APPLICATION NOTE

Design and Test Challenges of the Modern Electronically Scanned Array

Phased arrays are increasingly leveraged as the foundational RF architecture in a wide variety of applications in aerospace and defense. These electronically scanned arrays (ESAs) are constantly evolving with cutting-edge capabilities, requiring additional scrutiny throughout design, characterization, and production. A scalable and nimble test solution is required to handle and validate a multitude of scenarios, ranging from parametric test of components to validation of systems.

This application note will cover the uses and trends related to the modern ESA. It will relate these design trends to corresponding test challenges and needs, pointing out where new capabilities may be required. While addressing the development life cycles of the components, modules, and subassemblies that act as building blocks of the final system, the key test requirements will be summarized and explained and recommended solutions proposed. Finally, this application note will briefly examine the future of ESA architectures and map them to the latest developments in test systems.

An Introduction to Electronically Scanned Arrays

History and Evolution of Electronically Scanned Arrays

Traditionally, common electromagnetic applications such as radar and communications relied on a singular antenna integrated with a transmitter and a receiver. For dynamic applications, these antennas would be mechanically rotated or positioned to steer the radiated beam of RF energy at the target. For example, a search radar system antenna would be rotated over a determined horizontal axis, covering a spatial grid at a certain scan rate based on the speed of the mechanical system. In another example, a communications link is established by repositioning an antenna, as pictured in Figure 1, on its vertical axis to track an orbiting satellite.

FIG 1 A Traditional Parabolic Antenna with Mechanical Positioning to Track or Target a Satellite in Orbit

With the advances in solid-state electronics and the introduction of newer components that provide a controllable delay of the RF signal, it became possible to replace the traditional mechanical positioning of antennas with electronically steered RF energy. The fundamental concept was to take a common RF signal and split it over multiple antenna elements, each with its own delay or phase shift.

The resulting radiation pattern of these transmitted signals would result in focused energy in a particular direction due to constructive interference and attenuated energy in other directions from deconstructive interference. By electronically manipulating these phase offsets on each element, the interference pattern could be controlled, resulting in a steerable wavefront. The development of this technology was primarily driven by the need for more capable ground-based RADAR systems in the 1960s.

As solid-state technology has evolved into smaller, more efficient, and cheaper components, the use of phased array architectures became prevalent and more capable, leading to modern radar systems such as the AN/MPQ-53, as seen in Figure 2, used in Patriot surface-to-air missile batteries.

Today, ESA-based systems are found in a variety of applications, from ground-based systems to air, sea, and space-based platforms. Beyond radar, phased arrays can be found in adjacent electromagnetic applications such as imaging, communications, and the broader electronic warfare theatre.

Phased Array Theory and Architectures

The electronically scanned array can be segmented into four primary types. The first and original ESA is the passive electronically scanned array (PESA). In a PESA-based system, a single receiver and transmitter, commonly referred to as the receiver exciter (REx), is paired with a multielement solid-state array. Each radiating element contains a localized phase shifter module. When transmitting, the signal is amplified and distributed evenly across the array, with each copy being delayed by programming a frequency dependent phase shift. The independently delayed signals form again as a radiated wavefront with constructive interference, resulting in an amplified signal propagation in a known direction. This multielement control results in the ability to manipulate the corresponding wavefront to and from the natural boresight of the antenna, as seen in Figure 3.

Since the PESA architecture relies on a single transmitter and receiver to drive and receive from multiple elements, the effectiveness and scalability of the system is limited. The transmitter, for example, largely relies on traditional high-power active elements such as a klystron or magnetron, driving the cost and size of the resulting array. On the receive side, the lossy signal paths between the element and the receiver reduce the effective dynamic range and potentially limit the sensitivity of the system. This results in a reduced total number of radiating elements. As technologies have evolved and the application requirements for ESA missions have become more complex, there has been a shift to develop the second fundamental architecture—the active electronically scanned array (AESA).

