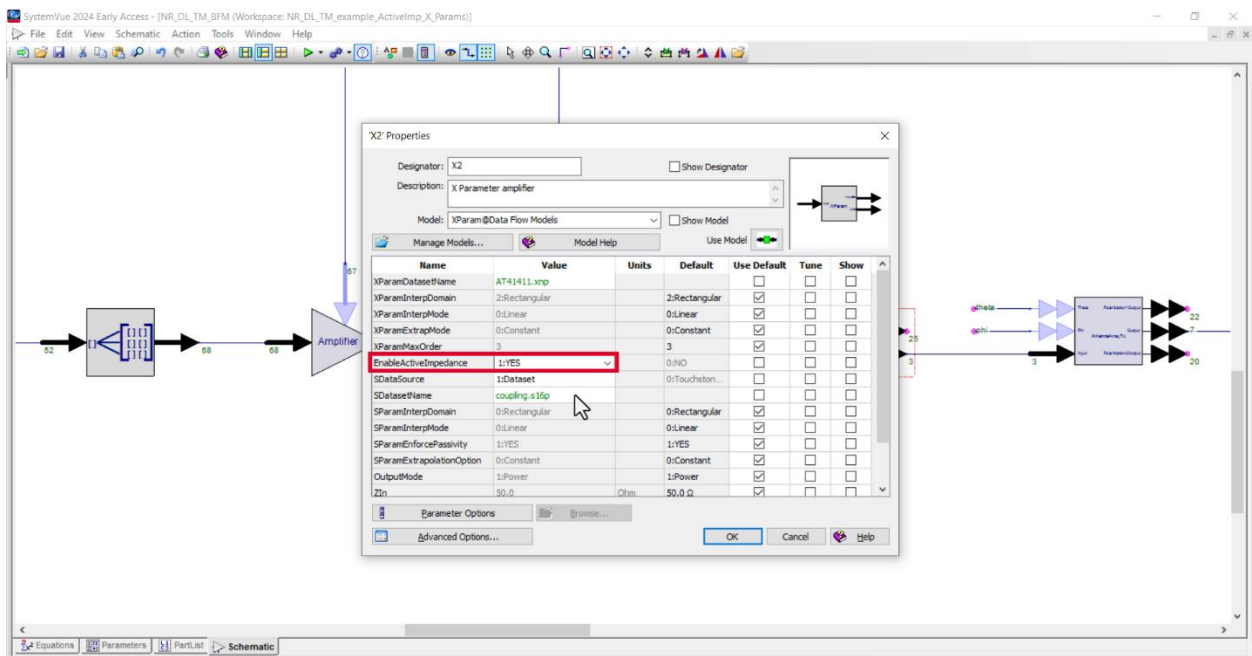


Figure 9. User interface dialog for enabling array active impedance calculations in W4503E

W4503E contains innovative enhancements to data flow simulation data storage to streamline the iterative calculations searching for power amplifier operating points. This avoids repeated passes where amplitude and phase values are the same as in prior passes. The innovative storage algorithm outpaces competing math-based behavioral simulation tools that must grind through each step of complex phased array calculations with large S-parameter arrays across a wide input signal bandwidth.

Another methodology incorporated in W4503E allows system designers to scale to much larger arrays while avoiding long simulation times. The idea is to build larger arrays from a detailed analysis of smaller ones, accurately extending behaviors from some elements to other similar ones in the model. Empirical analysis shows that each element displays significant EM coupling with adjacent elements and some coupling with elements two places away in any direction. After a two-element distance, coupling diminishes to insignificance. The two-element coupling distance observation suggests the minimum array size for detailed active impedance analysis should be 5x5, where each element's coupling is unique. A 5x5 array is convenient for illustration purposes, but other odd array sizes, such as 7x7 or 9x9, work with the method about to be described.

Figure 10 begins on the left with a single 5x5 subarray and its 25 uniquely numbered elements. Element 13 is coupled to every other element (all within a two-element distance), while Element 1 couples to only eight – a boundary condition. A naïve assumption would tile 5x5 subarrays to reach bigger uniform rectangular array (URA) sizes. However, with EM coupling between elements considered, simple tiling creates discontinuities, violating coupling behavior at the subarray boundaries. Element 1 in the upper right subarray in the middle of Figure 10, as analyzed in the 5x5 subarray, does not expect to couple with elements to its left, and the same for Element 21 in the upper left subarray looking to its right.

