How to Design and Test a Phased Array Antenna

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CONTENTS

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Background

Modern radar and communication systems rely on phased arrays to provide essential capabilities such as beamforming and beam steering. Beamforming offers numerous advantages for wireless communication links, which include:

- Reduced interference.
- Increased range.
- Expanded number of services.
- Improved security.

For decades, radar was the primary application space for phased array antenna (PAA) topologies. However, trends in component technologies like multiple transmit / receive (T / R) modules per chip and GaN power amplifiers (PA) continue to reduce the size and cost of PAA, as shown in Figure 1. The expanding market application potential paves the way for commercial communications and radar systems in automotive, health care, 5G, and SATCOM industries.

In 5G applications, the successful implementation of massive machine type communication (mMTC) and the extreme data throughput specified in the International Mobile Telecommunications-2020 (IMT-2020 Standard) depend on phased array technology. Similarly, agile scanning phased arrays provide the rapid tracking and continuous connection necessary for increasingly common low Earth orbit (LEO) satellites in the New Space arena and satellite communications.

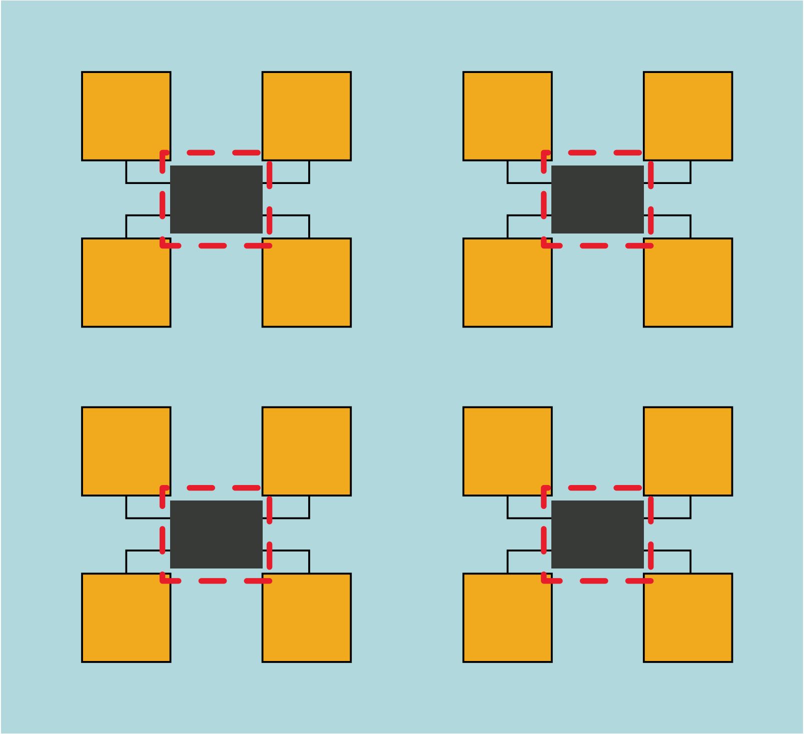


Figure 1. Example of four-by-four phased array antenna — the four individual beamformer integrated circuits (BFIC), outlined in red, drive the antennas

Back to Contents

Phased Array Fundamentals

An antenna array requires multiple individual antennas, called *elements*, to work together as a unit, as illustrated in Figure 2. Designers configure this collection of antenna elements in such a way that the radiation pattern of each element combines with neighboring antennas to form an effective radiation pattern called the *main lobe*. Designers also refer to the main lobe as the *primary beam*. The antenna array design maximizes the energy radiated in the main lobe while reducing the energy radiated in the sidelobes by leveraging the constructive and destructive interference of the signals in a process called *beamforming*.

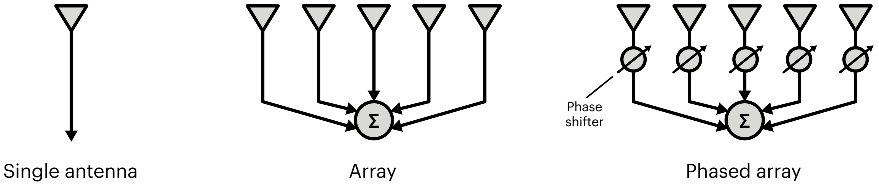


Figure 2. A single antenna operates alone as a passive radiating element, while an array of individual antennas work together to produce a higher gain

Modern phased-array antennas use hundreds or even thousands of antenna elements. The phased array antenna (PAA) performs beam steering through algorithms manipulating the independent phase and amplitude fed into each antenna element. Controlling the phase between elements steers the beam in a specific direction while controlling the amplitude shapes the beam pattern and reduces sidelobe levels. The *phase increment* refers to the necessary phase shift between adjacent elements to achieve a specific beam angle or direction.

Modern PAAs beam steer electronically, so engineers commonly refer to phased arrays as electronically scanned arrays (ESAs). However, the original antenna arrays that dominated classical radar systems scanned mechanically. A rotor steered the radiating element, and a gigantic antenna received signals. This approach resulted in a bulky, slow maneuvering system prone to single-point failures. Since evolving to ESA technology, phased array antennas continue to improve overall reliability in a smaller footprint.

Engineers use multiple approaches to phase shift individual elements. However, the simplest method is to use delay lines that can turn on and off between the elements and the source or receiver. During transmission, the delay lines delay the source signal to each element, as illustrated in Figure 3. For receive operations, delay lines delay the signal sent from each element to the receiver, then all the signals are summed – this process is often called *delay and sum*. Achieving high-resolution beam steering requires switch-controlled delay lines for each array element.

Back to Contents

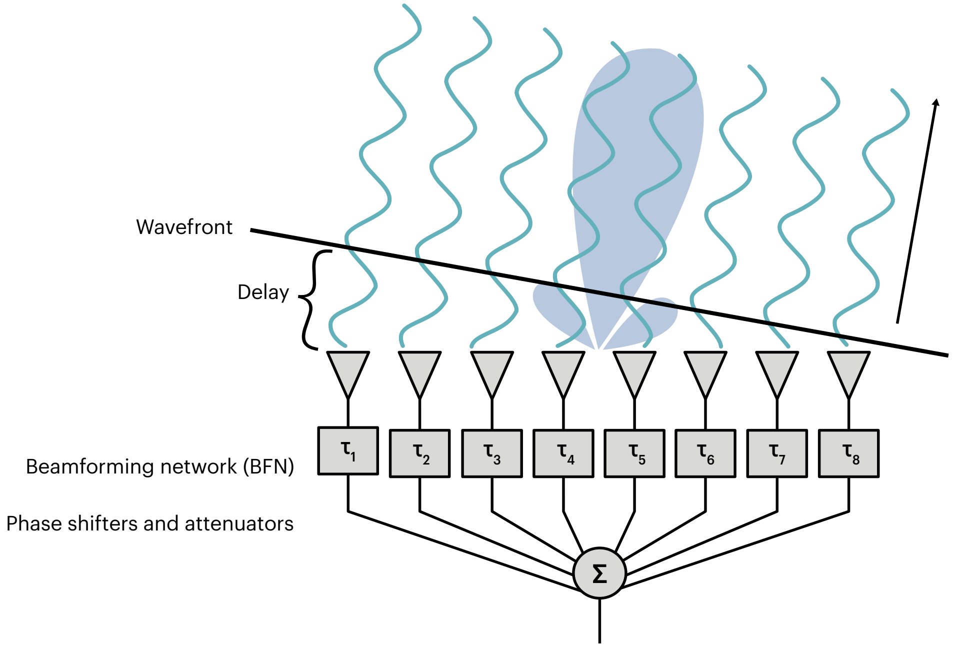


Figure 3. Varying the signal delay to each element shifts the individual wavefronts produced, which steers the beam. All the individual wavefronts combine to create a single wavefront propagating in the direction of the main beam from the antenna.

The phased array antenna enables almost instantaneous beam steering by electronically controlling element amplitude and phase adjustments. This feature allows for faster and more flexible searching. Beam steering speed varies significantly depending on the type of control interface to the phased array, whether the array has built-in memory for storing beam states, the clock speed of the controller device, for example, a microcontroller or field-programmable gate array (FPGA), and the efficiency of the control codes.

Instantaneous beam steering makes phased arrays ideal for modern communication system applications because, like radar systems that track multiple targets, multiple beams enable simultaneous communication with handsets, ground stations, or satellites.

Evolution of Phased Array Technology

Figure 4 illustrates the two main types of electronically scanned phased arrays:

- Passive electronically scanned phased arrays (PESA).
- Active electronically scanned phased array (AESA).

The traditional PESA implementation used separate attenuators, phase shifters, and other components. This centralized architecture connected all elements and the baseband source to a single pair of transmitter and receiver paths.

Modern phased arrays favor the distributed architecture of the AESA topology. AESAs integrate individual antenna elements and related transmit power amplifiers (PA), receive low-noise amplifiers (LNA), shifters, attenuators, and switches into a single T / R module package. The system connects the baseband source directly to the beamformer. Equipping each element with a transmitter amplifier enables the active phased array antenna to combine transmitter output power spatially. This process allows for the spatial combination of transmitter output power, resulting in a significant increase in total power compared to individual T / R modules. Additionally, this modular approach enables close placement of electronics to individual elements, significantly reducing signal loss. However, the performance benefits of AESAs come with greater development complexity and cost.

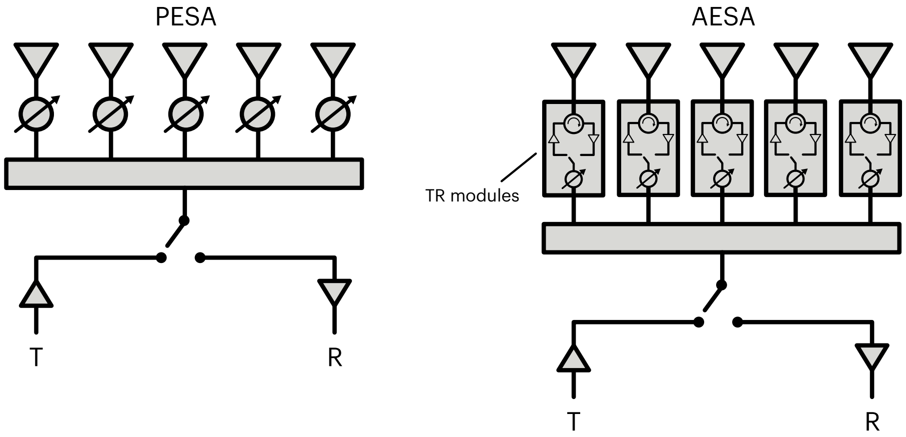


Figure 4. The AESA distributed architecture enables each element with a T / R module, reducing the distance and signal loss between the antenna and electronics, in contrast to PESAs

T / R modules are crucial in the phased array's RF performance. The LNA and PA function as the initial stage of the receive path and the final stage of the transmit path. As such, engineers optimize the receive sensitivity using data from the LNA's noise figure and gain measurements. Likewise, engineers optimize linearity and efficiency for transmission based on PA distortion behavior.

