MIMO/Phased-Array Antenna Systems, part 1

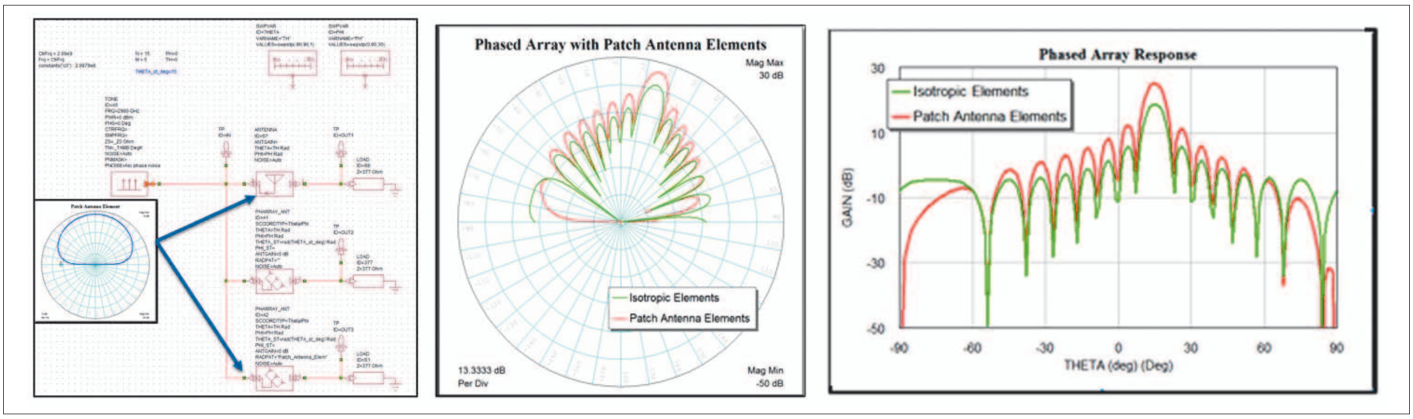

Figure 4. Two 15x5 element phased arrays based on isotropic and patch antenna radiation patterns with theta angle set to 15°

This application note discusses trends and presents recent advances in EDA tools for phased-array-based systems.

Phased-array antennas are becoming popular for a variety of applications such as automotive driver assist systems, satellite communications, advanced radar and more. The complexity and cost issues involved in developing communications systems based on phased-array antennas are being addressed through new functionalities in EDA software that support designers with the means to develop new system architectures and component specifications, as well as implement the physical design of individual components and verify performance prior to prototyping.

Design Management and EDA Tools

While actively-steered phased-array antennas have many advantages, they are extremely complex and their production, especially non-recurring development costs, is significantly higher than for conventional antenna design. As the industry shifts toward highly-integrated phased-array systems, it is critical for in-house systems expertise to work closely with hardware developers, with both fully exploring the capabilities and tradeoffs among possible architectures and integration technologies. In addition, a start-to-finish design flow made possible with EDA software has become critical in moving beyond the initial system simulation, which is focused on early architecture definition, to the development of link budgets and component specifications.

A preferred phased-array system design flow manages the start-to-finish front-end development, embedding RF/microwave circuit simulation and/or measured data of radio/signal-processing (behavioral) models within a phased-array system hierarchy. Such software enables the system designer to select the optimum solution, ranging from hybrid modules through fully-integrated silicon core RF integrated circuit (IC) devices, addressing the specific requirements of the targeted application.

Perhaps more importantly, a system-aware approach, carried throughout the entire phased-array development cycle, enables the team to continually incorporate more detail into their predictive models, observe the interactions between array components, and make system adjustments as the overall performance inadvertently drifts from early idealized simulations.

Design failure and the resulting high costs of development are often due in part to the inability of high-level system tools to accurately model the interactions between the large number of interconnected channels, which are typically specified and characterized individually. Since overall phased-array performance is neither driven purely by the antenna nor by the microwave electronics in the feed network, simulation must capture their combined interaction in order to accurately predict true system behavior. Circuit, system, and EM co-simulation enables verification throughout the design process.

