MILLIMETER-WAVE BEAMFORMING AND PHASED ARRAY BASICS

Anokiwave Is Now qorvo

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In 2024, Anokiwave was acquired by Qorvo. The combination of the two company's unique capabilities enables Qorvo to supply highly integrated complete solutions and SiPs for defense, aerospace and network infrastructure applications.

Anokiwave's innovative portfolio of active antenna ICs, combined with Qorvo's complementary products, global scale and significant market reach, provide new options for high integration and high-performance that will democratize phased array active antennas.

The following whitepaper was written to explain basic active antenna beamforming concepts that form the heart of the mmWave system, as well as the general beamforming architectures used in active antennas for applications such as 5G networks, SATCOM Flat Panel Arrays and Defense and Aerospace systems. References to Anokiwave have been updated throughout the paper to reflect this acquisition.

Executive Summary

Unprecedented demand for data is driving the need for more spectrum, due to scarcity in lower bands, the focus has turned to higher frequency bands, also known as mmWave spectrum. Systems utilizing mmWave spectrum can easily support the higher data rates and accommodate increased traffic demands that satisfy the insatiable need for faster, more robust connectivity.

Building a mmWave system is not trivial. Defense and Aerospace markets have used phased array antenna technology for years to overcome the high path loss associated with mmWave bands, however those systems were complex, expensive and required a high amount of technical know-how. As the market has grown into commercial applications, symmetric implementations of phased array antennas with silicon quad beamforming architectures in a printed circuit medium, with high volume/low cost scalability have become the preferred technology to enable a system that meets performance and cost points.

This article discusses the basic active antenna beamforming concepts that form the heart of the mmWave system, as well as the general beamforming architectures used in active antennas for applications such as 5G networks, SATCOM Flat Panel Arrays and Defense and Aerospace systems.

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"The global Millimeter Wave Technology market size is expected to reach USD 29.85 billion by 2030 and exhibit a CAGR of 40.20% between 2023 and 2030. Wireless communication demands, 5G network deployment, high data rate requirements, bandwidth capacity for data-intensive applications, demand for improved network latency, emerging Internet of Things (IoT) applications, advanced radar and imaging systems, security and surveillance applications and the need for high-speed wireless backhaul solutions is fueling the market's growth."[1]

Ubiquitous Connectivity requires mmWave Spectrum

by David Corman, Anokiwave, Inc.

The unprecedented demand for data is driving the growth of the mmWave technology market. As data consumption grows exponentially, more spectrum is needed. As frequency spectrum in the low to mid bands is becoming scarce, radios utilizing mmWave spectrum can easily support the higher data rates and accommodate increased traffic demands that satisfy the insatiable need for faster, more robust connectivity.

Active Electronically Steered Antennas (AESAs), also known as phased array or active antennas, are a key enabling technology for making mmWave communications successful. Phased array antennas are an established technology used by defense and aerospace applications to overcome high path loss associated with mmWave bands. They were not a viable option for commercial applications in the past due to their high cost and complexity. But now, with innovations in silicon IC technology, they are becoming a integral part of next-generation communications networks.

This article discusses the basic active antenna beamforming concepts that form the heart of the mmWave system, as well as the general beamforming architectures used in active antennas for applications such as 5G networks, SATCOM Flat Panel Arrays and Aerospace and Defense systems.

Active antennas implemented in 5G networks, as well as in defense, aerospace, military and satellite communication sectors, is driving a substantial growth in the use of mmWave spectrum.

Active Antenna Basics

An active antenna is defined by the Phased Array Antenna Handbook[2] as consisting "of multiple stationary elements, which are fed coherently and use variable phase or time delay control at each element to scan a beam to given angles in space." Thus, active antennas have electronically-steered beams with no moving parts; steering occurs within the ICs placed at the radiating elements in the antenna.

Active antennas with beamforming ICs have what is referred to as a "soft failure mechanism," meaning that, because there are many elements in an array, the failure of a few elements typically has little effect on the performance of the antenna as a whole. Active antennas can steer beams in microseconds, as well as support multiple, simultaneous, independently-steerable beams. With no mechanically gimbaled parts, they are low-profile and reliable. Active antennas are able to steer nulls and, since they have many elements, they have high degrees of freedom to block interferers and jammers. Active antennas are capable of generating precise, radiating aperture patterns.