During receive operations, the LNA determines the system link budget, noise figure, and the minimum detectable signal for the T / R module. Equation 1 shows the Friis formula for noise factor — the noise figure of the first amplifying stage, F1, sets the minimum noise figure for the overall receiver.

$$F_{\text{Total}} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 \cdot G_2} + \cdots + \frac{F_N - 1}{G_1 \cdot G_2 \ldots G_{N-1}}$$

Equation 1. Friis's formula shows that the total receiver noise factor (F_{Total}) accounts for the noise factor, F_N, and gain, G_N, of each stage — the first stage noise factor, F_1, dominates the overall receiver noise figure

Distortion effects negatively impact the performance of the transmitter path — particularly nonlinear distortion effects contributed by the power amplifier. The power amplifier occupies the last stage of the RF chain before the antenna. The PA's distortion significantly affects the quality of the transmitted signal. In-band distortion contributions cause particular concern since filtering proves ineffective. The power amplifier also contributes the most to energy consumption.

Biasing determines whether an amplifier behaves more linearly but less efficiently — or efficiently but with significant distortion. To achieve optimal performance from the T/R module, engineers must optimize the PA efficiency while ensuring linearity that aligns with strict regulatory standards. This trade-off between linearity and efficiency is crucial.

The communication systems industry considers error vector magnitude (EVM) as the benchmark figure of merit for in-band distortion. Modulation standards, such as 802.11ac and 5G New Radio (NR), set the minimum acceptable EVM level. As standard stringency increases, so does the need to accurately capture and optimize PA modulation distortion and EVM.

Aside from the amplifiers, passive components within the T / R module also contribute significantly to the overall performance of the phased array. For example, the phase shifters and attenuators in both the transmit and receive path of the T / R module control the antenna beam steering and determine the angular accuracy of the phased array. T / R modules need extensive testing to match across the phased array but characterizing them requires many different measurements. Since an active array antenna includes thousands of T / R modules, engineers need to test all the transmit and receive parameters rapidly and with a single connection to the module to manufacture cost-effective phased array antennas.

Transceiver architectures

Figure 5 shows the architecture of a basic pair of transmitter and receiver paths — the transmit path (upper) and the receive path (lower) connect a duplex to switch between the two. The transmit path starts with a waveform generator that produces low frequency signal. The signal then undergoes amplification, filtering, and up-conversion to the desired RF or microwave frequency for transmission. After another stage of filtering, the signal reaches the power amplifier. The PA gets the signal up to the power level needed for transmission. In the receive path, the filtered RF signal gets amplified by an LNA to avoid introducing additional noise and decreasing the signal-to-noise ratio (SNR). The amplified signal downconverts to a much lower frequency and then gets amplified and filtered again. The ADC digitizes the signal before entering the digital signal processing (DSP) chain. The Figure 6 block diagram only shows one conversion stage but transmit and receive paths commonly include multiple conversion stages to get the signals to the desired frequencies.

Figure 6 shows that each T / R module includes its phase shifter and attenuator. The T / R modules reposition the T / R path. In addition, the modules have a high power amplifier (HPA) on the transmit path and a limiter and LNA on the receive path. They also typically incorporate a switch or circulator to connect the antenna to the transmit and receive paths.

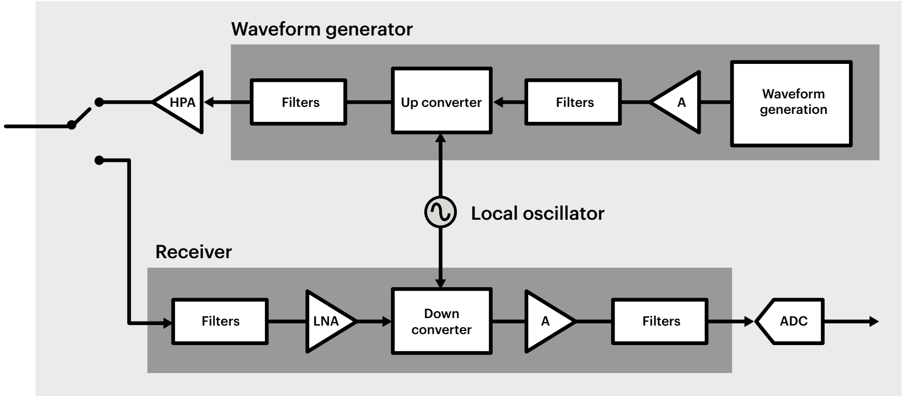


Figure 5. Basic transmitter and receiver architecture showing the stages of the RF transmitter and receiver paths

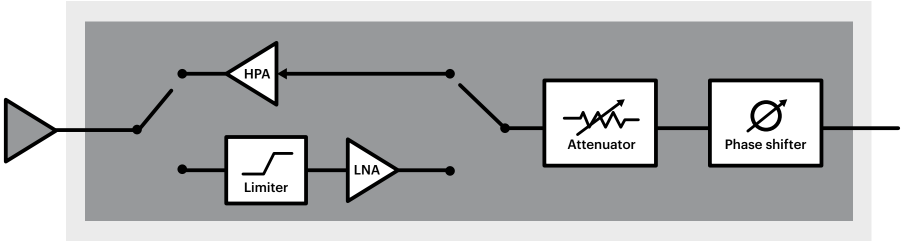


Figure 6. Each array element has a dedicated T / R module, including an attenuator and phase shifter

In transmit mode, the signal from the transceiver passes through the attenuator, phase shifter, and T / R switch to the power amplifier and then to the antenna. In receive mode, the signal from the antenna passes through the T / R switch, LNA, phase shifter, and attenuator to the receiver section of the transceiver. Transmitter power distributes through many small PAs to the antennas, while the baseband receiver receives signals through antennas, then amplifies the signal using many small LNAs.

AESAs are rapidly moving towards all digital T / R module architectures because they offer flexibility and additional capability on the transmit and receive side. Figure 7 shows the architecture of a basic digital T / R module (DTRM).

On the receive path, an ADC digitizes the downconverted signal. After that, the signal processes through the FPGA and feeds into the rest of the system through a digital interface. On the transmit path, the digital signal feeds into the FPGA through the digital interface, converts to an analog signal with a digital-to-analog converter (DAC), and then runs through the RF chain, where it is upconverted and amplified.

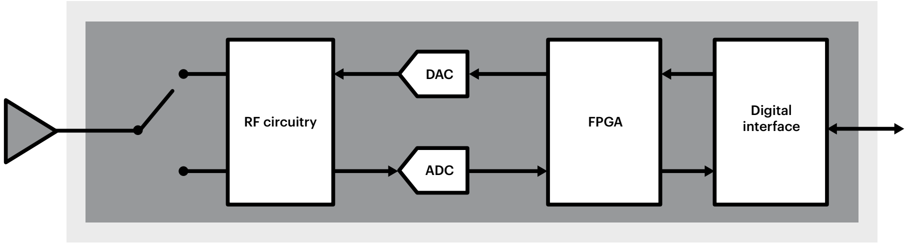


Figure 7. Digital T / R module architecture includes additional downconversion and upconversion, as well as digital control of the array

A DTRM has an integrated digital baseband with no access point in the RF to RF or RF to an intermediate frequency (IF). Similar architectures already appear in industries like satellite communications. In this case, uplink and downlink frequencies differ, so the module is often independent between the transmitter and the receiver. They often use multiple channels and work in a defined frequency range and bandwidth.

Beamforming methodology

Along with the two electronically scanned array architectures, phased arrays vary in the beamforming methodology they employ, as shown in Figure 8. The three beamforming methodologies are:

- analog
- digital
- hybrid

Passive arrays began with analog beamforming. The simple architecture included a single transmitter and receiver with a high-power front-end amplifier and only one transceiver pair. The transmit signal advanced to the multiple front-end modules and then to the array of radiated elements. Each front-end module consists of passive devices like attenuators and phase shifters. The single transmitter / receiver pair dictated every radiated element. The power amplifier in these PESA systems causes a single point of failure that makes the overall function of the array vulnerable. If the power amplifier fails, the entire system stops working.

The industry began implementing electronically scanned phased array (AESA) distributed architecture to ensure greater system robusticity. The antenna array system retains functionality even if several PAs behave suboptimally or fail. Some performance is lost, but the array still works despite losing one of these antenna elements. However, these active arrays continue to leverage analog beamforming.

Next-generation AESA systems use digital methodologies. This configuration provides a signal source and receiver behind each T / R module, enabling the most flexible beam control. Based on the demands of the application environment, the phased array could function as a single, large-scale antenna, some number of dedicated subarrays, or a *shared array*. A subarray uses different portions of the antenna array for different purposes, while a shared array generates multiple beams out of the entire array simultaneously.

For example, one subarray may perform object tracking while another group manages communications. The subarrays are dynamically repurposed as needed. Additionally, digital beamforming minimizes power loss in the transmitter and increases receiver sensitivity. However, digital beamforming also increases the development complexity and requires more components and space than analog beamforming. For low-beam count systems, analog beamforming offers the most cost-effective solution for power consumption and engineering complexity.

Alternatively, hybrid beamforming combines analog and digital beamforming features to optimize power, performance, and versatility requirements. As the beam count increases, hybrid beamforming serves as the middle ground, while digital beamforming offers the highest number of beams.