Phased-Array Design Flow

A leading phased-array design flow is available with VSS software, which provides full system

1.1. Surveillance	
1.1.1 Range:	460 km
1.1.2 Time:	< 5 minutes
1.1.3 Volumetric coverage:	hemispherical
1.2. SNR:	> 10 dB, for Z . 15 dBZ at r = 230 km
1.3. Angular resolution:	$\leq 1^{o}$
1.4. Range sample interval Δr	
1.4.1 for reflectivity estimates:	Δr < 1 km; 0 < r <230 km
	Δr < 2 km; r < 460 km
1.4.2 for velocity and spectrum width estimates (r < 230 km):	Δr = 250 m
1.5. Estimate accuracy:	
1.5.1 reflectivity:	≤1 dB
1.5.2 velocity:	≤1 m s^{-1}; SNR> 8 dB; $\sigma_v = 4$ m s^{-1}
1.5.3 spectrum width:	≤1 m s^{-1}; SNR>10 dB; $\sigma_v = 4$ m s^{-1}

Table 1: Requirements for 10 cm wavelength weather surveillance radars

Cadence Design System
www.cadence.com/go/awr

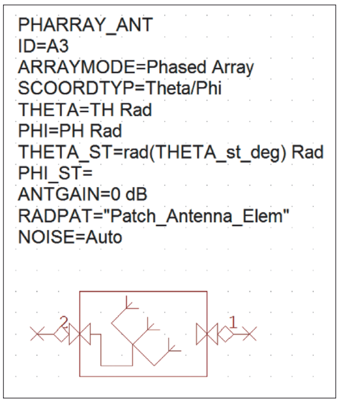

Figure 1: Single phased-array elements can model large scale (thousands of elements) arrays

performance as a function of steered-beam direction, inclusive of the antenna design, and the active and passive circuit elements used to implement the electronic beam steering. System components can be modeled in greater detail using Microwave Office circuit simulation, inclusive of EM analysis for antenna design and passive device modeling using AXIEM 3D planar and Analyst 3D FEM EM simulators.

These tools are fully integrated into NI AWR Design Environment software, supporting seamless data sharing within the phased-array hierarchy. Furthermore, individual antenna designs can be generated from performance specifications using the AntSyn antenna synthesis and optimization module, with resulting geometries imported into AXIEM or Analyst software for further EM analysis and optimization.

Highlights of phased-array analysis in VSS software include:

- Automate/manage the implementation of beamforming algorithms and determine phased-array antenna configuration from a single input/output block.
- Accomplish array performance for over a range of user-specified parameters such as power level and/or frequency.
- Perform various link-budget analyses of the RF feed network, including measurements such as cascaded gain, noise figure (NF), output power (P1dB), gain-to-noise temperature (G/T), and more.
- Evaluate sensitivity to imperfections and hardware impairments via yield analysis.
- Perform end-to-end system simulations using a complete model of the phased array.
- Simulate changing array impedance as a function of beam angle to study the impact of impedance mismatch and gain compression on front-end amplifier performance.

Defining Phased-Array Configurations

Specifications for any phased-array radar are driven by the platform requirements and the intended application. For example, weather observation, which has relied on radar since the earliest days of this technology, most commonly uses airborne surveillance radar to detect and provide timely warnings of severe storms with hazardous winds and damaging hail. The weather surveillance radars are allocated to the S (~10 cm wavelength), C (~5 cm wavelength), and X (~3 cm wavelength) frequency bands. While the shorter wavelength radars provide the benefit of a smaller antenna size, their radiated signals are significantly affected by atmospheric attenuation.