FIG 2 An AN/MPQ-53 Ground-Based Radar System Based on a Modern Passive Electronically Scanned Array (PESA) Architecture

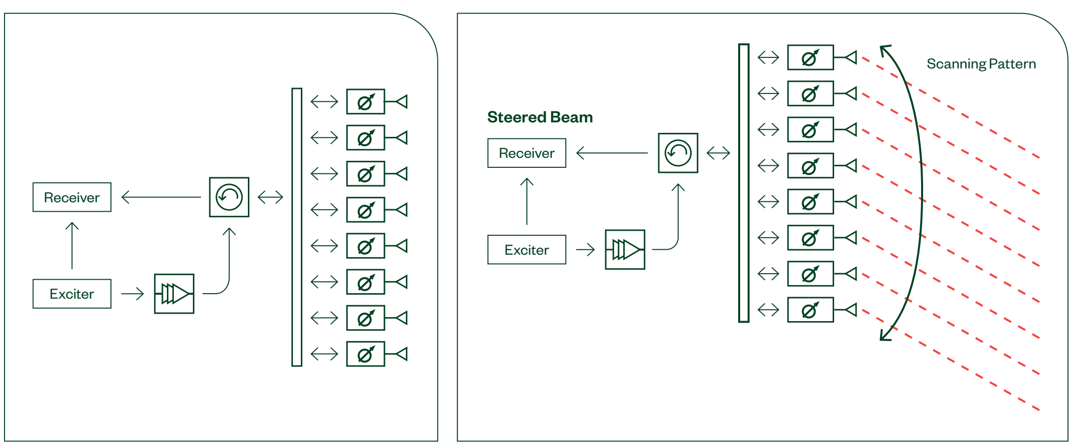

FIG 3 Left: A typical PESA block diagram.
Right: By programming each element with a frequency dependent phase offset, the individually delayed signals result in a directionally steered wavefront.

The AESA compliments the primary transmitter and receiver by placing active components closer to the radiating elements in the array, as seen in Figure 4. This advancement has primarily been driven by more effective active solid-state devices built on gallium arsenide (GaAs) and gallium nitride (GaN) processes. The passive phase shifter has been replaced with an integrated transmit receive (T/R) module that contains an optimized power amplifier (PA) for the transmit mode and a highly sensitive low-noise amplifier (LNA) for the receive mode. The programmatic delay or phase shift can be integrated in this T/R module or further back in the signal distribution network. Modern communication arrays typically integrate phase control, gain control, and signal distribution in an integrated element called an analog beamformer. The integration of the various fundamental functions of an AESA into core components and modules allows for highly scalable array topologies and a higher degree of optimization for the end application of the system.

A third type of ESA architecture that is being introduced in modern communication and radar systems is commonly referred to as a hybrid digital beamforming phased array. This is usually implemented by combining multiple instances of an AESA with digital beamforming on the backend, as pictured in Figure 5. Each AESA subarray consists of a single REx and a defined power of 2 multiple of T/R module enabled elements. These subarrays are then integrated into the full array along with a digital beamforming backend. The resulting architecture supports an aggregate wavefront that has been digitally synthesized, or clusters of independent beams leading to multimode or multifunctional application capabilities.

The final common phase array type removes the analog phase shifter capability and replaces it entirely with digital beamforming. This architecture, pictured in Figure 5, typically integrates a REx with each radiating element. The fully digital beamforming array provides several key benefits, including flexibility, multibeam support, and improved reliability via fully redundant signal chains per element. These advantages come with corresponding challenges related to the complexity of the design, such as synchronization requirements between channels, cost of implementing a full signal chain, and the volume of digital data from the aggregate array.

Modern ESA Architectures and Capabilities

With the introduction of ESAs, including the PESA, AESA, and digital beamformers, a wide variety of electromagnetic applications and missions have been explored and enhanced. These applications range from broadband communications, high-resolution imaging and radar, and the cognitive multifunction domain of electronic warfare.

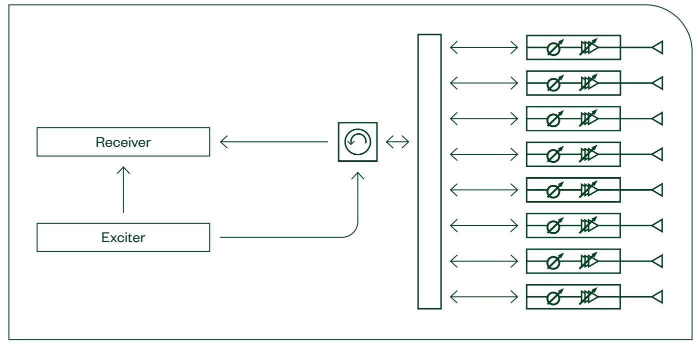

FIG 4 The active electronically scanned array (AESA) implements analog beamforming with a dedicated transmit receive (T/R) module per antenna element.