For 5G communications, the antennas operate at mmWave frequencies such as 24 GHz, 26 GHz, 28 GHz, 37 GHz and 39 GHz, while the SATCOM flat panel antennas operate at Ku-Bands (10.7 to 14.5 GHz) and Ka-Bands (17.7 to 31 GHz). At these high frequencies, the wavelengths are very short, allowing many antenna elements to be placed in a compact, highly directive aperture, which offsets the high path loss at mmWave frequencies. Another key benefit of the highly directive beams is that they provide spatial diversity, where multiple beams can reuse the same frequency spectrum, thus greatly increasing system capacity.

To make it practical and efficient for mmWave systems, Anokiwave, now Qorvo, applied the essential technology of active antennas to a line of Silicon Core ICs covering the different millimeter-wave bands of 5G and SATCOM networks to create high performance systems that meet commercial cost points.

Beamforming Principles and Considerations

The analysis of beamforming by an active antenna is basically an exercise in complex arithmetic. As shown in Figure 1, we have a linear array along the x-axis, with the antenna elements spaced by d, which is equal to a free-space wavelength divided by two. If each element is energized by the appropriate phase, then a beam can be formed coherently in the far field at the desired direction.

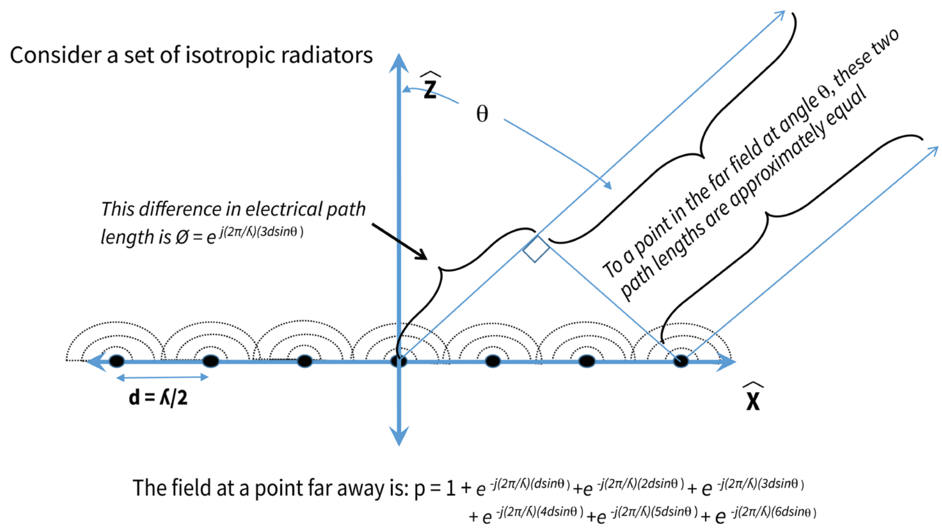


Figure 1: Analysis of Active Antenna Beamforming

In Figure 2, we take an example of an aircraft target that is not in the boresight direction of the array, such that the range from the aircraft to each element in the array is slightly different. The fact that the elements are spaced at d apart, and the angle of arrival of energy from the aircraft is Θ, then the incremental path length difference between adjacent elements is d*cos(Θ). To compensate for this difference in path length, we can place phase shifters behind each element. When the appropriate phase shift is applied, we can coherently form a beam in the far field. Remember that, to form a beam, energy must arrive at the summation node at the same phase, at the same amplitude and at the same time. We call this “coherent combining.”