Back to Contents

Digital beamforming

- includes a ADC and DAC per element
- provides minimal power loss and increased receiver sensitivity
- offers scan flexibility (whole array, subset, or individual element)
- increased power and space requirements

Analog beamforming

- shares one ADC and DAC across all elements
- experiences power inefficiency and receiver sensitivity losses
- provides limited beamforming flexibility
- enables small footprint implementation

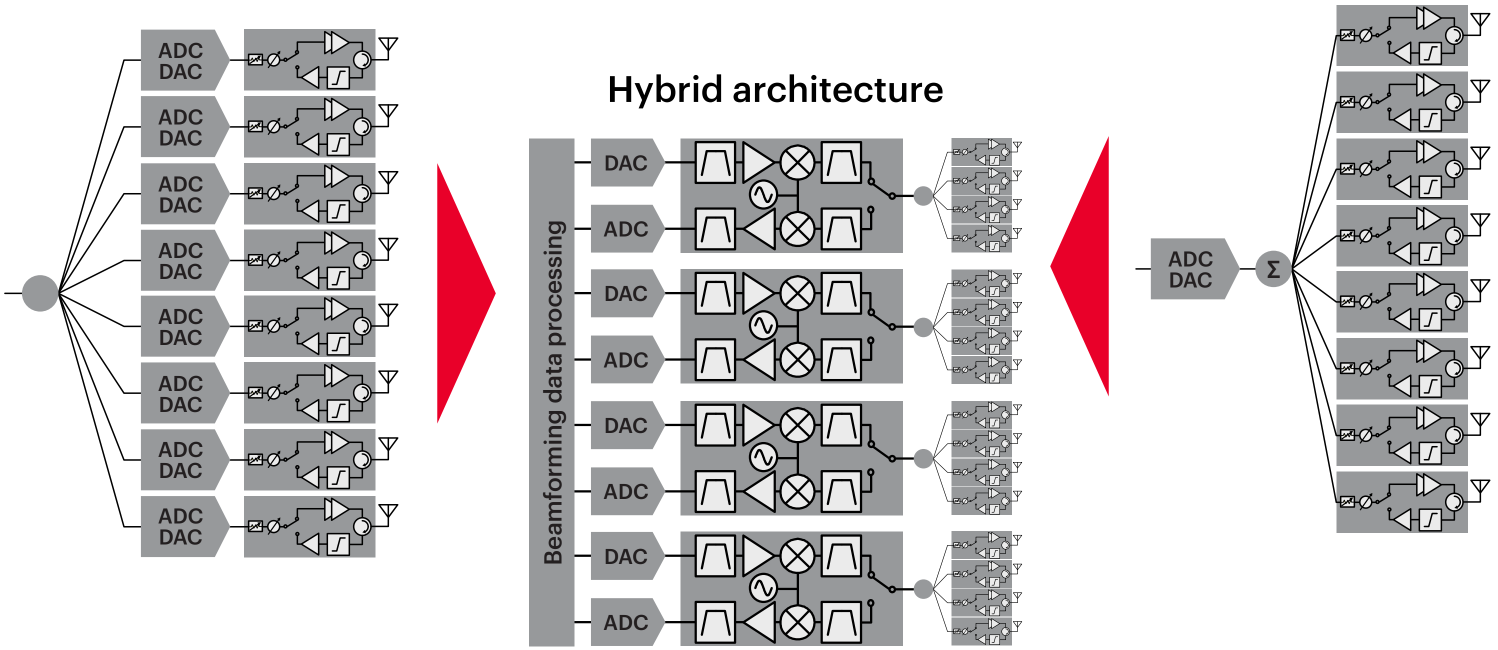
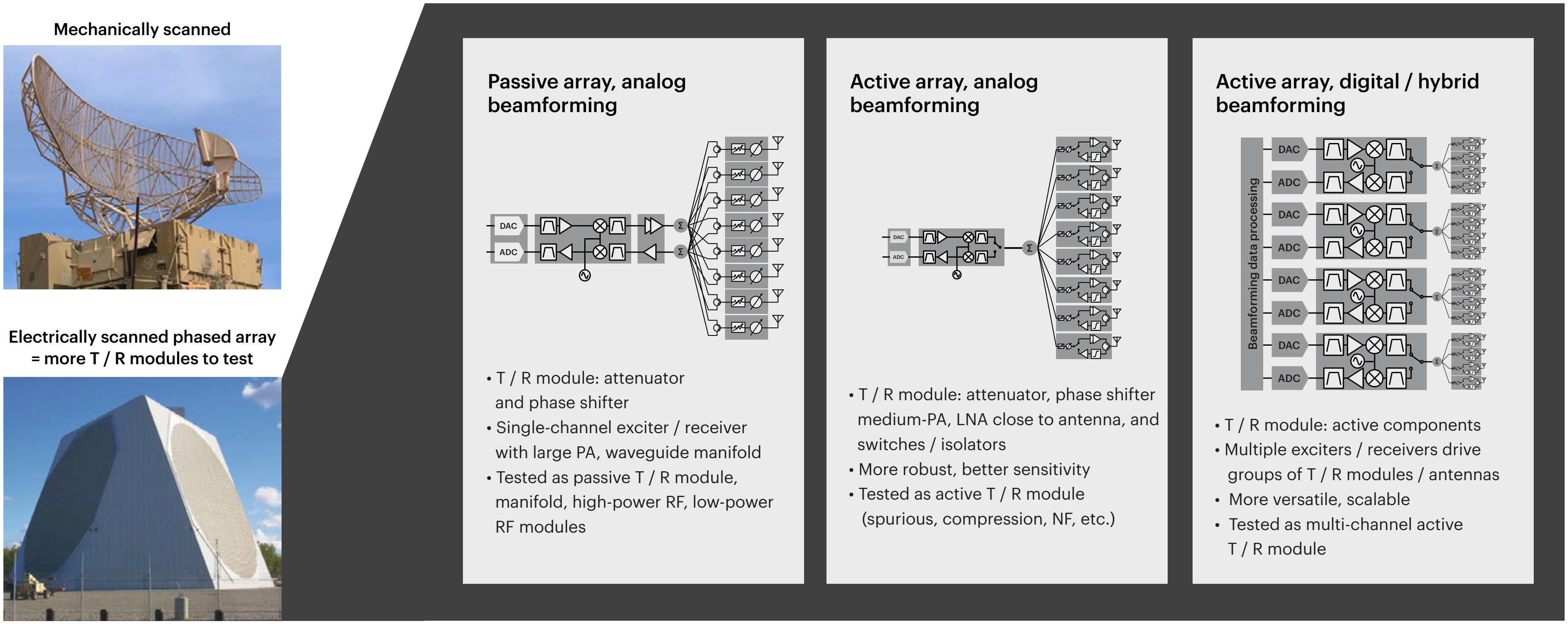


Figure 8. The three primary beamforming methodologies: analog, digital, and hybrid

Back to Contents



Mechanically scanned

Electrically scanned phased array = more T / R modules to test

Passive array, analog beamforming

- T / R module: attenuator and phase shifter
- Single-channel exciter / receiver with large PA, waveguide manifold
- Tested as passive T / R module, manifold, high-power RF, low-power RF modules

Active array, analog beamforming

- T / R module: attenuator, phase shifter medium-PA, LNA close to antenna, and switches / isolators
- More robust, better sensitivity
- Tested as active T / R module (spurious, compression, NF, etc.)

Active array, digital / hybrid beamforming

- T / R module: active components
- Multiple exciters / receivers drive groups of T / R modules / antennas
- More versatile, scalable
- Tested as multi-channel active T / R module

Figure 9. Beam scanning approaches, antenna system architecture, and beamforming methodology evolution

Figure 9 shows the four stages of phased array technology evolution. The original phased arrays were mechanically scanning passive arrays that performed analog beamforming. The industry advances from electronically scanned array (ESA) technology to analog beamforming while subsequently adopting AESA technology. The AESA enables lower RF power per element in the front end and allows lighter, smaller structures to replace bulky waveguide manifolds. This platform makes room for more elements in a system and includes digital beamforming. Hybrid beamforming allows for even greater performance optimization.

While AESA and digital beamforming enable significant performance benefits, both also increase system complexity.

With the current trend toward planar structures, the whole phased array will become smaller, lighter, and less expensive. However, the system will also require more components integrated into a smaller form factor. Ultimately, front-end and back-end RF and digital sections are fully integrated and attached directly to the antenna array, driving full size, cost, power, frequency, and bandwidth scalability.

Phased Array Antenna Workflow

A phased array system offers performance advantages such as enabling multiple beams, agile beam steering, beam pattern optimization, and graceful degradation with component aging and failure. These advantages offer both hardware and software designers the opportunity to explore novel analytical algorithms and engineering techniques to improve the overall system design as it applies to radar, communication, and satellite systems.

Theoretically, phased array antennas generate as many beams as the beamforming network requires. However, the practical limitations lie within the actual capacity of the hardware. Figure 10 shows the intensive process to create and implement a phased array using a three-step workflow:

- design and simulation
- development and manufacturing
- deployment and field servicing

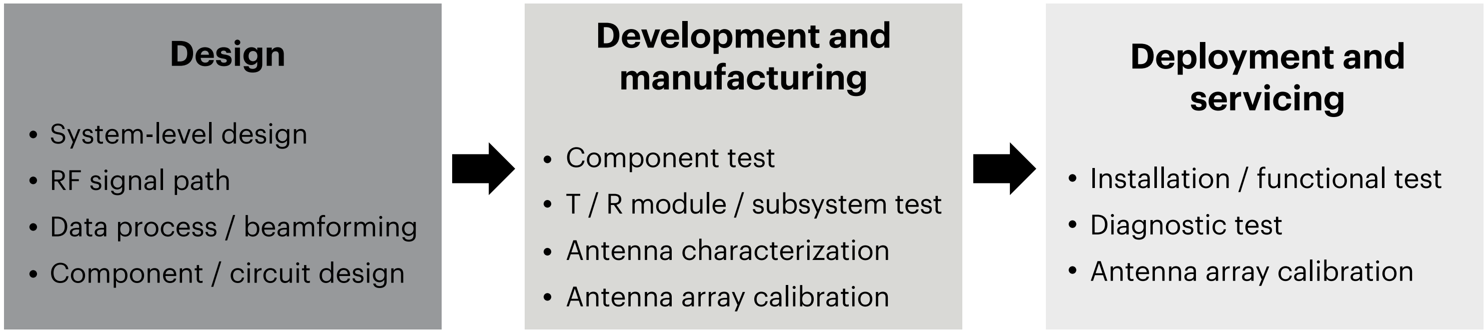


Figure 10. Phased array antenna development and implementation workflow

The design phase includes system-level design, investigation of RF signal path and architecture, selection of digital data processing and beamforming methodologies, and the design of components and circuits. With the defined design, engineers move on to spin development, component, and module manufacturing. Different test purposes exist within this phase:

- Discrete component testing.
- Subsystem RF performance characterization.
- System performance testing with antenna array characterization.
- Antenna array calibration.