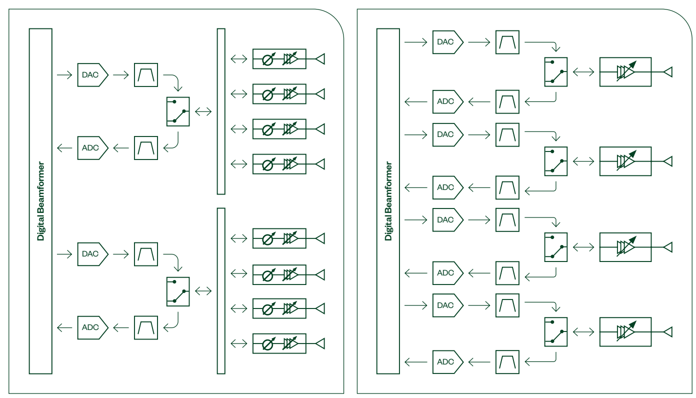

FIG 5 Left: A hybrid digital beamforming array combines multiple AESA subarrays with a digital beamformer to create an aggregate system. Right: A fully digital beamforming array implements a REx with each T/R module and array element.

The communications industry has been advancing at a steady rate towards better global coverage and higher data throughput. Whether it's the upcoming 5G telecommunications or the latest in satellite datalinks, the ESA serves as the fundamental electromagnetic workhorse. The wideband, multichannel capabilities of the ESA effectively correct redundancies and errors in remote locations versus throughput and data rates when the environment is free from obstacles and interference. Modern datalink transmitters can be digitally steered to track the orbits of communication satellites, providing longer and higher fidelity contacts. In today's 5th and 6th generation fighter programs, the AESA tracking radar is the centerpiece of the electromagnetic capabilities. These systems range from hundreds to thousands of active radiating elements with the ability to dynamically switch detection modes such as a synthetic aperture radar (SAR) used for high-resolution imaging or precision detection and tracking.

Some next generation AESA arrays can allocate different subarrays with multifunction capability, allowing for adaptive solutions to the complex electromagnetic tactical environment.

The ESA plays a role in electronic warfare as well, primarily augmenting capabilities in the electronic attack (EA) and electronic protect (EP) domains. On one side of the electromagnetic theatre, modern AESA radars are capable of advanced, built-in protection features, allowing for adaptive and robust wartime capabilities. Opposite this, modern EA systems can leverage ESA architectures to implement more capable jamming solutions.

The ESA Design Life Cycle and Challenges in Test

Whether it's for radar or satellite communications, developing an ESA is a multistep process that starts with the design or selection of fundamental components. That initial step is followed by integration and validation of those components into functional modules. Lastly, system level verification occurs after the modules are integrated into the final array. Each stage consists of key modeling, characterization, and ultimately production test activities, with correlation across the life cycle being paramount.

Component Design and Characterization

There are a wide range of components that go into the modules and subassemblies of an ESA-based system, including DC power supplies and regulators, passive signal conditioning and filters, and active RF components. Validating the performance of these components over time, temperature, and potentially under the application conditions is crucial to ensure system performance and prevent failures later in the development cycle.

Given the advances in solid-state processes, RF components specifically are becoming more cutting edge, with wider RF performance capabilities, increased efficiency, and smaller form factors. PAs, LNAs, and frequency translating mixers are fundamentally driving the capabilities and scale of the modern ESA, especially within newer AESA architectures. To ensure proper system design and reduce time to market, it's becoming even more important to validate performance early and drive correlation with both design models and the modules and systems they're eventually integrated into—connecting design, validation, and test throughout the product life cycle.