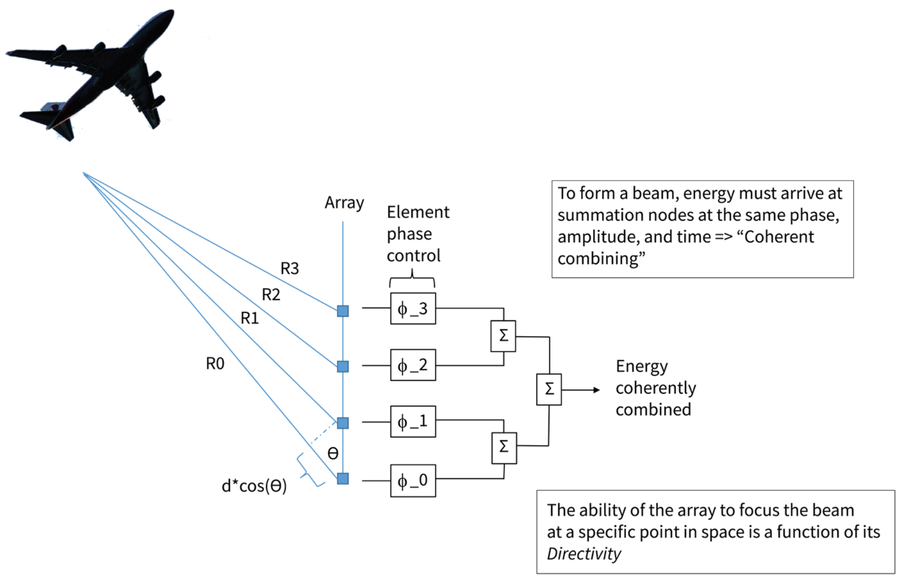


Figure 2: Coherent Summation of Energy - Linear Array

Array Directivity and Gain

Directivity is the measure of how concentrated the antenna gain is in a given direction relative to an isotropic radiator. It follows a 10*log(N) relationship, where N is the number of elements in the array. Gain, however, takes into account directivity as well as ohmic and scan losses.

So, in general, array gain equals 10*log(N), plus the embedded element gain (G_e), minus the ohmic and scan losses:

Array gain = 10*log(N) + $G_e - L_{OHMIC} - L_{SCAN}$

G_e is the embedded element gain, which is the gain of a single radiator embedded in the array. If the radiating elements are spaced λ/2 apart in both the azimuth and elevation directions, then the area of each element is $\lambda^2/4$. Since antenna gain is $4\pi/\lambda^2 * A_e$, where A_e is the effective area of the antenna, then the G_e equals π or 5 dBi.

Note that for every element added to an array, the G/T of a receiver (Rx) array increases by 10*log(N). As the aperture size increases, the noise figure stays constant. In contrast, the equivalent isotropically radiated power (EIRP) of the transmitter (Tx) array increases by 20*log(N), with every element added, array gain and transmit power are added in the far field. It is clear, then, that G/T is much more challenging to achieve with an active antenna than EIRP.

Figure 3A shows how G/T varies with array size. In this plot, the assumed lattice spacing is λ/2, the system noise figure is 5 dB, and 0.5 dB of loss has been included for both feed loss and radome loss. Figure 3B shows how EIRP varies with antenna size and RF power/element. In this graph, the same λ/2 lattice spacing is used, and +9 dBm transmit power per element is assumed.

