Design

Designing Next-Generation AESA Radar

Part 2: Individual Antenna Design

Figure 8: Antenna design "Specsheet" user interface showing the electrical requirements input (a), physical constraints input (b) and database of candidate antenna types for use in EM optimization

In the previous example, the 15 x 5 array presented the radiation patterns for an ideal isotropic antenna (gain = 0 dBi) and a simple patch antenna. In addition to the array configuration itself, the design team will likely want to specify the radiation pattern and size constraints for the individual antenna elements. This operation can be performed using the synthesis capabilities in AntSyn, the antenna synthesis software from NI.

AntSyn uses an electromagnetic solver driven by proprietary evolutionary algorithms to explore multiple design options based on antenna specifications defined by the engineer. These specifications include typical antenna metrics, physical size constraints and optional candidate antenna types (the user may select from a database of antenna types or let the software automatically select likely antenna types to optimize), s. figure 8.

AntSyn creates antenna geometries from its database of design types and then applies EM simulation and its unique evolutionary optimization to modify those design to achieve the required electrical performance and size constraints. A run time update of the design types under investigation is listed along with a "star" rating system to indicate which designs are close to achieving the desired performance. Users are able to review the results and design styles as the simulation progresses. Promising designs can then be exported into an EM tool from NI or supported third-party EM simulators, figure 9.

The design flow between AntSyn and NI AWR Design Environment is shown in figure 10, where AntSyn takes antenna requirements and generates an antenna for use in the NI EM tools which will create the antenna pattern for the VSS phased array model.

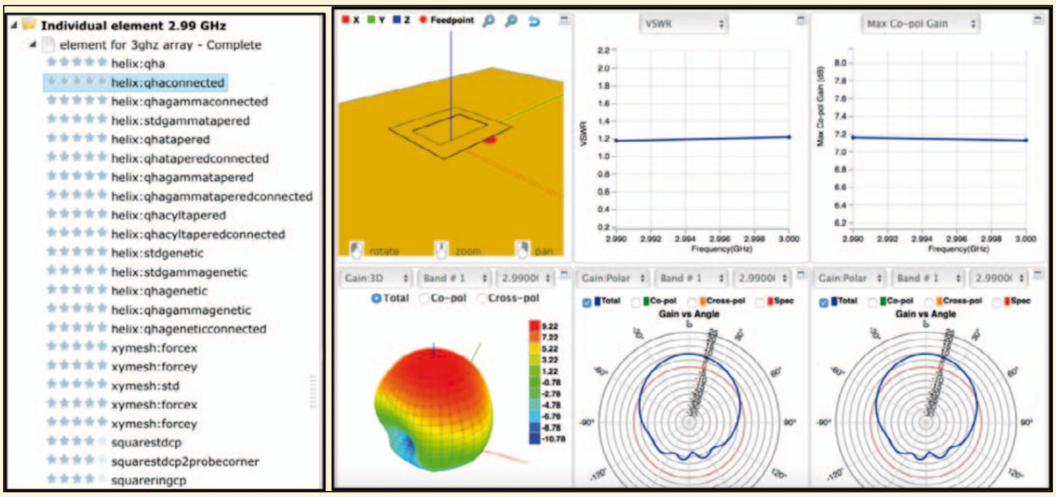

Figure 9: The AntSyn project tree (left) lists the original specsheet as well as all attempted antenna designs with their "star" rating showing how well the antenna came to desired results. Individual antenna results can be viewed with the interface (right) and exported to supported EM tools

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AntSyn			NI AWR Design Envionment	
User design input	Synthesis	Export Data	Operation	Product
Electrical Properties	EM optimization based on evolutionary algorithm provides design candidates that achieved user specifications	Analyst (3D) AXIEM (planar) ANSYS HFSS (3D) CST (3D) WIPL (3D) DXF (layout) STEP (3D Geometry)	Import AntSyn model (XML) as an EM structure in AXIEM or Analyst (planar or 3D) using EM socket.	AXIEM or Analyst
Frequency, VSWR, Gain Pattern, Polarization			Perform EM simulation to generate radiation pattern	AXIEM or Analyst
Physical Properties				
Geometric constraints, Ground plane details, Dielectric properties			Assign radiation pattern to phased array model	VSS
Antenna Type				
Planar, Horn, Dipole, Helix , etc.			Simulate new array pattern	VSS
			RF Link Budget design	VSS
			Array/Feed network interactions	VSS/Microwave Office
			Feed network design	Microwave Office