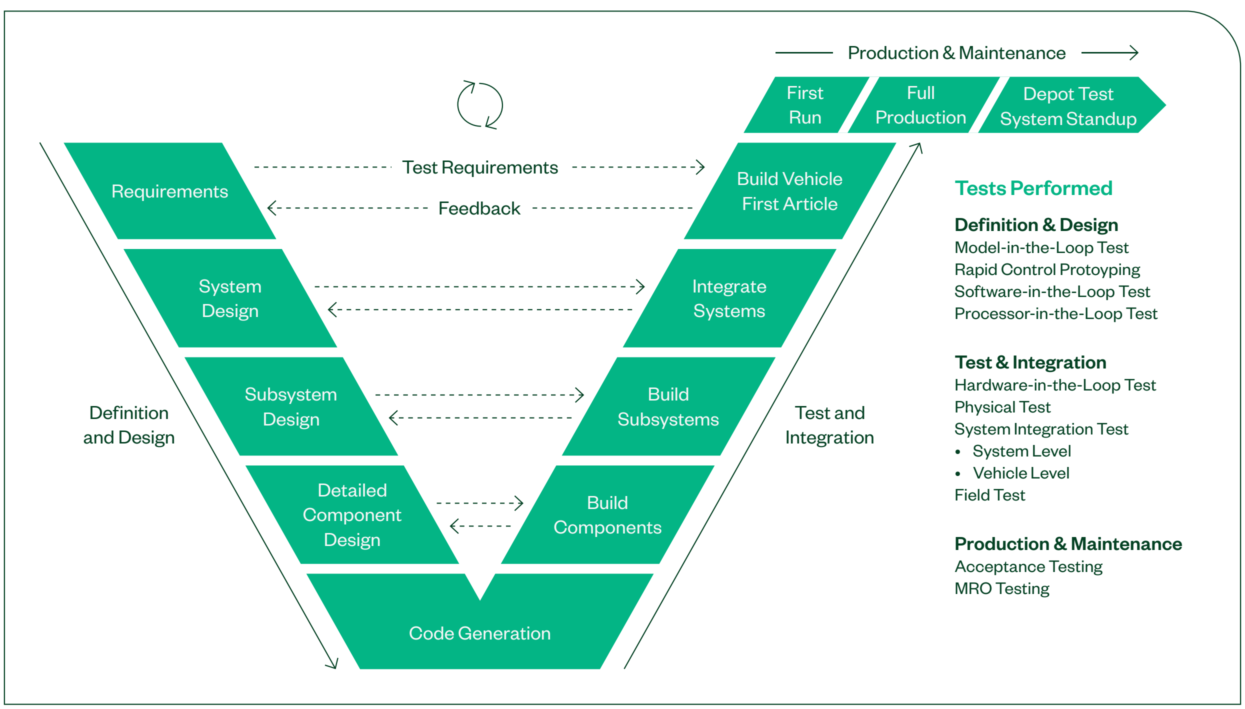

FIG 6 A typical product life cycle. Increased design complexity and application requirements are accelerating the need for better correlation across all stages of design, validation, and test.

At its core, an optimized test plan and solution for ESA component characterization must ensure that the basic RF and DC parameters can be measured to validate the component back to its design or provided specification sheet. These parameters typically include measurements such as return loss, gain, phase, noise figure, linearity, and compression. Depending on the design of the DUT, the stage in development (that is, on wafer versus packaged), and the end application of the ESA system, the stimulus used for these fundamental measurements may vary in complexity. This could include single or multitone CW signals and more complicated pulsed waveforms with timing information. To meet this challenge, the test equipment and software selected must be versatile enough to support a wide variety of waveforms and corresponding measurements.

FIG 7 A typical validation bench or automated test system includes a wide variety of RF, DC, and digital instrumentation. Depending on specific capabilities, vendor compatibility, and software control, integration of the various instruments into a cohesive test system can be challenging.

To correlate to the end use of the ESA system, it may also be valuable to perform application specific validation even at the component level. Historically, these tests have been performed at the system level in a range test so that the full signal path and antenna can be validated. Given that modern ESA architectures can include hundreds or thousands of radiating elements, all of which would contribute to the resulting performance, it may not be cost or time effective to build an entire system.

As such, the ability to support application-based measurements in addition to fundamental RF parameters is highly valuable when choosing your test solution. For instance, a PA designed for a T/R module in an AESA radar may be further characterized by measuring the pulse-to-pulse stability. This measurement analyzes the stability of the DC or RF signal with respect to amplitude and phase, ensuring the device under test (DUT) is stable over time and temperature under more realistic conditions.

The RF measurement is particularly challenging given the sensitivity to amplitude and phase. This results in the need for a highly linear, phase coherent stimulus and response system to ensure that the test solutions measurement floor is significantly better than the DUT. Depending on the type of pulsed signal used, being able to scale from narrow to wide measurement bandwidth is also important while maintaining optimal dynamic range.

For communication applications, it may be pertinent to use wideband modulated signals to validate the DUT. For example, a common measurement for wireless communications components is noise power ratio (NPR). In this measurement, the device is stimulated by a wideband noise or multitone signal to measure the dynamic range of a quiet channel while there is energy in adjacent channels. This is especially important for components used in ESA systems deployed to satellites given the need to maximize capability while minimizing the power draw of the system. To drive towards power efficiency, it's ideal to operate the active components as close to saturation as possible. NPR provides an indicator of how well the DUT will operate under these conditions.