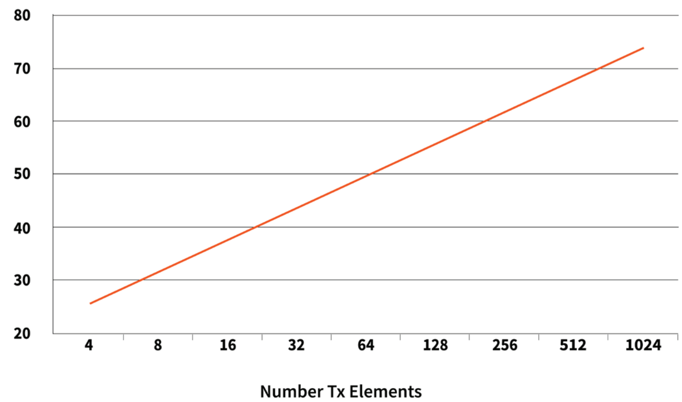


Figure 3A: Example G/T vs. Number of Elements

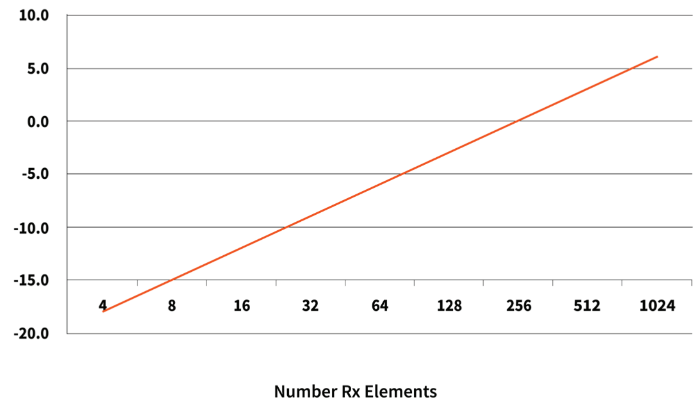


Figure 3B: Example EIRP vs. Number of Elements

System engineers typically generate detailed G/T and EIRP budgets that consider a wide range of variables, including system noise figure, embedded element gain, frequency of operation, transmit power per element, loss between the element and the T/R functions, scan loss, the effect of polarizers and radomes and temperature.

Figure 4 shows some examples of linear arrays — specifically 16, 32, and 64 elements. The graph shows main lobes and side lobes. The antenna directivity follows 10*log(N), as established previously, where N is the number of elements in the array. Every time the size of the antenna is doubled, the beam width halves, and the directivity doubles, or increases by 3 dBi.

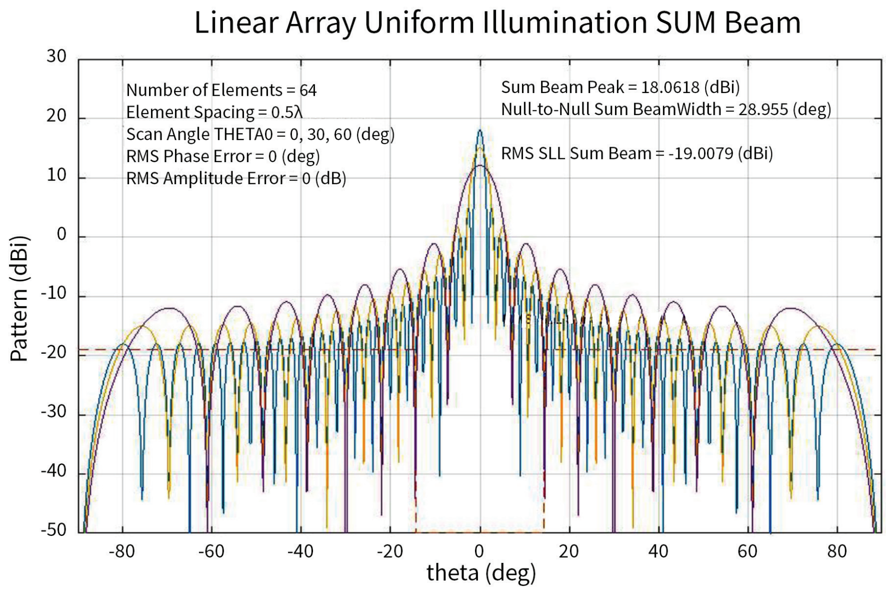


Figure 4: Examples of Uniformly Illuminated Linear Arrays: 64, 32, 16 Elements

One characteristic of using phase shifters to steer active antenna beams is called beam squint (Figure 5). Phase shifters electrically steer a beam by approximating time delay. The result is that they only steer the beam perfectly at the center frequency; they understeer at the maximum operating frequency, and they oversteer at the minimum operating frequency. Yet, phase shifters are preferred over time delay functions because of the trade-off between accuracy and circuit size. In fact, phase shifters provide good accuracy for almost all active antenna applications, with the exceptions being very wide instantaneous bandwidth applications, such as EW, or very large arrays.

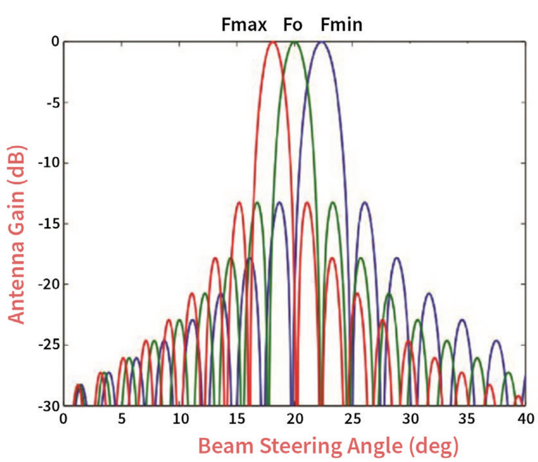


Figure 5: Beam Squint

Another characteristic of all active antennas is the loss of aperture gain as the beam is steered away from the boresight direction — defined as $\Theta=0$. This characteristic, called scan loss, follows $10*\log(\cos^N(\Theta))$ power, where Θ is the scan angle off boresight and N is a numeric value, typically in the 1.3 range, which accounts for the non-ideal isotropic behavior of the embedded element gain.