Figure 10: Operations and products used to create a new antenna design for EM analysis and incorporation into the VSS phased array model

Due to its relatively small size and easy fabrication, a square ring patch antenna was chosen from the potential antennas created by AntSyn. The antenna was exported using the AXIEM options and then imported into a new EM structure (AXIEM) in the initial phased array project. The re-simulated antenna is shown in figure 11. This simulation provided the antenna pattern used to replace the original patch antenna used in the 15 x 5 phased array (figure 12a) with the new antenna pattern shown in 12b. The new phased array results for both the original antenna (red trace) and the square ring patch (green trace) are shown in figures 12 c and d.

Modeling Complex Interactions

The mutual coupling between antenna elements affects antenna parameters like terminal impedances, reflection coefficients and hence the antenna array performance in terms of radiation characteristics, output signal-to-interference noise ratio (SINR), and radar cross section (RCS). The most recent release (version 13) of VSS includes new capabilities for more accurate simulation of these parameters including enhanced modeling of element patterns, including mutual coupling. The next section will look at these recent advances in advanced phase array modeling, including accurate representation of the feed structure.

As mentioned, designers can define gains or full radiation patterns for each antenna element in the phased array. This allows them to use different radiation patterns for internal, edge and corner elements of the phased array, s. figure 13. The radiation pattern of each antenna element will likely be affected by its position in the phase array.

These patterns may be measured in the lab or calculated in the integrated electromagnetic (EM) simulator such as AXIEM or Analyst. A simple approach to characterizing the appropriate radiation pattern for a given element is to use a 3X3 phased array and excite one element, either the internal element, one of the edge elements, or one of the corner elements, while terminating all others.

This will provide the internal, edge, and corner element radiation patterns, which can then be automatically stored in data files using the NI AWR software output data file measurements (the same technique used in the example above). This approach would include the effect of mutual coupling from first-order neighbors. An array with a larger number of elements may be used to extend mutual coupling to first- and second-order neighbors.

It is also important to capture the mutual coupling between neighboring elements. The VSS phased array model does this through a coupling table defined in configuration file. Different coupling levels can be defined based on distance from each other.

In figure 14, the coupling, which is specified in magnitude (dB) and phase (degrees), is defined for two different distances (adjacent side elements: radius c1 and adjacent corner elements: radius c2).

Modeling Impairments and Yield Analysis

RF hardware impairments of the array will affect the resulting side lobe levels and beam patterns, and ultimately reduce system-level performance. For transmitter arrays, side lobe levels from imperfectly formed beams may interfere with external devices or make the transmitter visible to countermeasures. In radar systems, side lobes may also cause a form of self-induced multipath, where multiple copies of the same radar signal arrive from different side lobe directions, which can exaggerate ground clutter and require expensive signal processing to remove. Therefore, it is critical to identify the source of such impairments, observe their impact on the array performance, and take steps to reduce or eliminate them.