Integrated Modules and Subassembly Validation

Once individual components are designed and validated, they're often integrated into modules or subassemblies that can then be scaled up to the final ESA system architecture. These modules usually provide a specific function or group of functions key to how the ESA will work. As the level of integration increases, so does the complexity of test. These modules often include multiple signal paths and digital control, multiplying the number of test points required for performance validation and requiring a more complicated set of test instrumentation.

One of the most common modules, particularly in the latest and greatest AESA systems, is the T/R module. This module combines a high power transmit path with a highly sensitive receive path in a single front end generally designed to interface directly to a radiating element. These two paths either operate in parallel with isolating and directional elements such as circulators and limiters or in a time multiplexed manner with solid-state switches. In addition to the core functionality, other components such as programmable amplitude and phase control can also be included, adding another layer of digital control to the DUT. Although the test plan and measurements are often very similar to the fundamental RF component validation discussed previously, these tests must be integrated and synchronized with the digital control, and the coverage must increase to account for the various programmable states of the module.

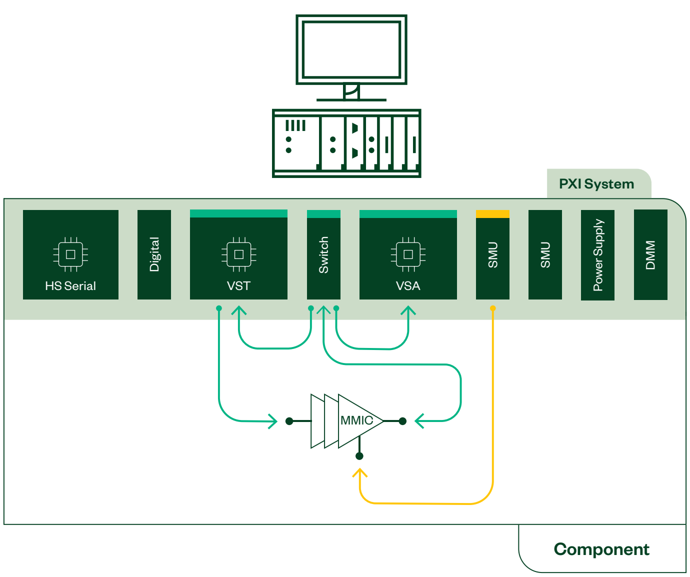

FIG 8

To reduce complexity and improve scalability, a modular, platform-based test system can be implemented to meet the wide range of I/O instrumentation needs and measurement capabilities. Software integration, triggering and synchronization, and data movement challenges are solved by consistent and well-defined interfaces.

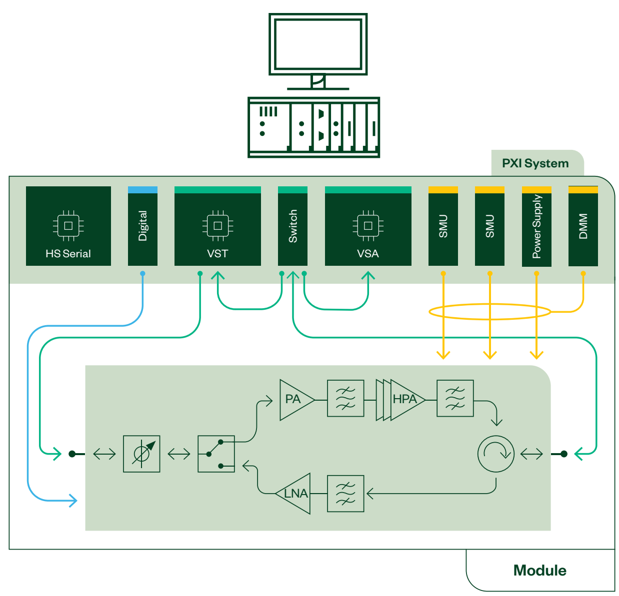

FIG 9

Building on the platform-based test system approach, the solution for testing a component such as a PA can be scaled up to include integrated digital control and expanded RF or DC I/O. This allows for easily transitioning to test a more complex DUT, such as a T/R module.

Taking a step further toward system integration, multiple T/R modules may be combined with a signal distribution network to create a multichannel subassembly. Combining the multiple channels with individual control of amplitude and phase provides the beam steering functionality that is core to the ESA architecture. From here, these multichannel subassemblies can be integrated together to build out to the final element count of the system.

These subassemblies also create a scaling challenge for the corresponding test solution. From an RF signal perspective, the test engineer can add switching to the test solution to multiplex the instrumentation to the corresponding channels of the DUT.