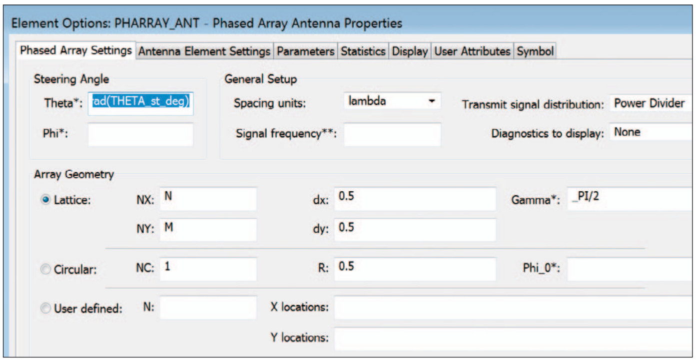

Figure 2: Phased-array parameter dialog box

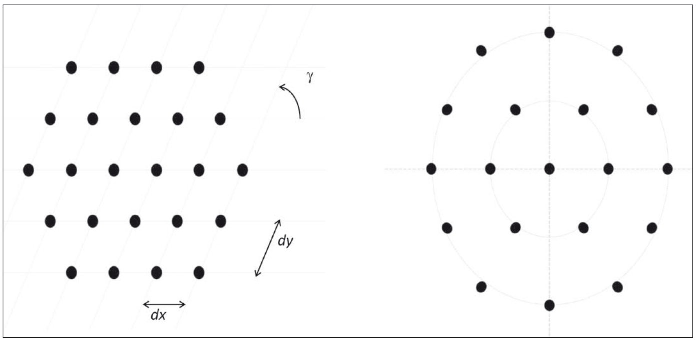

Figure 3. Standard VSS array geometries: lattice (left), circular (right)

Requirements for 10 cm wavelength (S-band) weather surveillance radars, based on years of experience with the national network of non-Doppler radars (WSR-57), are shown in Table 1.[1]

These requirements showcase some of the application specific metrics that drive range, frequency, antenna size, and gain. These factors represent the starting point for the system designer, who will also weigh cost and delivery concerns and available semiconductor and integration technologies, when considering possible architectures and defining individual component performance targets.

VSS software provides system designers with the capabilities needed to convert these requirements into hardware specifications and work out the initial design details. Starting with the

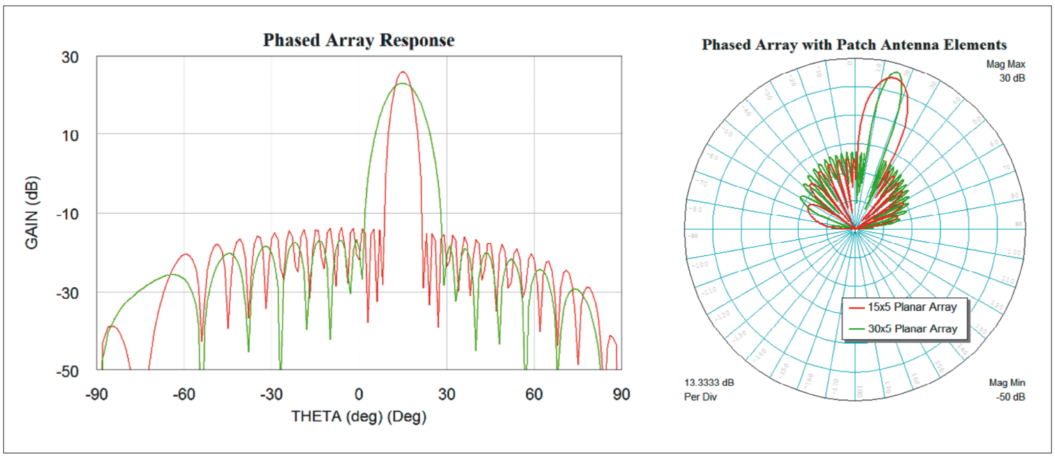

Figure 5: Radiation patterns for 15x5 and 30x5 arrays and side-lobe behavior for array (5 x 15)