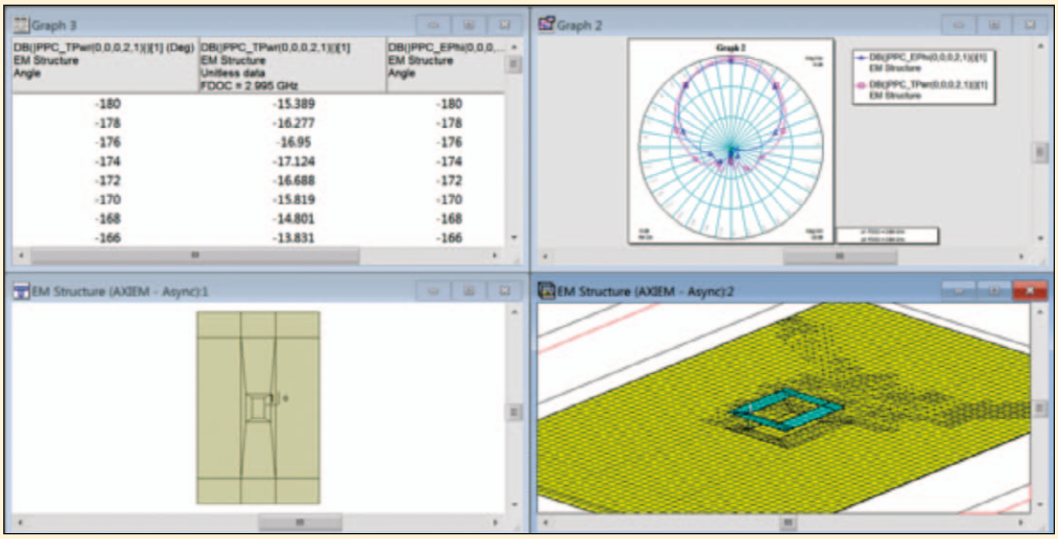

Figure 11: AntSyn generated square ring antenna imported into AXIEM and simulated to generate antenna patterns used by VSS phased array model

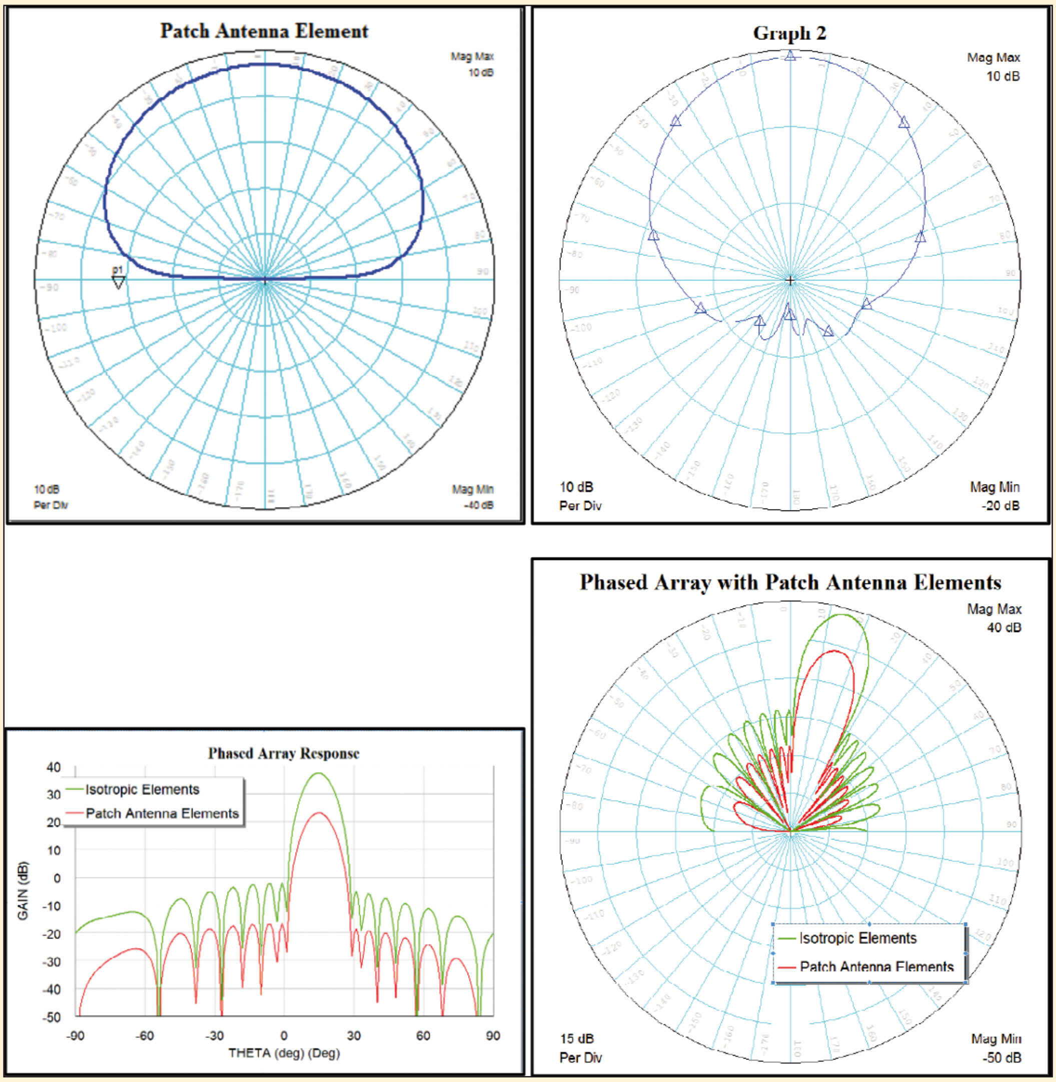

Figure 12: a) original antenna pattern of single patch antenna used in original phased array analysis, b) antenna pattern for square ring antenna generated by AntSyn, c) and d) comparison of radiation patterns from phased arrays based on simple patch antenna and square ring patch