Alternatively, multiple test instruments can be used in parallel with each instrument connected to a single channel. In the first scheme, the solution is typically optimized for cost with the potential negative side effect of being slower in test time and limited in coverage. This is particularly true when measuring the interaction between multiple channels under a common stimulus. The second scheme trades off some cost optimization for the ability to test all channels in parallel. Regardless of which topology is decided on, it should be noted that the digital control and synchronization of the DUT configuration with test instrumentation has also scaled in complexity, and the ideal solution must account for this.

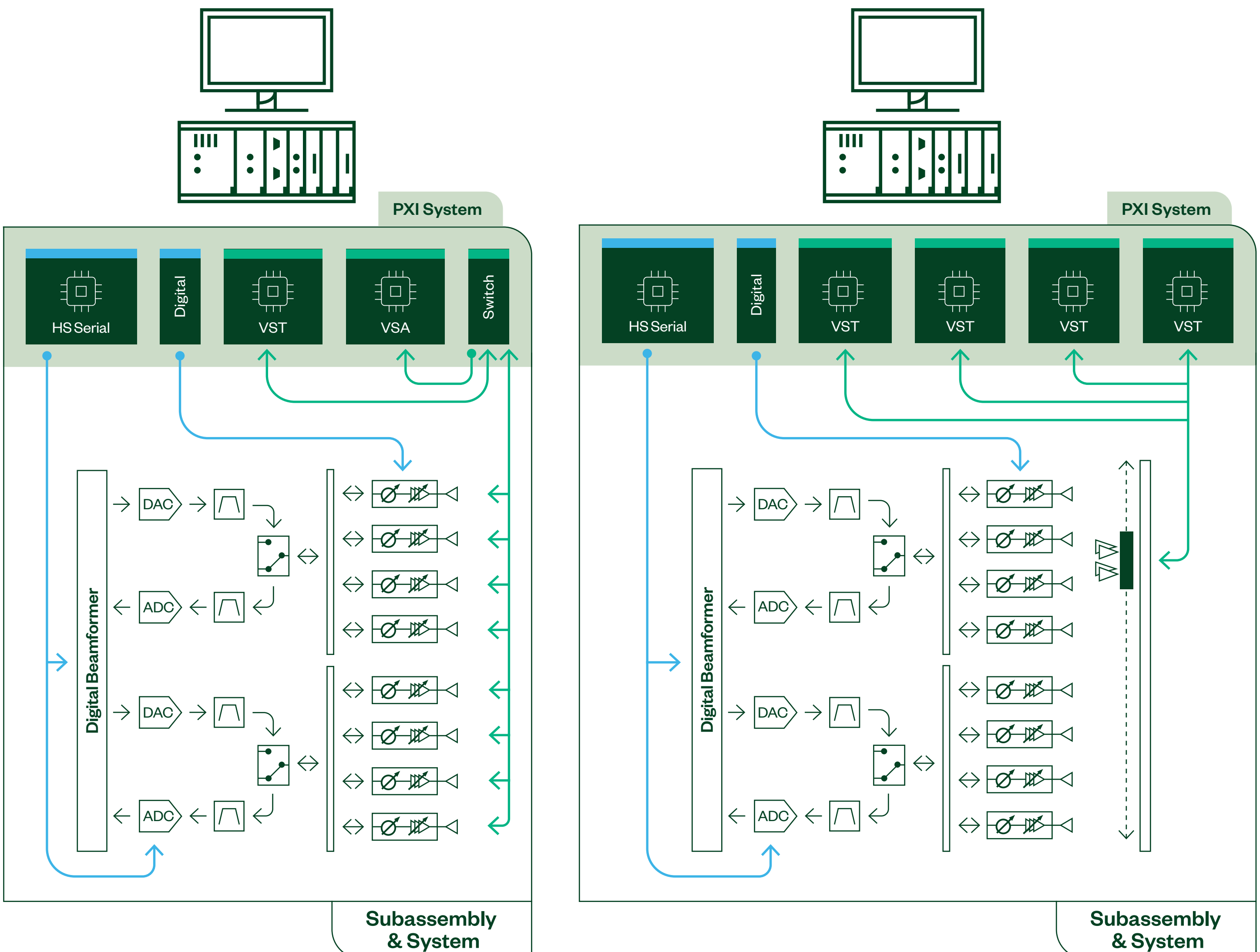

FIG 10 At the subassembly or system functional test level, the platform-based test solution can be reoptimized to match multichannel RF interfaces, either in a switched or parallel instrument manner.