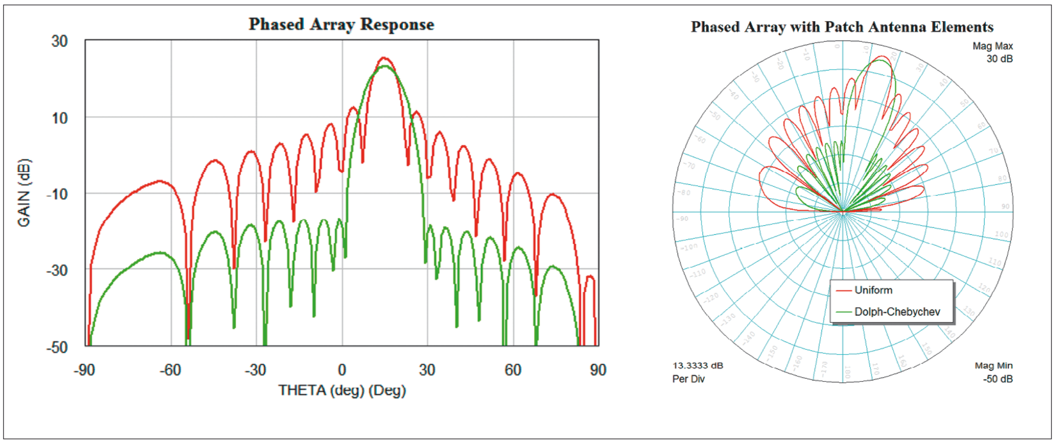

Figure 6: 5 x 15 patch array with uniform vs. Dolph-Chebyshev gain tapering.

phased-array configuration, VSS is able to represent thousands of antenna elements with a single model, enabling the antenna design team to quickly produce radiation patterns with basic array properties such as number of elements, element spacing, individual element gain or radiation pattern (imported measured or simulated antenna data), array configuration, and gain taper. The model, shown in Figure 1, allows designers to specify the array's physical configuration based on various standard lattice and circular geometries, as well as custom geometries.

The array behavior is easily defined through a parameter dialog box or a data file containing configuration parameters such as gain and phase offset, theta/phi angles of incidence, number of elements in both X/Y locations (length units or lambda-based), spacing, and signal frequency. This model greatly simplifies early exploration of large-scale phased array configurations and individual antenna performance requirements versus the old method of implementing such a model using basic individual blocks, where array sizes were generally limited to several hundred elements, each modeled as a single input/single output block.

Figure 2 shows a portion of the VSS parameter dialog box used to quickly define an antenna-array architecture using standard or custom geometries. The lattice option allows configuration of the phased array in a lattice pattern, which is configured using the number of elements along the X and Y axes, NX and NY, element spacing along these axes, dx and dy, and gamma, the angle between these axes. Setting gamma to 90° results in a rectangular lattice, while setting it to 60° creates a triangular lattice. Any positive value for gamma may be used to configure the lattice, while the circular option enables configuration of circular phased arrays with one or more concentric circles. The number of elements in each concentric circle and the radius of each circle can be defined as vectors by variables NC and R. Examples of lattice and circular array configurations are shown in Figures 3a and b.

To demonstrate some of the capabilities of the phased-array model, an example project was constructed showing two 15x5 element arrays operating at 2.99 GHz (Figure 4).

One model represents an array of lossless isotropic antennas defined simply by setting the antenna gain to 0 dBi, while the elements of the other array utilize a data set containing the radiation pattern of a single simulated patch antenna. Both arrays use a lattice configuration with a walvelenth/2 spacing between elements and uniform gain tapering. For the simulation shown, the steering angle (theta) was set to 15°. Note that the antenna and phased-array blocks support specifying the signal direction