The VSS phased array configuration file, allows engineers to simulate array imperfections due to manufacturing flaws or element failure. All gain/phase calculations are performed internally and yield analysis can be applied to the block in order to evaluate sensitivity to variances of any of the defining phased array parameters. As an example, VSS was used to perform an element failure analysis on a 64 element (16 x 4) array, producing the plots in figure 15 which illustrate the side lobe response degradation.

RF impairments can also be caused by any number of items relating to the feed network design and related components. Systematic errors that may be compensated include inter-chain variations caused by asymmetrical routing (layout), frequency dependencies, noise, temperature, and varied mismatching due to changing antenna impedance with steer angle which also impacts amplifier compression. Therefore, it is imperative to be able to simulate the interactions between the antenna array and the individual RF links in the feed network.

RF Link Modeling

NI AWR software products include the simulation and modeling technology to capture these impairments accurately and incorporate these results into the VSS phased array assembly model. This is an important functionality since RF links are not ideal and can cause the array behavior to deviate significantly. The phased array assembly can operate in either the RX or TX modes, supporting the configuration of the array element geometry, each element's antenna characteristics, the RF link characteristics, and the common linear characteristics of the combiner/splitter used to join the elements together. The configuration is performed primarily through a text data file, with commonly swept settings either specified directly via block parameters (such as steering angles), or specified in the data file but capable of being overridden via block parameters (such as individual element gain and phase adjustments).

The configuration of the phased array assembly may be divided into several sections:

- Array geometry - defines the number of elements, their

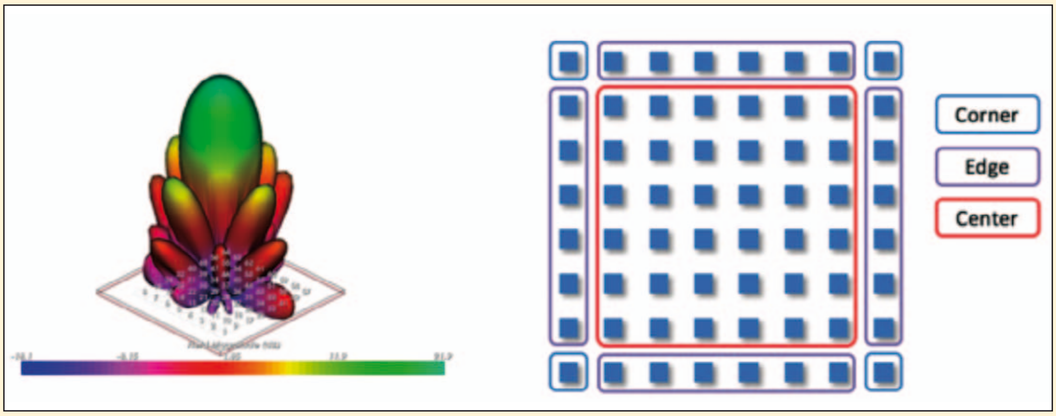

Figure 13: The VSS phased array model supports assigning different antenna patterns to individual elements, allowing designers to more accurately represent corner, edge and center elements

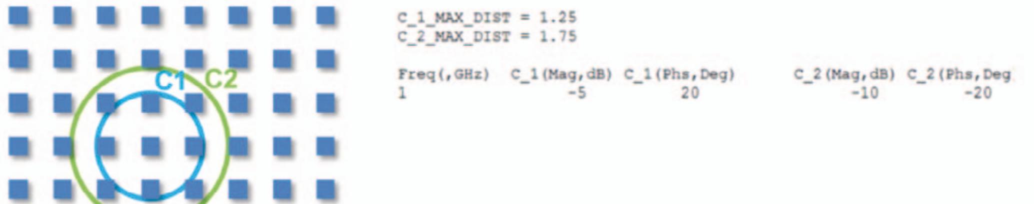

Figure 14: 64 element array showing the mutual coupling table used in the configuration file to specify the amount of coupling between elements, allowing more accurate simulation of terminal impedances, reflection coefficients, etc.