Boundary conditions need addressing if tiles are to scale without repeating detailed analysis. Moving into a 10x10 array, remapping array elements starting from their positions in the 5x5 subarray solves the edge discontinuities. Each element is no longer unique, and coupling in the full 10x10 array is accurately represented using only the 25 elements from the 5x5 array. Element 13 repeats in the remapped 10x10 array on the right of Figure 10, where the two-element coupling distance in any direction applies. Similarly, other elements repeat with their coupling relationships in the 5x5 subarray preserved.

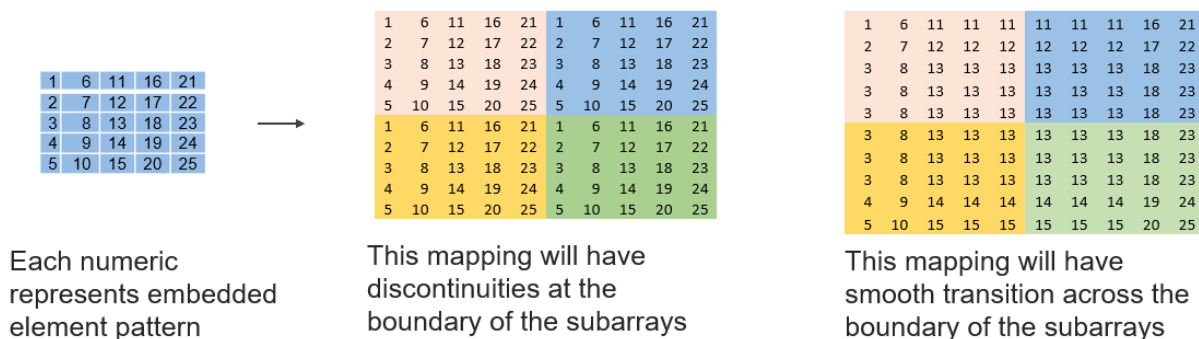


Figure 10. Remapping 25 elements from a 5x5 array into a 10x10 array, preserving positional coupling relationships

Exhaustive analysis of the 5x5 subarray with load pull and EM coupling recognized results in accurate S-parameter properties for each of its 25 elements. Simplifying the 10x10 array with 75% fewer unique elements by mapping their associated S-parameter properties into a larger S-parameter matrix provides significant gains in simulation time, and the savings grow with even bigger arrays. The method also preserves fidelity – simulations of 10x10 arrays with simplified remapped elements agree to four decimal places with simulations of 10x10 arrays using 100 unique elements. Generalizing the technique allows system architects to accurately model phased arrays of hundreds or even thousands of elements.

Other enhancements in W4503E include:

- A sum-of-powers directivity algorithm in the simulator normalizes each antenna element's radiation pattern to its directivity pattern and then computes the pattern of the entire array. It includes a fine-resolution computation and can be constrained to a phi/theta subset of the array. Using sum-of-powers directivity improves system-level behavioral simulation speed by an order of magnitude.
- S-parameters of splitter/combiner models, with several combinations offering enhanced fidelity with compact representations.
- HFSS antenna patterns using azimuth/elevation coordinates and phi/theta.

Creating Digital Twins of Phased Arrays

For satellite communication designers, Keysight System Design with the **W4815B Satellite bundle** offers a superset of the W4503E element with the same phased array simulators plus signal libraries for Satellite Comms, 5G, and Cellular. It includes a digital pre-distortion (DPD) kit and a Systems Tool Kit link to integrate mission scenario planning into System Design architectural models.

Recognizing and incorporating load pull and array active impedance effects on phased array performance using system-level behavioral simulation in System Design lays the foundation for creating a digital twin for a phased array design. Performance can be evaluated virtually, even for large arrays in complex missions with satellite and mobile kinetics modeled. Changes to deployed systems can be simulated before release, reducing risk and costs by deploying successfully on the first attempt.

Keysight System Design and the W4503E element provide today's industry's most advanced design and simulation capability for phased arrays. Adding this capability to a workflow tightens the connection between circuit design and system architecture, with continuity for high-fidelity circuit-level models ensuring efficient and accurate system-level simulation. System architects are more productive and can confidently focus on exploring and optimizing phased array designs for their applications.

For more information on these Keysight RF System Design EDA solutions, please visit:

[Keysight System Design Overview](#)

[W4815B PathWave System Design, Satellite](#)

[W4503E PathWave Phased Array Simulation](#)

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