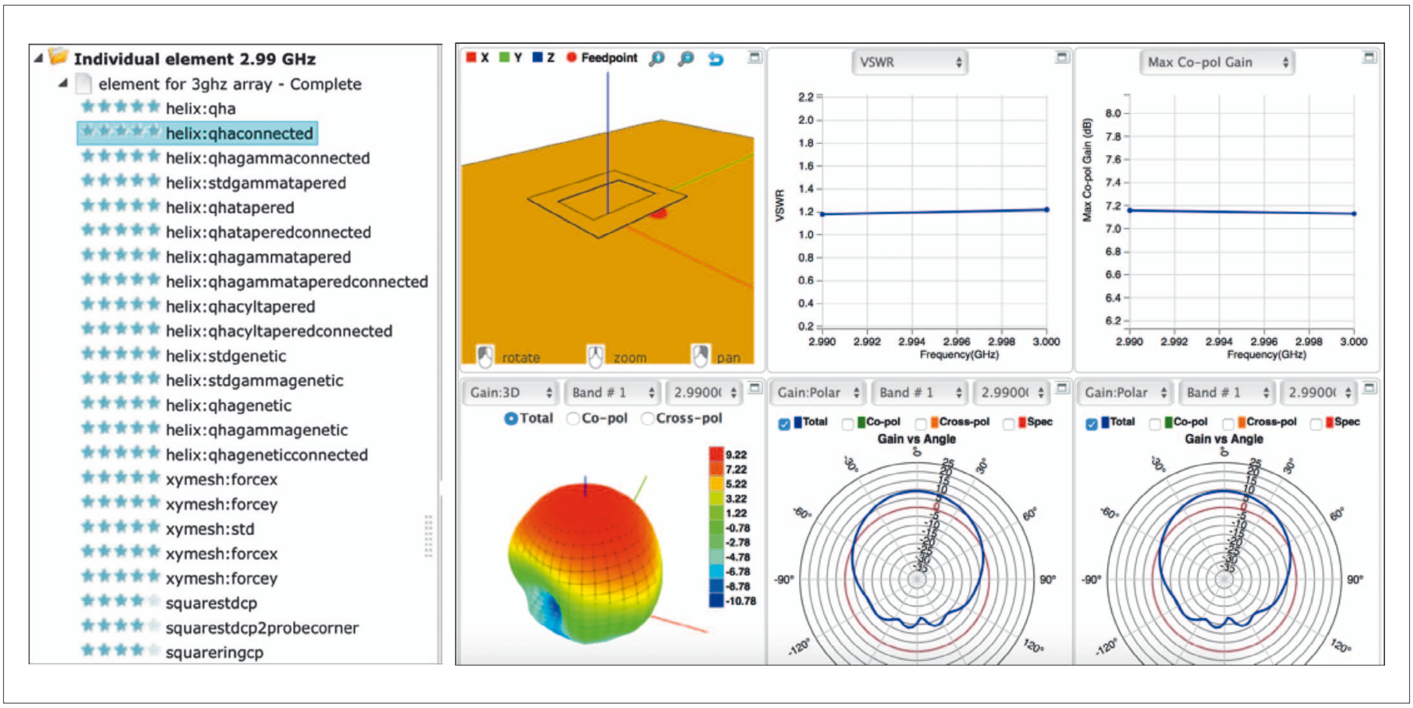

Figure 7: The AntSyn project tree and candidate antenna designs with their star rating. Results can be viewed and exported

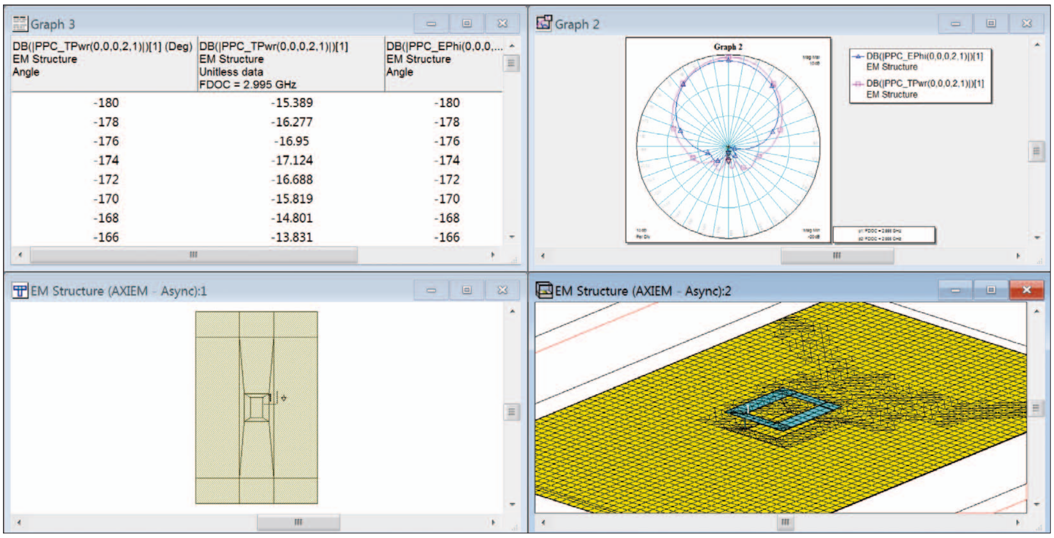

Figure 8: Square-ring antenna imported into AXIEM and simulated to generate antenna patterns used by the VSS phased-array model.

using U/V coordinates as well as theta/phi angles (Figure 5).