Looking to the Future—the Continued Evolution of ESA Applications

The Digital Future of Phase Arrays

While solid-state processes such as GaAs and GaN are allowing for more efficient and integrated RF front-end components and modules, there are similar investments being made in the backend of the ESA system as well. This includes multichannel ADCs and DACs with increased sample rates, allowing for directly sampled RF signaling, as opposed to traditional frequency translation architectures. These converters are being integrated together with cutting-edge DSP and FPGA-based backends, creating wideband, low-latency systems on a chip. Ultimately, these two trends are leading to the next phase in ESA evolution—the fully digital AESA.

Unlike current PESA and AESA architectures that rely on a reduced set of converters and frequency translation stages feeding hundreds or thousands of antenna elements through beamformers and signal distribution networks, the digital beamforming array attempts to pair wideband transmit and receive pairs directly with the antenna elements. This allows for the amplitude, phase, and frequency control of the signal at each element to be digitally synthesized, improving response times and precision. It also enables more capable systems from a multifunctional perspective, as individual or grouped channels can be repurposed in a software-defined manner. For example, a subarray or set of digital signal chains can be configured to instantiate a communication link while the rest of the array continues to operate as a radar.

These benefits and capabilities also come with an increase in test solution complexity. From an RF performance perspective, the integration of components and digital data interfaces removes traditional test points at the component and module levels, reducing the effectiveness of some types of test equipment. To scale the test solution, the validation engineer will need to combine wideband RF signal generators and analyzers with high-speed digital transceiver solutions, effectively creating a synthetic mixed I/O instrument capable of both digital and RF interfaces, as seen in Figure 11.

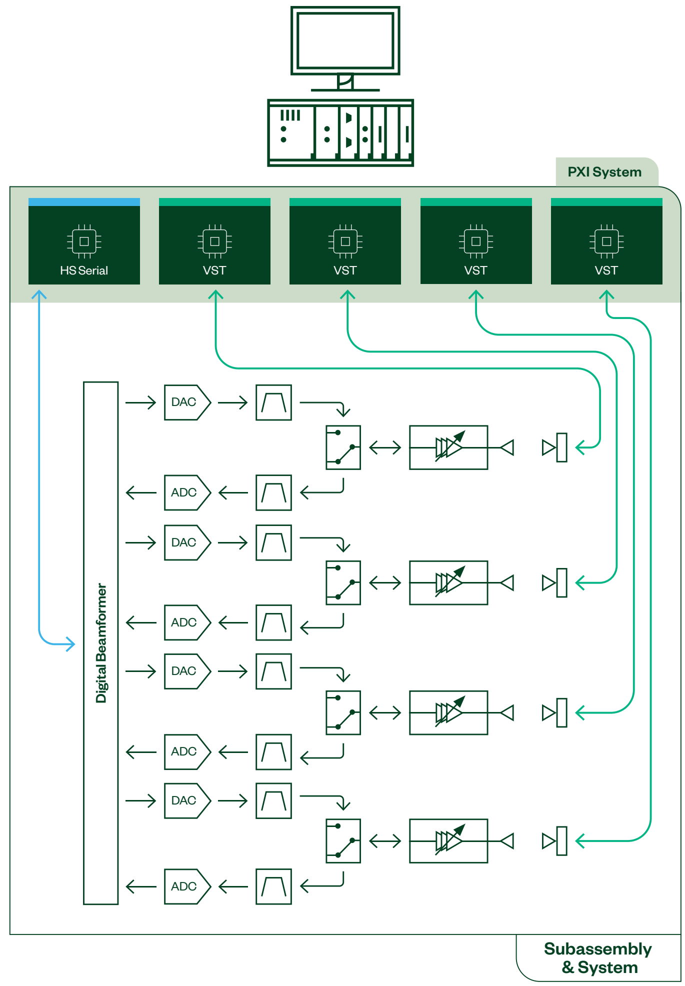

FIG 11 A modular test system configured to be a virtual multichannel digital and RF instrument. This allows for testing the scales from functional parametric test to system validation.

A Scalable Test Solution—Driving Down Time to Market for Future ESA Systems

As we have covered in previous sections, ESA architectures and phased array systems are continuing to evolve and expand in complexity and capability as they become adopted in a wide range of electromagnetic applications. In particular, the shift from traditional PESA and AESA architecture to the hybrid or fully digital beamforming phase array enables more functional and flexible multibeam capability and improved reliability. The trade-off for this enhanced system is an increase in testing complexity to properly validate the end product.