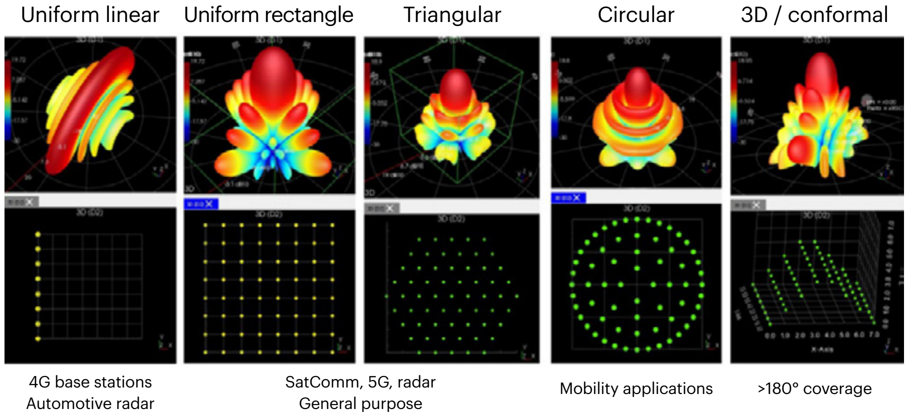
Engineers tested subsystems independently in traditional architectures. However, modern architectures have more variability and are often highly integrated. A few modern devices only integrate a digital / analog baseband and front-end module, while others include high-power or radiating elements in a single module. There is no test port access in between since modern architectures integrate the RF front-end section with the digital baseband.

Phased array design principles

Every phased array system must satisfy a mask of radiated spurious emissions. If not, the phased array can fail final deployment and acceptance in the field. The phased array antenna radiates spurious harmonics and intermodulation distortion in unintended directions due to amplifiers and mixers in the antenna system. These spurious emissions interfere with nearby antennas and communication systems and, as such, violates FCC regulations. Unfortunately, addressing these issues during field testing or deployment proves challenging and costly.

Engineers must pass spurious testing before building hardware without spending weeks in the test range. System-level simulation tools like the Keysight PathWave System Design software enable engineers to account for non-linearity, identify spurious emissions, and pass the Federal Communications Commission (FCC) and National Telecommunications and Information Administration (NTIA) spectral emission mask (SEM) before any hardware spins. Designers can use simulation software to quickly experiment with and define parameters such as phased array configuration, element patterns, element size and spacing, scan angle, and amplitude taper. In addition, design software simulates sub-array and shared array configurations applicable to dynamic servicing.

Figure 11 shows the phased array configuration of the individual array elements. Configuration affects the phased array system's overall performance, capabilities, and efficiency in beam control, coverage, resolution, and interference management.


Uniform linear
Uniform rectangle
Triangular
Circular
3D / conformal

4G base stations
Automotive radar

SatComm, 5G, radar
General purpose

Mobility applications

>180° coverage

Figure 11. Phased array configurations and their associated radiation patterns simulated in PathWave System Design software grouped by common industry applications

Two distinct, but mutually influential design concepts, phased array configuration and element pattern, govern the PAA geometry. The configuration determines the overall array's beam control. At the same time, the behavior of an individual element, referred to as an element pattern, characterizes its radiation pattern or response pattern without considering the array configuration. Phased array configuration helps determine each element's sensitivity, gain, directivity, and sidelobe levels. A well-designed element pattern with high gain, low sidelobes, and suitable directivity contributes to a high-performance phased array.

Back to Contents

The possible operating frequency of the system depends on the element size and spacing. The size of each antenna element directly relates to the wavelength of the transmitted or received signal. The element's size must suit the signal's wavelength for efficient radiation or sensitive reception to ensure the antenna couples with the electromagnetic (EM) wave.

Larger elements in an antenna array result in narrower beams, which affects the beamwidth and leads to higher angular resolutions. This characteristic makes them well-suited for precise targeting or object detection. Smaller and more efficient elements contribute to an overall more efficient array system in terms of power consumption, signal transmission, and reception. Designers typically space elements a half-wavelength apart as larger element spacing risks greater frequency sensitivity and distortion terms at off-carrier frequencies. Figure 12 shows the increasing dispersion of radiated beam power as element spacing increases.

Designers spatially interleave elements in large arrays that perform multiple functions. *Spatial interleaving* refers to a technique used to enhance the performance of the array system by strategically distributing multiple subarrays in a specific spatial configuration for adaptive beamforming applications. However, greater element spacing potentially results in unwanted spatial images due to under-sampling. To address this, designers apply dithering throughout the array. *Dithering* in phased arrays involves introducing small, controlled variations in the phase and amplitude settings of the individual antenna elements to compensate for errors. Despite these complexities, spatial interleaving supports wide-angle scanning applications.

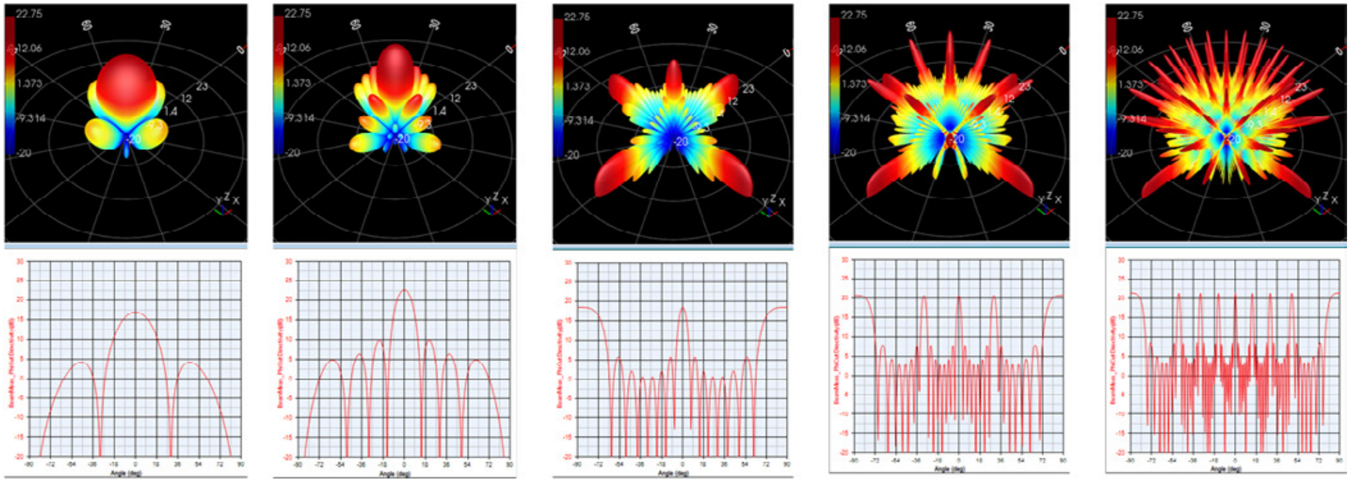
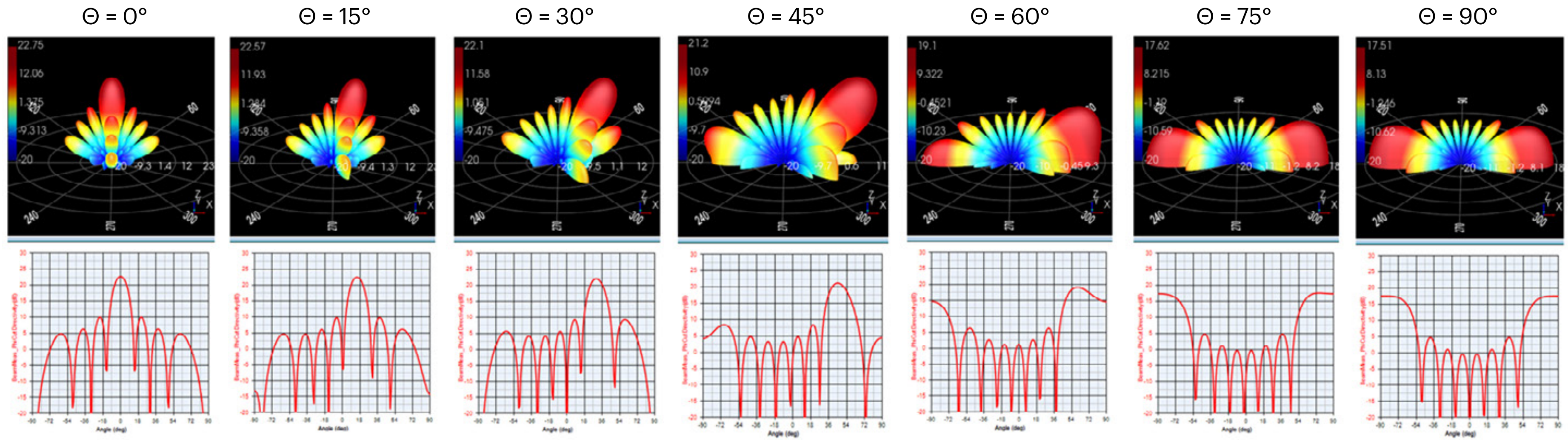


Figure 12. An example of an eight-by-eight array beam pattern with elements at incrementally increasing element separation (left to right) increasing the effective cross-section area "A" of the array, yielding higher gain and narrower directivity