placement, and any geometry related gain and phase tapers

- Antenna characteristics – defines antenna gain, internal loss, polarization loss, mismatch loss, and radiation patterns for both receive and transmit configurations
- RF link characteristics – defines links for individual elements including gain, noise, P1dB. Supports 2-port RF nonlinear amplifiers using large signal nonlinear characterization data typically consisting of rows of input power or voltage levels and corresponding output fundamental, harmonic, and/or intermodulation product levels. Frequency-dependent data is also supported
- Assignment of antenna and RF link characteristics to individual elements

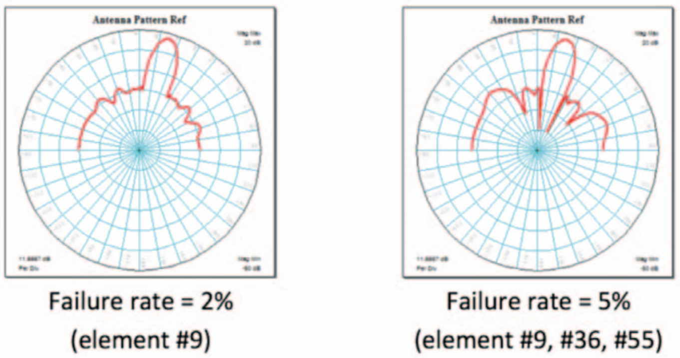

Figure 15: Side lobe degradation to element failures 2% and 5%

- Power splitter characteristics – splits the incoming signal into n-connected output ports
- Mutual coupling characteristics (previously discussed)

One common challenge is that not all RF links should be equal. For example, gain tapers are commonly used in phased arrays; however, when identical RF links are used for all antenna elements, elements with higher gains may operate well into compression while others operate in a purely linear region, causing undesired array performance.

To avoid this problem, designers often use different RF link designs for different elements. While this is a more complicated task, it will result in more efficient phased arrays and VSS phased-array modeling allows them to achieve this.

To assist the design team creating the feed network and provide the RF link to the systems team, VSS includes capability to automatically generate the characteristics of the phased array element link defined by these data tables. The designer starts by creating a schematic-based link design per the system requirements. A "measurement" extracts the design characteristics, which can include circuit-level design details (i.e. nonlinearities) through Microwave Office co-simulation, and saves a properly formatted data file for use with the phased array assembly model, s. figure 16.

In-situ Nonlinear Simulations

An accurate simulation must also account for the interactions that occur between the antenna elements and the driving feed network. The problem for simulation software is that the antenna and the driving feed network influence each other. The antenna's pattern is changed by setting the input power and relative phasing at its various ports. At the same time, the input impedances at the ports change with the antenna pattern. Since input impedance affects the performance of the nonlinear driving