The VSS array model provides antenna designers with a rapid and straightforward tool to observe key antenna metrics, providing a means to examine the main beam and side lobe behavior as a function of any number of variables, including array size and configuration, gain versus steering angle, and the occurrence of grading lobes as a function of element spacing and/or frequency. From these results the array design team can develop an optimum configuration for the given requirements such as range and overall array physical size. In addition, the team can provide design targets for the individual antennas and incorporate subsequent antenna simulation results back into the array analysis.

Control of the amplitude excitation through gain tapering is often used to control beam shape and reduce the side-lobe levels. A number of commonly-used gain tapers are implemented in the phased-array block. Gain taper coefficient handling defines whether the gain taper is normalized or not.

If it is, the taper is normalized to unit gain. Standard gain tapers implemented in the phased-array model include Dolph-Chebyshev, Taylor Hansen, and uniform. The earlier example (15x5 element patch array) was re-simulated with uniform versus Dolph-Chebyshev gain tapering, showing the impact on the main beam and side lobes, as shown in Figure 6. In addition, the user can define custom gain tapers by specifying the gains (dB) and phases for each array element.

Individual Antenna Design

In the previous example, the 15x5 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 software, which uses an EM 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).

AntSyn software (Figure 7) creates antenna geometries from its database of design types and then applies EM simulation and its unique evolutionary optimization to modify those designs 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 NI AWR Design Environment or through AWR Connected third-party EM simulators.

Due to its relatively small size and easy fabrication, a square-ring patch antenna was chosen from the potential antennas created by AntSyn software. The antenna was exported using the AXIEM options and then imported into a new AXIEM EM structure in the initial phased-array project. The re-simulated antenna is shown in Figure 8.

This simulation provided the antenna pattern used to replace the original patch antenna used in the 15 x 5 phased array, with the new antenna pattern shown in Figure 9. The new phased-array results for both the original antenna (red trace) and the square-ring patch (green trace) are shown in Figure 9 as well.

The end will follow in the next issue

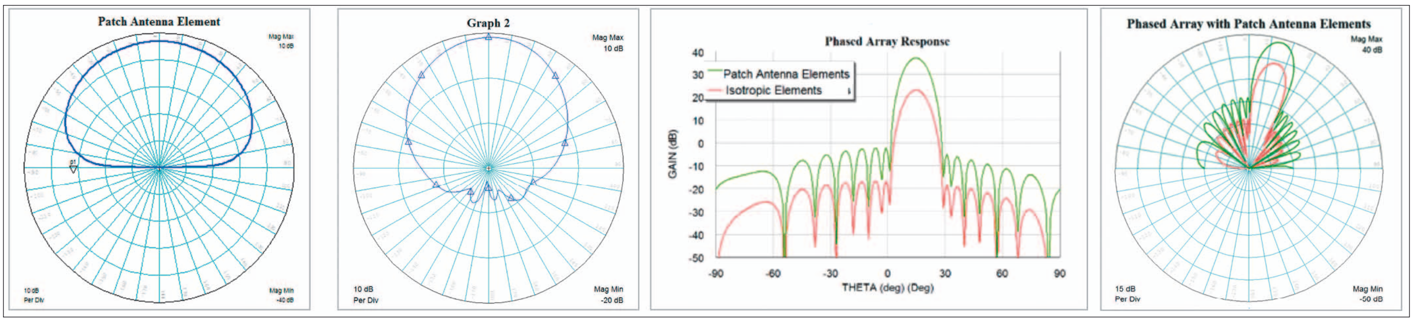

Figure 9: Patterns of single-patch and square-ring antennas generated by AntSyn and comparison of radiation patterns from phased arrays based on simple patch antenna (red) and square-ring patch antenna (green)