To meet the demands of validating and testing these systems and applications, test solutions need to evolve from traditional program specific designs to a scalable, software-connected platform approach. Maximizing leverage and reuse of modular instrumentation allows for easier integration and abstraction and smooth transitions through design validation, production, and maintenance test. It also provides the validation or test engineer the agility, as seen in Figure 12, to meet the test needs of the wide variety of DUT types and interfaces seen in the life cycle of the modern ESA system.

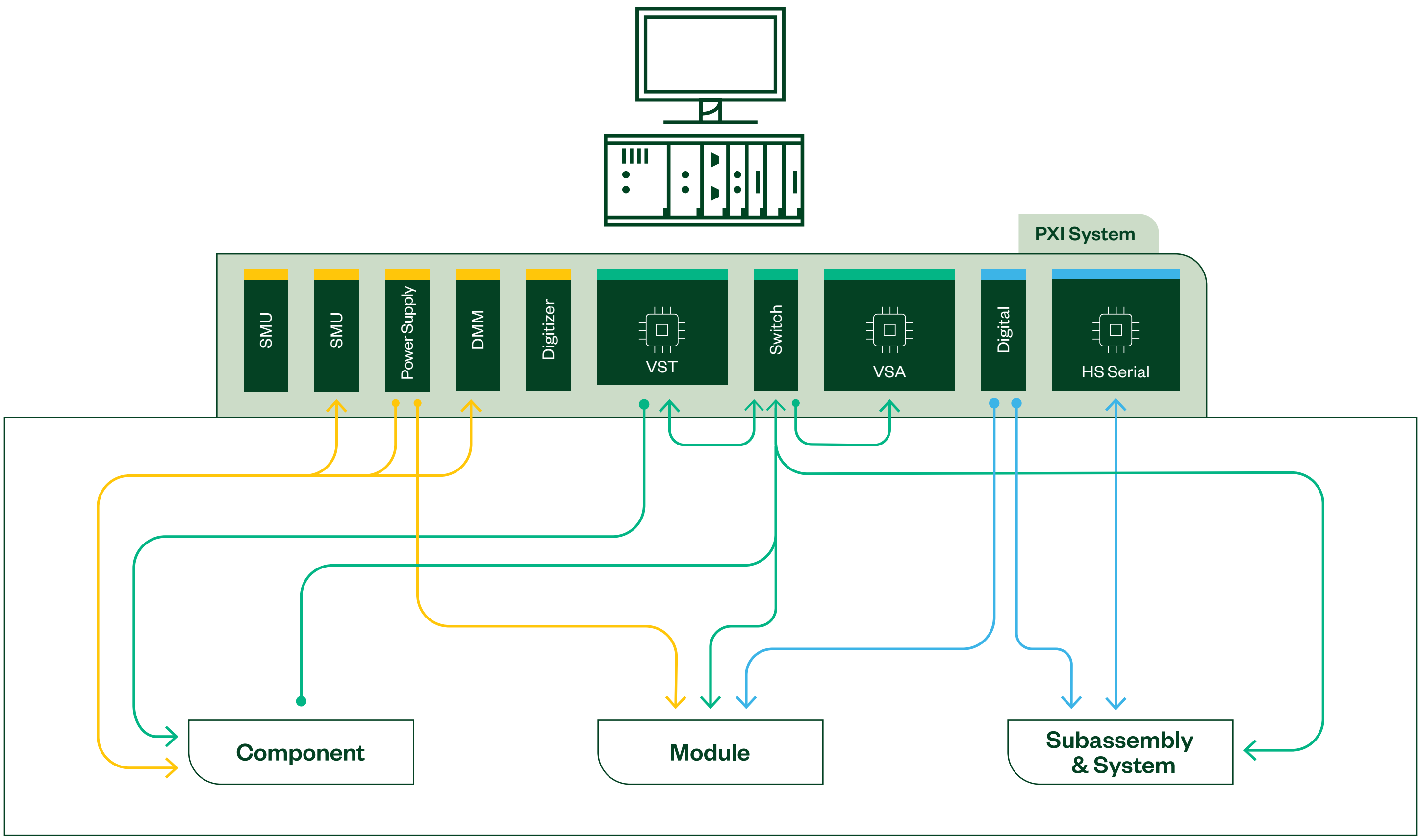

FIG 12 A scalable, modular test platform lends itself well to a successful test strategy for the wide range of ESA architectures and systems deployed in today and tomorrow's electromagnetic theatre.