Figure 6 plots scan loss in dB vs. scan angle, measured in degrees. Note, at the origin, where the boresight angle is zero, there is no scan loss. As the scan angle is increased to 45 degrees, there is 2 dB scan loss. If scan angle is increased to a practical limit of 60 degrees, there is 4 dB scan loss. Active antennas must therefore be oversized to provide the required G/T and EIRP under maximum scan conditions.

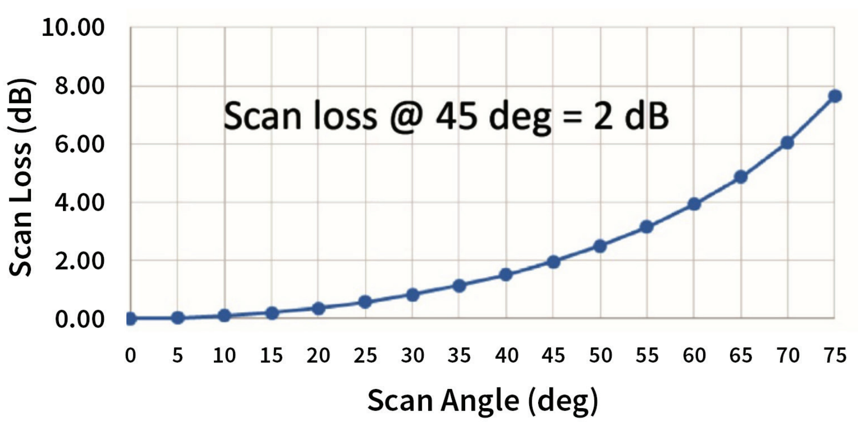


Figure 6: Scan Loss

Tapering is the process of assigning different gains to the various elements within the array, where the center elements are assigned the highest gains, and the outer elements are assigned lower gains. Figure 7 illustrates how various levels of taper can be achieved. The example shown is a 64-element array, so that the maximum gain of each curve occurs at element 32, which is the center of the array. Note that, the more quickly element gain is reduced as the elements get farther from the center of the array, the greater the suppression of side lobes. The graph in Figure 7 shows us the effect of side lobe levels of -20, -30, -40, and -50 dB.