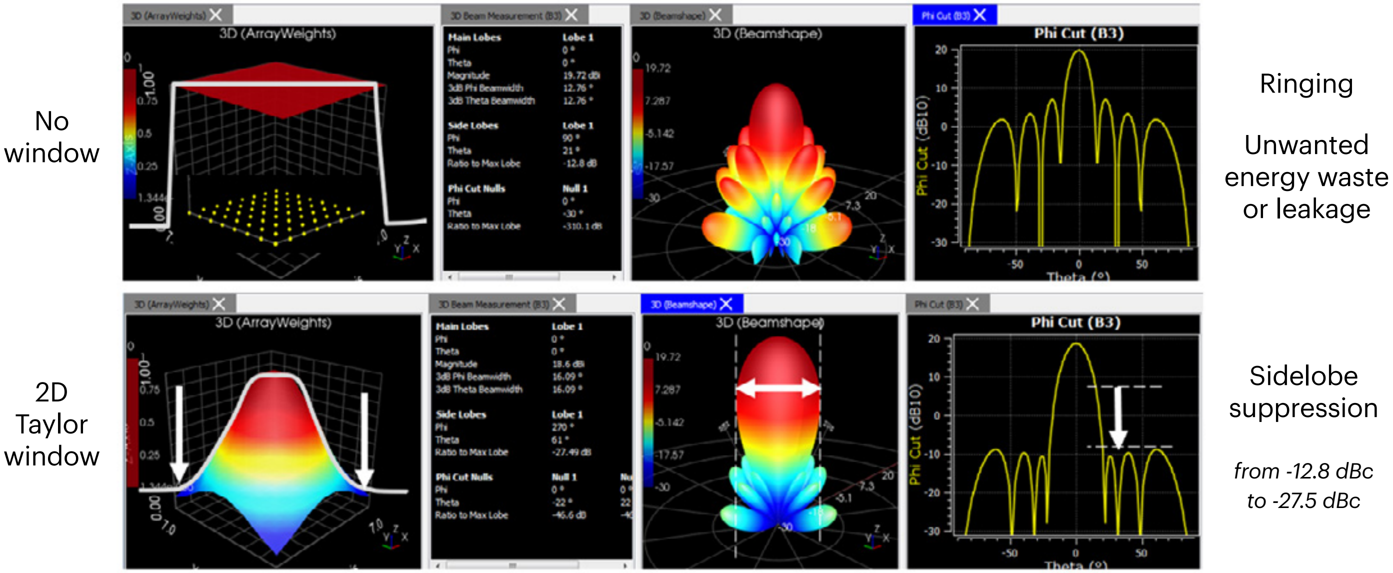
Θ = 0° Θ = 15° Θ = 30° Θ = 45° Θ = 60° Θ = 75° Θ = 90°

Figure 13. An example of an eight-by-eight array beam pattern with scan angle incrementally increasing (left to right), reducing the effective cross-section area “A” of the array, directivity, and power supplied to the primary beam

The *scan angle* refers to the angular direction in which the phased array steers the main beam. Figure 13 shows how the scan angle directly impacts the phased array system’s coverage and capabilities. A specific type of sidelobe called *grating lobes* appears in phased array antennas due to the discrete and periodic nature of the array’s element spacing and phase settings. Proper control of these sidelobes reduces interference from unwanted signals and improves the signal-to-noise ratio (SNR). By controlling the scan angle, the array focuses on specific regions of interest, maximizing the likelihood of detecting and tracking targets. The scan angle also determines the coverage area of the phased array.

Amplitude tapering refers to the controlled variation of signal amplitude applied to the individual elements in the phased array. Designers typically use amplitude tapering to shape the radiation pattern of the array. Varying the amplitude distribution across the elements controls the width of the main beam while reducing the amplitudes of elements that contribute to high sidelobe levels. This process also helps improve the overall efficiency of the array. Amplitude tapering also works in conjunction with phase shifters to steer the beam electronically.

For example, Figure 14 illustrates the inefficient beam pattern of an array with constant amplitude weighting. The prominent sidelobes in the beam result from spatial ringing acting like a rectangular window weighting function in terms of signal processing. These sidelobes reduce the main lobe's width and power. To address this, designers apply a windowing function across the face of the array, reducing the sidelobe power.


No window

Ringing

Unwanted energy waste or leakage

2D Taylor window

Sidelobe suppression

from -12.8 dBc to -27.5 dBc

Main Lobes	Lobe 1
Phi	0 °
Theta	0 °
Magnitude	19.72 dBi
3dB Phi Beamwidth	12.76 °
3dB Theta Beamwidth	12.76 °

Side Lobes	Lobe 1
Phi	90 °
Theta	21 °
Ratio to Max Lobe	-12.8 dB

Phi Cut Nulls	Null 1
Phi	0 °
Theta	-30 °
Ratio to Max Lobe	-310.1 dB

Main Lobes	Lobe 1
Phi	0 °
Theta	0 °
Magnitude	18.6 dBi
3dB Phi Beamwidth	16.09 °
3dB Theta Beamwidth	16.09 °

Side Lobes	Lobe 1
Phi	270 °
Theta	61 °
Ratio to Max Lobe	-27.49 dB

Phi Cut Nulls	Null 1
Phi	0 °
Theta	-22 °
Ratio to Max Lobe	-46.6 dB

Figure 14. An eight-by-eight array beam pattern before and after applying amplitude tapering

Antenna polarization also impacts beam propagation. Antenna polarization refers to the orientation of the electric field component of an EM wave radiated or received by an antenna. The electric field propagates vertically, horizontally, or any angle in between.

The following propagation directions are associated with three categories of antenna polarization:

- **Vertical polarization** is the oscillation of an antenna's electric field on the vertical plane parallel to the ground.
- **Horizontal polarization** is an electric field oscillating in a plane parallel to the ground, perpendicular to the vertical axis.
- **Circular polarization** has two categories — right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP).

The antenna polarization designer's choice depends on various factors, including the application, desired coverage area, and potential sources of interference. For effective communication, the polarization of the transmitting and receiving antennas must match. Designers call matching beam pattern polarizations *co-polarization* (co-pol). In most cases, mismatched polarizations, or *cross-polarized* (cross-pol) beam patterns cause signal attenuation, reduced signal quality, and increased interference. However, specific scenarios benefit from intentionally employing cross-polarization, like mitigating interference caused by co-polarized signals coming from different directions or improving reception in environments with significant multipath propagation.

Dual polarization in phased array antennas refers to using two perpendicular polarizations for transmission and reception within the same antenna system. This approach effectively doubles the capacity of the antenna system by enabling it to transmit and receive two independent data streams concurrently. To implement dual polarization, designers either make each antenna element radiate and receive signals with both horizontal and vertical polarizations, called *co-located dual polarization*. In co-located dual polarization, each element includes two sets of radiating or receiving structures, each oriented for one of the orthogonal polarizations.

Spatial dual-polarization is two separate physical antenna elements with different polarization orientations adjacent to each other. Spatial dual polarization depends on controlling the phase and amplitude of the signals fed to the vertical and horizontally polarized elements.

Dual polarization specifically benefits radar, cellular, and satellite communication systems. To implement such polarizations, designers use simulation tools like Keysight PathWave System Design software to compute the total co-pol and cross-pol array beam patterns from individual element polarization to design polarization-selective phased array antennas.

Circuit and system design considerations

Because of the integrated nature of phased array systems, designers must validate all layers of the device design, from individual components to the complete system. Modern arrays often integrate the RF circuitry with the radiating elements. Millimeter-wave (mmWave) frequency phase array antennas usually integrate with beamforming radio-frequency integrated circuits (RFIC) in a system-in-chip (SiC) to reduce loss and address size constraints. Antenna, RF, and system engineers must work together to produce the system. There are several significant design issues to consider when addressing the interplay between antenna arrays and RFIC:

- nonlinear component behavior
- discrete-valued states
- broadband squinting
- element coupling
- element failure

A small module often contains multiple monolithic microwave integrated circuits (MMICs). The system engineer designs a complete RF chain using many component behavioral models in the early phases of phased array design. From these models, the designer decides system-level and component-level target specifications. Importing component parameters from circuit design and simulation software like Keysight PathWave Advanced Design System (ADS) into the system-level simulation software provides designers with an integrated platform to refine and validate their phased array hardware iterations before investing in a prototype. This testing is crucial for active devices due to their nonlinear behavior.

When driven into compression, amplifiers generate spurious distortion products that radiate in all directions and increase sidelobe levels by distorting amplitude taper across the array. At best, bypassing the validation of amplifiers before building a phased array results in costly hardware iterations in the lab. At worst, it leads to deployment failure due to FCC violations.

Design teams use scattering parameters (S-parameters), antenna radiation patterns, and component X-parameters acquired from the antenna and circuit design in a system-level simulation to model behavior effectively. Circuit designers and system engineers often focus on system-level distortions such as intermodulation distortion (IMD) products and the third-order intercept (TOI) terms, especially in receiving systems. The phased array's active components, like amplifiers and mixers, typically introduce these terms.

X-parameters perform a similar role to S-parameters by characterizing the behavior of both linear and nonlinear components under large-signal conditions. While they precisely reduce to S-parameters in small-signal analysis, X-parameters describe a broader range of component behavior.

Back to Contents

However, because X-parameters contain information on all the harmonics and intermodulation spectra generated in response to large signals, they are much more powerful than S-parameters or any other nonlinear models available in the industry. X-parameters correctly characterize impedance mismatches and frequency mixing behavior, enabling fast, accurate simulation of cascaded nonlinear X-parameter blocks representing active devices.

Circuit designers follow the MMIC design flow from front-end schematic design to back-end layout and create preliminary power amplifier (PA) designs with linear and nonlinear simulation and extracted X-parameters. The system engineer validates the accuracy of the generated model and compares it with the actual circuit-level MMIC PA by inserting both the X-parameter model and MMIC PA design into a nonlinear simulation setup. This approach enables system and circuit designers to achieve first-pass design success for the module after a few iterations of all major MMIC components.

Other components within the phased array's T / R modules also require design optimization. T / R modules depend on internal digital phase shifters for this beam steering control and digital attenuators to control the sidelobe power level. These digital components only allow a finite number of control bits, making quantized phase and amplitude states vulnerable to quantization error. Other sources of error for these frequency-dependent components include phase shifter insertion loss and attenuator insertion phase.

Because discrete-valued states impact beam accuracy and sidelobe levels, measuring the S-parameters of these parts with all combinations of control bits enables complete and accurate performance characterization. The PathWave System Design software accurately models the phased array T/R modules by accepting S-parameter data as a function of both states and frequency.

As the trend towards broadband signals in commercial and defense industries continues, using this phase-shifting method to beam steer presents a beam steering problem. Phase is a function of frequency — the beam direction changes within the signal's bandwidth. Phase distortion across frequency causes phased array squinting.

Phased array squinting refers to the phenomenon where the primary beam of a phased array antenna system deviates from its boresight direction (the direction of maximum gain) due to the changing phase relationships of the signals fed to the individual antenna elements. Squinting leads to misaligning the main beam with the target of interest, reducing signal strength.