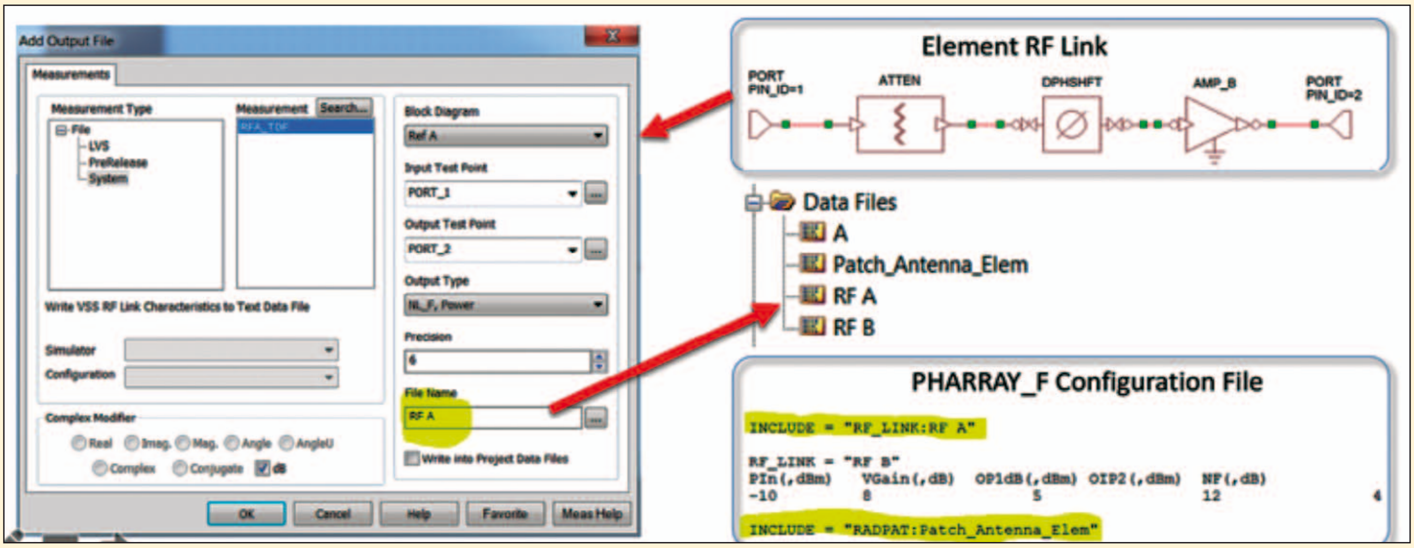

Figure 16: Measurement in VSS extracts characterization of RF link designs and allows assignment for individual elements in the phased array

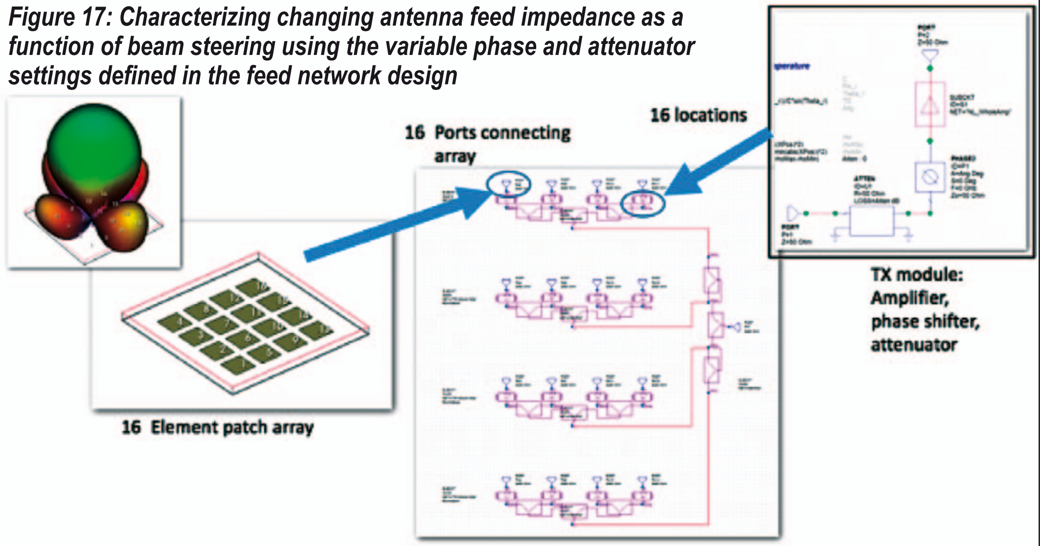

Figure 17: Characterizing changing antenna feed impedance as a function of beam steering using the variable phase and attenuator settings defined in the feed network design

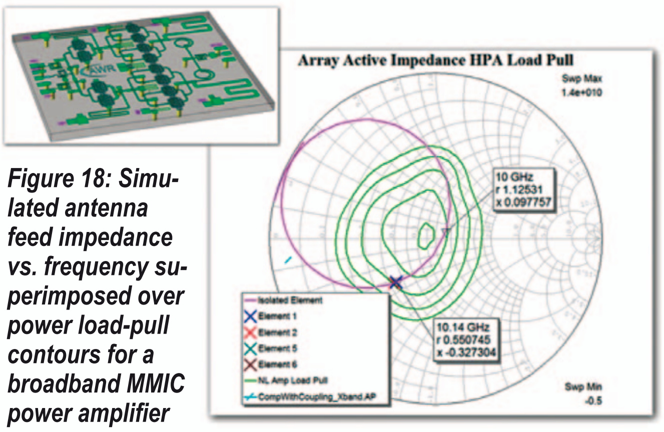

Figure 18: Simulated antenna feed impedance vs. frequency superimposed over power load-pull contours for a broadband MMIC power amplifier

circuit, the changing antenna pattern affects the overall system performance.