Back to Contents

Fortunately, designers use time delay methods as a frequency-independent workaround to control the beam direction. However, time delay beam steering presents control accuracy challenges. Maintaining exact time delays can lead to significant expenses. To balance development costs and mitigate squinting, designers employ *multilevel / multistage* design, flexibly using both phase shift and time delay methods in simulation. PathWave System Design enables designers to experiment with hybrid time delay / phase shift beamforming for practical squint correction in broadband applications.

After defining the circuits and subsystems of the array, the designers perform system path analysis with system-level simulations to refine the phased array hardware. This analysis enables engineers to identify and fix under-specified or over-specified components before prototyping the physical hardware.

System path analysis also helps detect problematic *element coupling*. Phased array element-to-element coupling often results in blind spots in specific scan directions, larger sidelobes, impedance variation across scan angles, and reduced gain. Using PathWave System Design software with 3D electromagnetic (EM) simulation software like Keysight EM Design (EMPro) enables designers to automatically build and solve arrays of N elements to obtain an NxN coupling S-parameter matrix. This approach produces the best accuracy by mathematically computing the reflection coefficient of each element over the scan angle.

Robust design simulation enables the most efficient process for specifying the circuits and subsystems necessary for optimum system performance and accounts for graceful element degradation and failure. Element failure increases the difficulty of controlling beam steering, sidelobe levels, and power transfer. Graceful degradation maintains beam directions despite partial failure.

Using PathWave System Design's Monte Carlo random or user-specified failure analysis enables the development of robust mission-critical designs, including redundant elements and adaptive beamforming algorithms. Phased arrays do not catastrophically fail when some antenna elements fail, so designers must find the acceptable extent of failure for a phased array. Monte Carlo simulations model the failures of elements randomly or in a custom fashion. Modern scalable phased arrays contain subarrays, so Monte Carlo simulations also model the failure mechanism at a subarray level.

Phased array OTA test basics

After design comes verification testing, development, and manufacturing; this workflow phase ensures that the phased array prototype meets the design specifications and establishes manufacturing feasibility. While vector network analyzers (VNA) manage phased array circuit and subsystem characterization, testing the full functionality of the phased array system, namely radiation pattern, requires over-the-air (OTA) antenna range testing. The two kinds of range tests are far-field and near-field testing.

Developers conduct far-field range measurements at relatively long distances from the antenna under test (AUT). System developers consider the region beyond the Fraunhofer distance as far-field. At this distance, the receive antenna views EM waves as essentially planar waves. Antenna applications mostly center on long-range communication, so designers define most antenna parameters for the far-field. As such, direct far-field (DFF) measurements do not require any additional calculations. For indoor far-field testing, developers use *anechoic chambers*. An anechoic chamber creates an environment where RF waves absorb rather than reflect, leading to an almost complete absence of echoes or reverberations.

Although DFF range measurements seem straightforward, developers struggle with far-field testing because of phase taper and range size. The Fraunhofer distance only approximates the far-field region. So, the EM waves received by the antenna approach planar waves are not perfect. Figure 15 shows 22.5 degrees of phase taper at the phase front. The phase taper introduces some errors in the sidelobes and nulls in the antenna radiation pattern.

Measurements may require five times the Fraunhofer distance or farther to get acceptable error levels. The impractical or impossible setup of DFF range setups often stems from their large footprint, which depends on the antenna diameter and test frequency. Setting up the far-field range outdoors leaves it susceptible to interference and dependent on weather conditions.

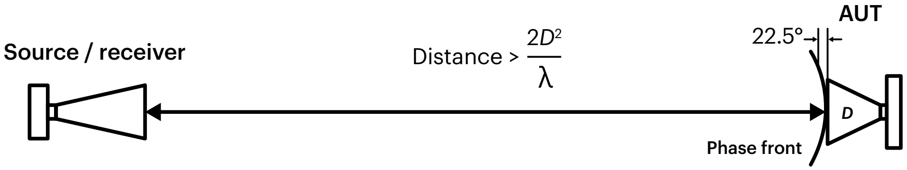


Figure 15. A far-field range measurement setup uses the approximated Fraunhofer distance. In this setup, "D" represents the aperture diameter of the antenna, and "λ" represents the test wavelength associated with the test frequency. The test frequency produces phase taper that leads to sidelobe error.

A compact antenna test range (CATR) makes indirect far-field range measurements at a short distance. Figure 16 shows how it uses a reflector to collimate the radiated spherical wavefronts from the source antenna into planar wavefronts. The CATR method allows far-field measurements of the individual elements and the full array in a much shorter distance than a direct far-field measurement. The controllable setup enables engineers to avoid the phase taper seen at the Fraunhofer distance. However, developers face challenges because of the increased number of reflection error types to manage and the cost of conventional CATR solutions.

Back to Contents

Basic Antenna Pattern Measurements

Plane wave illumination

Direct far field

- Range length > $2D^2/\lambda$
- < 22.5° Phase curvature
- Friis path loss $\propto \lambda^4/D^4$

Parabolic reflector (CATR)

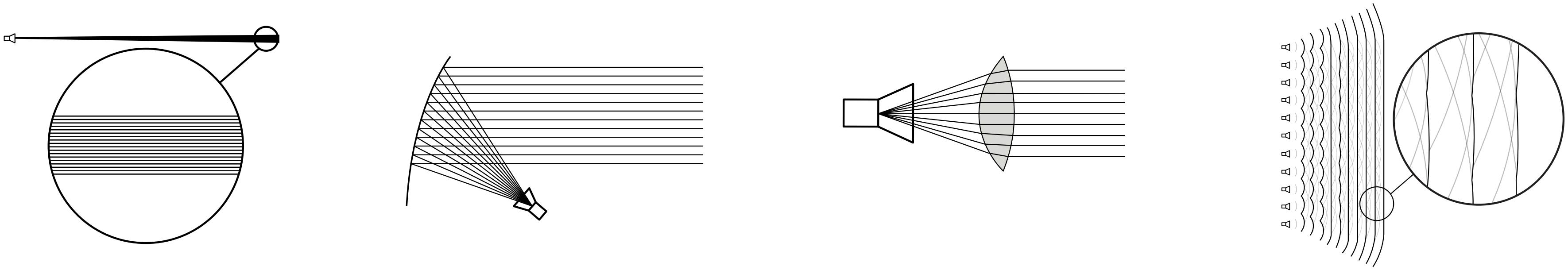
- Range size depend on the reflector size, which is proportional to D
- Phase Flatness ~ ±5-10°
- Path loss depends on the reflector focal length (distance from feed to reflector)

Lens

- Range length driven by focal length + DUT size
- Path loss ∝ antenna - lens separation and loss tangent of dielectric

Plane wave generator

- Potential for very short range lengths
  - Range length driven by probe spacing and DUT size
  - Planarity varies by distance
- Path loss offset by array gain



Pictures only for illustrative purposes.

Figure 16. Engineers employ various kinds of antenna test ranges

Back to Contents

Developers execute three main types of near-field range measurements on the antenna under test (AUT) using a small probe antenna to scan:

- Planar probes scan the plane in front of the antenna.
- Cylindrical probes scan the cylinder around the antenna.
- Spherical probes scan the sphere around the antenna.

The results translate to far-field range measurements with various mathematical techniques. Planar measurements translate to the far-field using Fourier Transforms or other transforms, while cylindrical and spherical measurements use cylindrical or spherical harmonics.

Near-field testing yields complete pattern characterization in one data acquisition without any phase taper. It also significantly reduces the space necessary for testing. However, one of the challenges associated with PNF measurements for flat panel phased arrays is the difficulty introduced by the precise positioning of the probe antenna. These challenges include probe coupling errors and compensation, scan plane truncation, source / temperature stability over probe scan duration, and narrowband far-field transformation. Evaluating the noise figure and wideband signal distortion from near-field data introduces complexity. Wideband arrays with wide beam scan ranges further amplify the complexity.

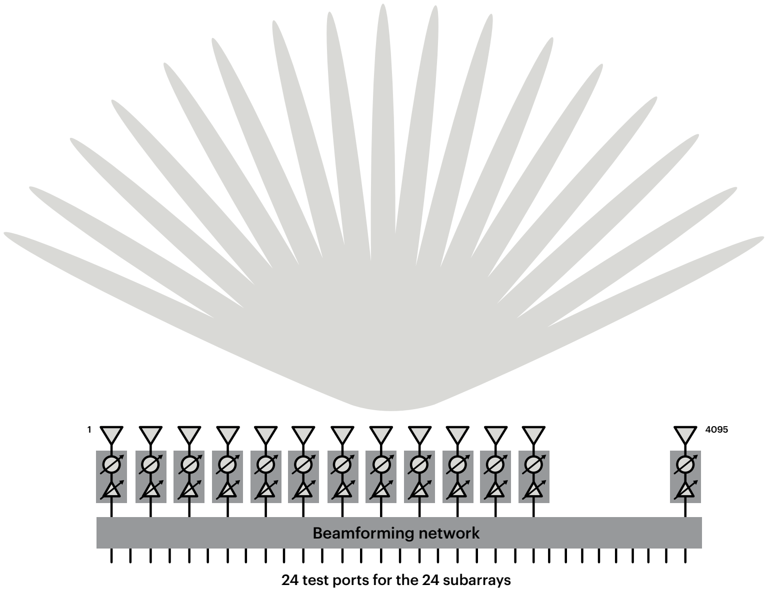
Figure 17 shows radiation pattern measurement techniques versus antenna types. Depending on the type of antenna under test or test parameters, some measurement techniques work better than others. For example, a near-field approach and compact ranges better suit high-frequency antenna testing than an outdoor range or anechoic chamber. When measuring low sidelobes, the near-field techniques outperform any far-field options.

	Near-field			**Far-field**		
High gain antenna	Excellent	Good	Good	Adequate	Adequate	Excellent
Low gain antenna	Poor	Good	Good	Adequate	Good	Excellent
High frequency antenna	Excellent	Excellent	Excellent	Good	Poor	Excellent
Low frequency antenna	Poor	Poor	Good	Good	Fair	Poor
Gain measurement	Excellent	Good	Good	Excellent	Good	Excellent
Close sidelobes	Excellent	Excellent	Excellent	Good	Poor	Excellent
Far sidelobes	Adequate	Excellent	Excellent	Good	Poor	Good
Low sidelobes	Excellent	Excellent	Excellent	Variable	Poor	Good

Figure 17. Testing technique for radiation pattern range versus antenna type and test parameter

The features of AESA architecture make measuring all the antenna patterns of modern phased arrays extremely time-consuming. Many of the antenna patterns require verification testing and optimization. Figure 18 shows a typical AESA antenna with 24 test ports, two polarizations per test port, tested at 21 frequencies. This phased array needs 8,281 antenna beam positions tested per test port, polarization, and frequency. Developers must test over eight million antenna patterns to meet these test requirements — this process characterizes the array and ensures there are no gaps in coverage.

Traditionally, developers and manufacturers calibrated their arrays by scanning a near-field probe over each element. However, with over 1,000 element arrays, probe testing takes tens of hours to complete. To meet commercial demand, development teams of phased array systems must efficiently implement alternative test methods for calibrating and verifying performance.



Θ scan angle: ±45°
Φ scan angle: ±45°
24 test ports
2 polarizations
21 frequency points
8281 ‘beam’ positions per port
polarization, and frequency

8281 x 24 x 2 x 21 =
~8.3 million antenna patterns!

All AESA antenna developers utilize near-field measurement techniques to measure their antenna patterns

Figure 18. AESA architecture makes measuring all the antenna patterns of modern phased arrays extremely time-consuming

Phased array test considerations

Addressing these challenges demands streamlining the development cycle to enable engineers to make cost-effective, high-quality phased arrays faster. Conventional over-the-air (OTA) measurement setups use segregated control software, which prevents synchronization between the positioner, test instrument controls, beamforming controls, and chamber.

To deliver fast, fully automated measurements, the Keysight phased array test solution integrates and synchronizes digital control of the high-performance Keysight PNA-X vector network analyzer (VNA), the Keysight VXG-C vector signal generator, and a compact antenna test range (CATR) with positioner, as well as the phased array antenna beamforming integrated circuit channels. This approach maximizes measurement speed while delivering advanced three-dimensional data visualization for deeper insights into your OTA test results.

The Keysight phased array calibration and characterization test solution offers a comprehensive and user-friendly software interface and accommodates various phased array antenna performance verification tests. These tests include fast gain and phase calibration, antenna radiation pattern measurements, antenna gain-to-noise-temperature (G / T), and RF to direct digital measurements — all within a single OTA test configuration using the Keysight portfolio of compact antenna test ranges.

Engineers must calibrate the antenna array to precisely beam steer. The calibration process compensates for relative RF variance between channels due to component, printed circuit board, and beamforming network manufacturing differences. Additionally, electronic components require stored calibration files to perform under varying operating conditions like frequency or temperature. The slow scanning speed of standard planar near-field (PNF) probes that near-field probing uses interferes with the fast and accurate phased array element channel calibration developers need.

Pairing the CATR with the PNA-X VNA enables a suite of calibration routines and beam pattern measurements that sweep across azimuth and elevation and allow user-defined spherical angles. The Keysight phased array antenna calibration software characterizes the amplitude and phase of each array element with high levels of accuracy, reducing calibration time from hours to only minutes. This solution enables developers to measure beam patterns corresponding to multiple array states: calibrated / uncalibrated, vertical / horizontal active polarization, and more. Figure 19 shows a 256-element array with two defective elements before and after calibration.

Back to Contents

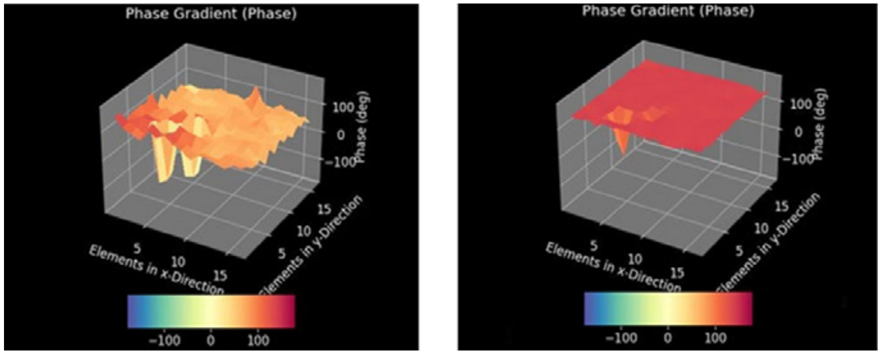


Figure 19. Antenna array before calibration (left) and after calibration (right)

Along with rapid calibration, developers also need fast and accurate beam pattern measurements, including effective isotropic radiated power (EIRP), scan loss, and cross-pol isolation. Beam performance validation requires measurements of 3D antenna beam patterns to verify the proper antenna gain, sidelobes, and null depth for 5G and satellite frequencies.

The EIRP in Figure 20 represents the equivalent power needed to achieve the same power density as the antenna under test (AUT) when radiating from an isotropic antenna in a specific direction. This process helps developers ensure efficient signal transmission. The EIRP accounts for the transmitter's power output and the antenna's gain in a specific direction. Quantifying the radiated power from an antenna system frequently considers both the transmitter power and the antenna's directivity. Vital to regulatory compliance, EIRP enables engineers to validate their system conformance to radiated power limits in a specific direction to prevent interference with other systems.

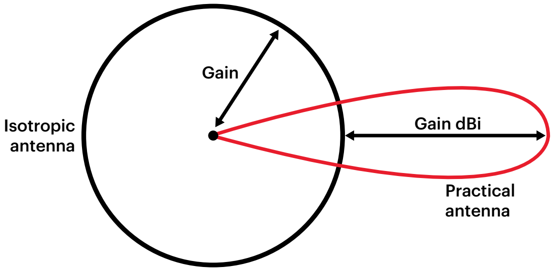


Figure 20. EIRP is a measure of transmitter power output represented in decibels relative to one milliwatt (dBm), and the antenna gain in a specific direction is in decibels isotropic (dBi)

Engineers design phased arrays to produce a narrow main lobe and maximize gain in the boresight direction. When the beam steers away from this direction, the power distributes over a broader area, resulting in a reduction in gain known as *scan loss*. Scan loss occurs in all phased array systems, particularly those that need to rapidly change pointing direction to track moving targets, adjust for interference, or perform scanning functions in radar or communication applications. Scanning loss degrades with angle from broadside for planar arrays with microstrip patch elements. Engineers mitigate scan loss by optimizing the phase and amplitude settings for different scan angles through system calibration and advanced beamforming algorithms.

Cross-polarization isolation refers to the degree to which the antenna system isolates signals of different polarizations. A high cross-polarization isolation indicates that the antenna system effectively rejects signals with orthogonal polarization, reducing the potential for interference and crosstalk.

Along with maximizing the primary beam strength, developers must identify the location of the sidelobes and nulls to tune the antenna for maximum radiation efficiency. A *null* indicates a region of reduced signal strength or sensitivity in a specific direction, surrounded by lobes of higher signal strength. It occurs due to interference patterns resulting from the constructive and destructive interference of waves radiated by different elements in the array.

Null depth refers to the level of suppression or reduction in the intensity of a radiation pattern's null and measures how effectively the phased array antenna system minimizes signal exchange in a specific direction. A deeper null indicates a higher degree of suppression in that direction, meaning that the array's radiation pattern attenuates signals from that direction more effectively. System developers want to maximize null depth to improve interference rejection and radiation pattern shaping while reducing crosstalk.

The Keysight phased array test solution software platform integrates digital control of the compact antenna test range (CATR) with the positioner, Keysight PNA-X vector network analyzer, Keysight VXG-C vector signal generator, and beamforming channels. This approach maximizes measurement speed while delivering advanced three-dimensional data visualization for deeper insights into your over-the-air (OTA) test results for both passive and active antennas. It enables the measurement of antenna radiation patterns and system EVM within a single OTA test configuration.

Figure 21 shows how nonlinear distortion products interfere with the desired signals and introduce spurious components into the beam pattern that unintentionally alter the main lobe direction and sidelobe levels. These changes impact the accuracy of target localization and tracking. To perform nonlinear measurements of the array beyond swept gain compression, such as error vector magnitude, the VXG-C vector signal generator provides a wideband modulated signal through a booster amplifier. The PNA-X vector network analyzer comes equipped with the Keysight PathWave vector signal analysis (VSA) software that supports other demodulation metrics, such as error summary tables, spectrum and time displays, and constellation diagrams.

The modulation distortion application enables developers to perform coherent measurements of input and output signals on the PNA-X, computing EVM directly without needing demodulation through spectral correlation. The VSA software provides signal demodulation and many other analysis features, enabling the developer to view the EVM data in conventional I / Q constellation diagrams. The VSA software enables the PNA-X to execute coherent measurements of the modulated input and output signal magnitude and phase. Paired with the Keysight modulation distortion software, the PNA captures an active device's linear and nonlinear response. The PNA-X measures EVM, adjacent channel power ratio (ACPR), and noise power ratio (NPR) with that data.