In this case, the input impedance of each element in the array must be characterized for all beam steering positions. The array is only simulated once in the EM simulator. The resulting S-parameters are then used by the circuit simulator, which also includes the feed network and amplifiers. As the phase shifters are tuned over their values, the antenna's beam is steered. At the same time, each amplifier sees the changing impedance at the antenna input it is attached to, which affects the amplifier's performance.

In this final example, the PAs are nonlinear, designed to operate at their 1 db compression point (P1dB) for maximum efficiency. They are, therefore, sensitive to the changing load impedances presented by the array. The beam of a 16 element array is steered by controlling the relative phasing and attenuation to the various transmit modules, figure 17. In practice, the harmonic balance simulation used to characterize the power amplifiers with Microwave Office takes substantial time to run with 16 power amplifiers. Therefore, the beam is steered with the amplifiers turned off. The designer then turns on the individual power amplifier for specific points of interest once the load impedance from the directed antenna has been obtained.

At this point the designer can directly investigate the power amplifiers non-linear behavior as a function of the load (antenna) impedance. With the load-pull capability in Microwave Office, the PA designers can investigate output power, compression and any other number of non-linear metrics defining the amplifier behavior, figure 18. With a detailed characterization of the RF links for each individual element, the overall system simulation is able to indicate trouble areas, figure 19 that would have previously gone undetected until expensive prototypes were made and tested in the lab.

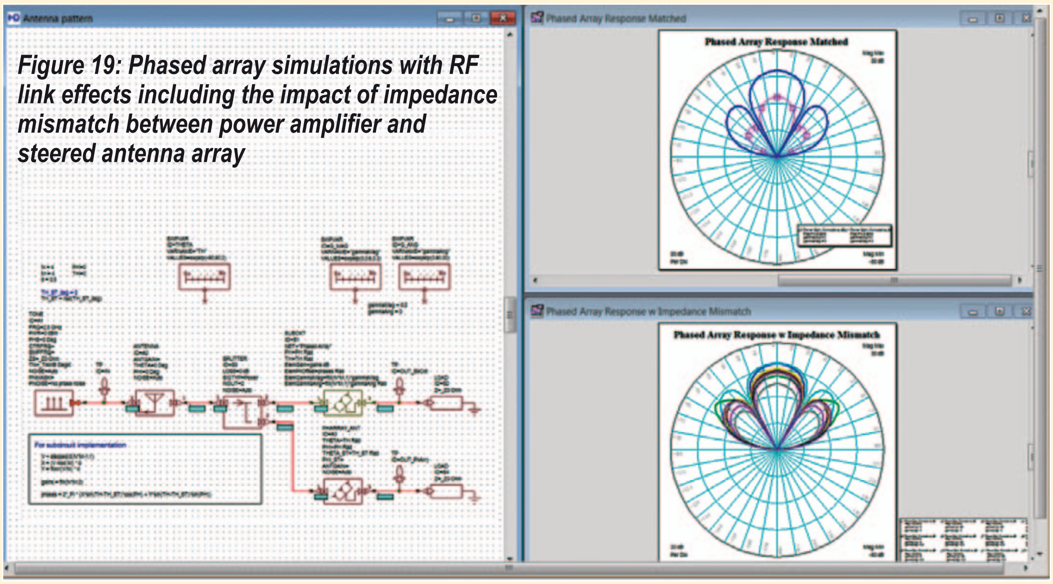

Figure 19: Phased array simulations with RF link effects including the impact of impedance mismatch between power amplifier and steered antenna array

Conclusion

The capability to design and verify the performance of the individual components along with the entire signal channel that defines the AESA radar is a necessity as element counts increase and antenna /electronics integration advances. Through circuit simulation, system-level behavioral modeling, and electromagnetic analysis operating within a single design platform, development teams can investigate system performance and component-to-component interaction prior to costly prototyping.

References

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2. www.astron.nl/other/workshop/MCCT/MondayPatel.pdf