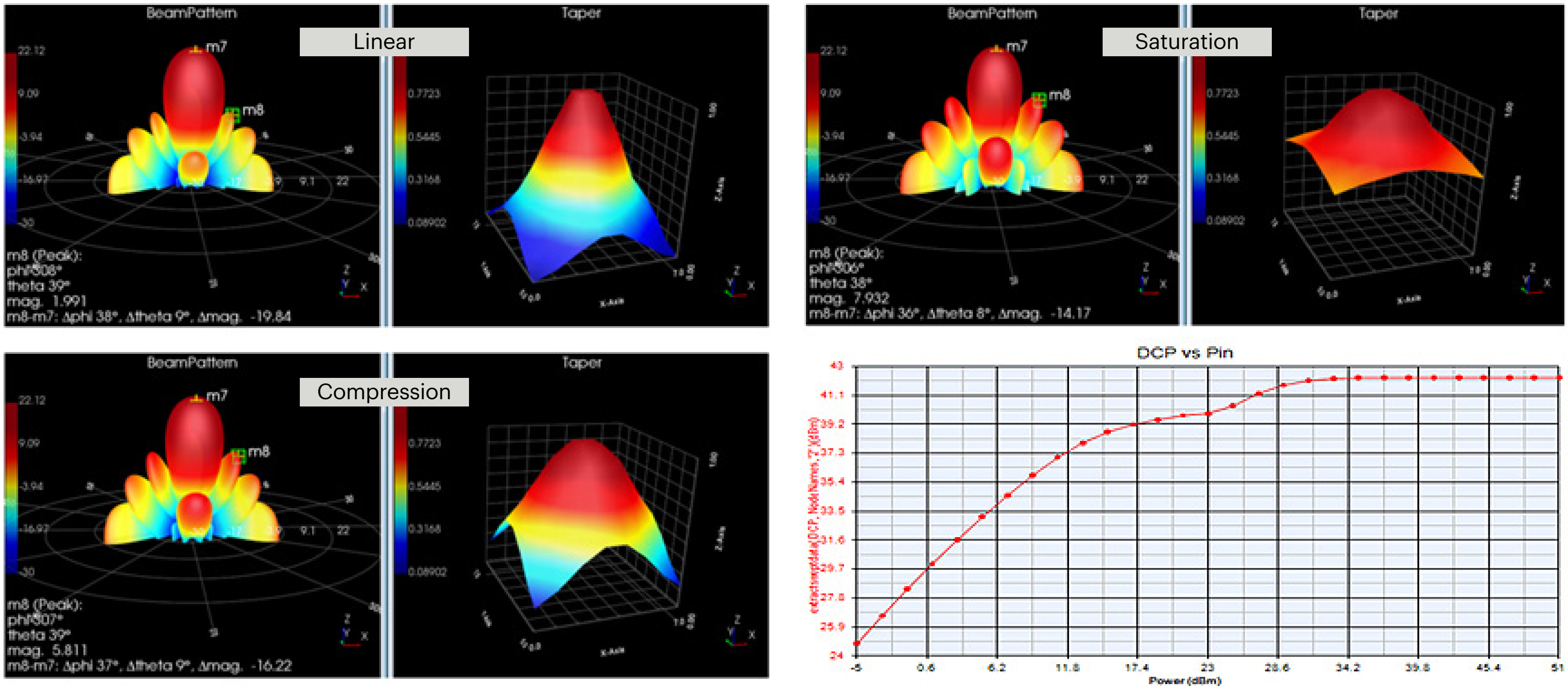


Figure 21. Impact of nonlinear devices on beam pattern

Using the PNA-X network analyzer instead of conventional signal analyzer setups to measure phased array EVM offers benefits beyond a simplified verification setup. Because network analyzers take ratio measurements, collecting EVM data on the PNA-X requires no demodulation, improving test speed.

Additionally, the PNA-X solution delivers the lowest residual EVM due to wider system dynamic range and fully vector-corrected calibration. The low residual EVM enables developers to capture only the phased array antenna's EVM. The solution gives engineers the functionality to measure the EVM of individual active array elements given a low enough noise bandwidth.

Back to Contents

EVM primarily pertains to a phased array antenna (PAA) transmission. Developers use the noise figure as the key figure of merit (FOM) for receiver components, like low-noise amplifiers (LNAs). However, an AESA antenna derives gain from both the element configuration and electronic amplification integrated within the antenna structure. This integration makes it impractical to directly measure the active array elements' noise figure.

Instead of noise figure measurements, engineers use signal-to-noise ratio and G / T to characterize system-level active phased array sensitivity and efficiency. Gain, measured in decibels (dB), represents the antenna's ability to collect and concentrate signals from a specific direction. *Noise temperature* measurements capture the noise power present in a receiving system. The value represents the equivalent temperature of a noise source producing the same amount of noise power.

Lower noise temperature indicates better receiver performance. Engineers measure noise temperature in absolute temperature, Kelvin (K). Antenna gain-to-noise (G/T) measurements, expressed in units of dB / K (decibels per Kelvin), combine the concepts of gain and noise temperature to provide insight into the system's ability to receive weak signals effectively while minimizing the impact of noise. A higher G / T ratio indicates better system sensitivity and the ability to receive weaker signals while maintaining a good SNR. For applications that need to detect weak signals in the presence of noise, such as satellite communication systems, deep-space communication, and radar applications, engineers depend on G / T measurements to certify system robustness.

Measuring G / T with the traditional Y-factor method is challenging with an AESA. The hot noise must be 70 dB above kTB (where "k" is the Boltzmann constant, "T" is the absolute temperature of the load, and "B" is the measurement bandwidth) to overcome range loss. Generating such a high excess noise ratio (ENR) challenges even precision noise sources. The cold-source method on the PNA-X leverages integrated low-noise receivers to measure G / T directly, requiring no noise source for calibration or testing. This approach measures the antenna in an antenna range, as shown in Figure 22.

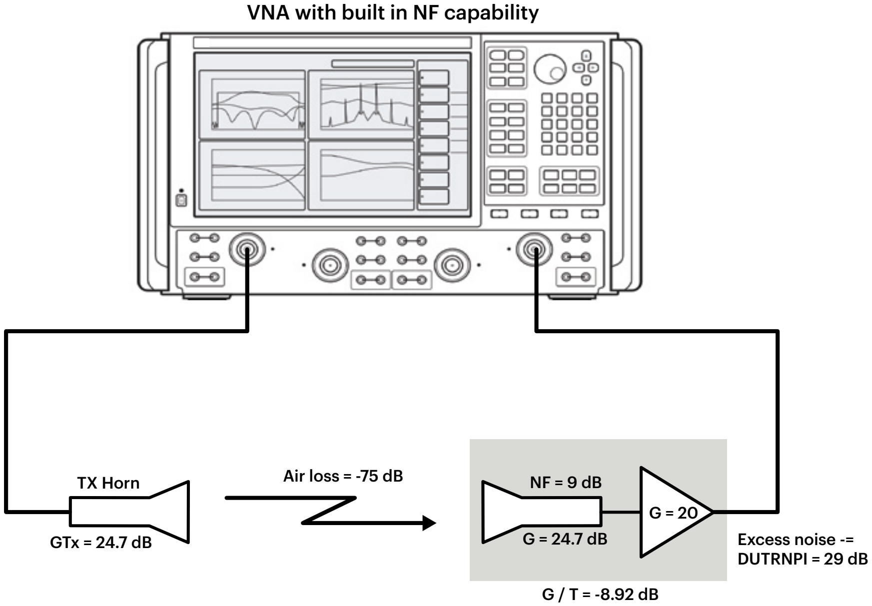


Figure 22. Antenna range measurement for G / T using the PNA-X network analyzer

Deployment and field servicing

The environment of non-terrestrial applications, like navigation, surveillance, and satellite or deep space communication, makes field servicing impossible. This situation stresses the importance of design and verification robustness as the system must survive both deployment and long-term operation without troubleshooting or maintenance. For space systems, the overall system fails once a critical level of component failure occurs.

For terrestrial applications, like 5G communications, once the phased array deploys into the field environment, providers must maintain the phased array antenna's performance through field servicing. The key challenges for 5G network deployment are characterizing mmWave path loss and coverage. 5G operators and equipment manufacturers require a ruggedized OTA solution for network and user equipment (UE) field testing that optimizes and validates network performance.

To measure the phased array's effective coverage, the Keysight FieldFox handheld microwave analyzer over-the-air (OTA) solution measures and displays control channel power, physical cell identifier, synchronization signal block (SSB) index, and channel signal qualities to gain insight into network utilization and capacity.

Since 5G control channels are not always on, locating the 5G signal challenges field technicians. Switching into RTSA mode on the FieldFox enables technicians to quickly and reliably detect 5G signals and control channels. Technicians gain insights into beamforming performance by measuring signal power levels across azimuth and elevation from the base stations. Figures 23a and 23b illustrate that FieldFox provides a unique, portable measurement solution for channel acquisition, RF probing, and signal-to-noise ratio enhancements when used with a phased array antenna.

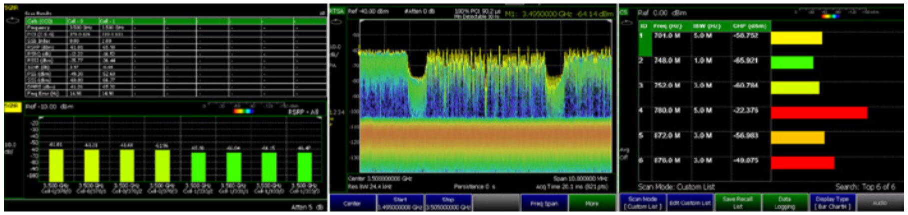


Figure 23a. FieldFox phased array measurements including (left to right) SSB index and cell identification, 5G control channel detection, and coverage test optimization through channel scanning

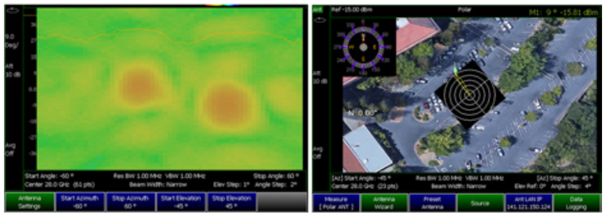


Figure 23b. Scan heat mapping (azimuth vs. elevation) and polar antenna pattern using 2D image mapping

Back to Contents

Summary

Phased array antennas have a longstanding history in radar systems and are still widely used in the aerospace and defense industries today. They serve multiple purposes, such as rapid multi-target search and tracking operations, achieving higher resolution, and improving detection performance. Phased array antenna systems have found applications in many industries as advancements in production technology generate function blocks such as front-end T / R modules, signal sources, and receiver baseband digital processors on a single SiC.

The operational requirements at Ka and Ku frequency bands, especially for the communications industry, rely on the beamforming and steering capabilities of phased arrays. Engineers must optimize design and test cycle time to meet high-volume production demands in expanding commercial markets. However, the extreme complexity and increasing system integration of phased array systems present many testing challenges. Keysight offers solutions that cover the entire phased array workflow.

- Keysight PathWave System Design, Keysight ADS, and Keysight EMPro system and circuit simulation software solutions enable rapid and robust system design.
- The Keysight phased array test solution offers a complete, synchronized system characterization system, including radiation pattern and EIRP, gain, EVM, ACPR, NPR, and G / T on a single test setup.
- The FieldFox handheld analyzer equips field engineers with the ruggedized OTA field solution they need for successful 5G network deployment.

Back to Contents

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Related Products

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- VXG-C vector signal generator
- Compact antenna test range
- FieldFox handheld microwave analyzer
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