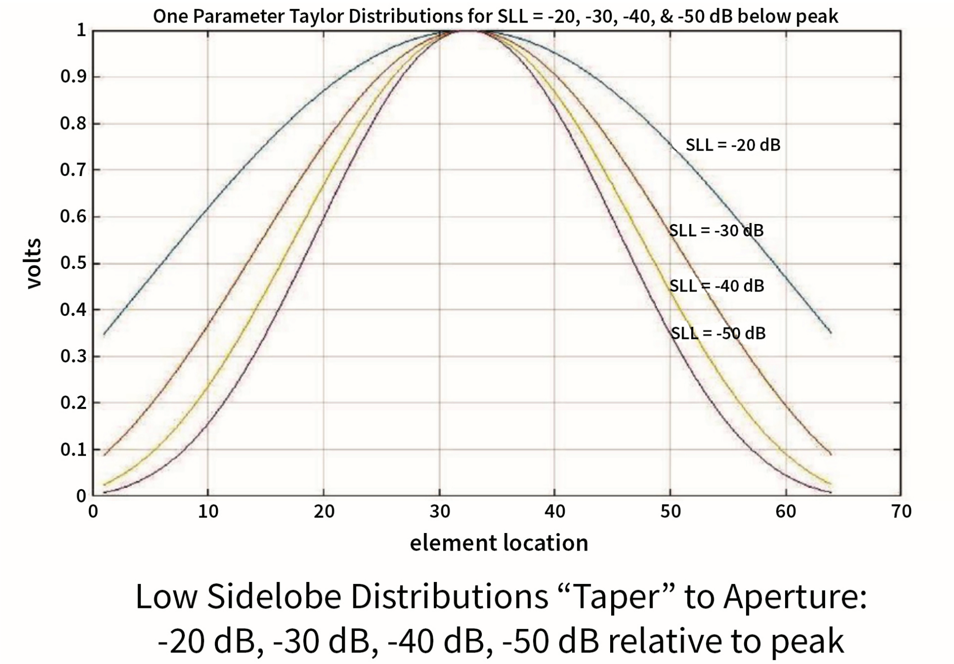


Figure 7: Tapering vs. Side Lobe Level

This is why beam forming typically includes amplitude control per element, not just phase control. If all elements are treated with the same gain, it is called "uniform illumination." Uniform illumination results in -13 dBc first side lobe levels, which may be unacceptable for some applications due to regulatory, interference or stealth reasons.

Gain control allows the system engineer to adjust the gain per element to achieve the desired lower side lobe levels.

Figure 8 shows superimposed side lobe levels for various amounts of applied taper — specifically -20, -30, -40, and -50 dB, relative to the peak. Observe the side lobe level suppression, caused by the applied taper. This is a 64-element array with a directivity of 18 dBi (10*log(64)).

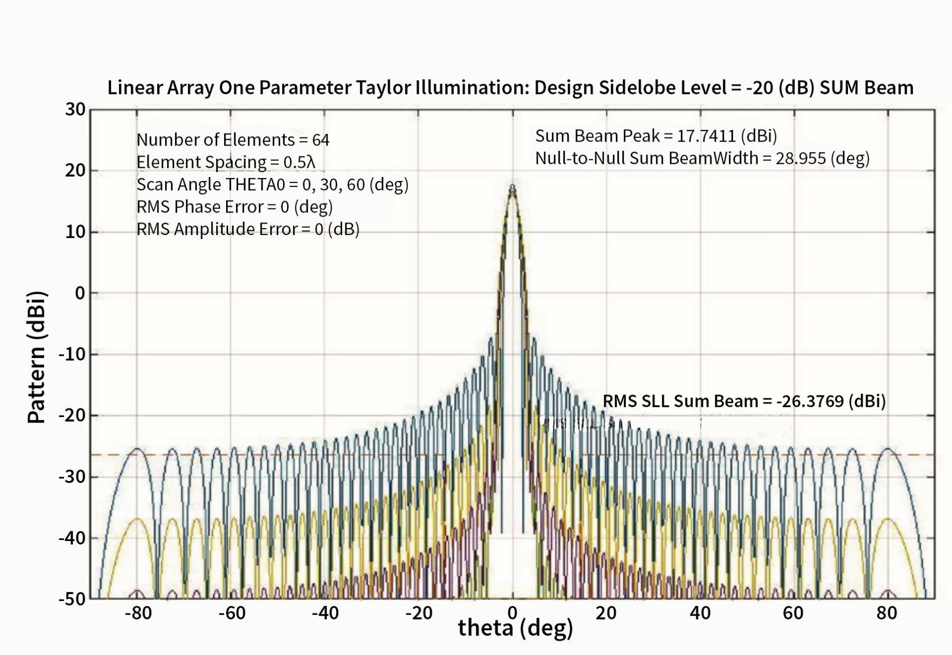


Figure 8: Sample Taylor Distributions: -20 dB, -30 dB, -40 dB, -50 dB Relative to Peak

Qorvo ICs typically provide gain controls at the element in the 0–31.5 dB range, in 0.5 dB steps, which is generally sufficient to provide for amplitude taper and other host system control needs. A final note is that taper does not change with scan angle.

Taper can be a good thing, but it does come at a price. When taper is applied, the directivity is less than uniform illumination for the same size array, and the beam widths are broader. Table 1 shows a range of different tapers applied to the array. The top row is the uniform illumination with -13 dBc side lobes, as previously described. Shown below are rows for -20, -30, -40 and -50 dB side lobe levels. Note that their directivity is decreasing, and the efficiency is decreasing. As shown in the table, if a -50 dB taper is applied, a full 2 dB efficiency is lost on the array.

Desired SLL dB (wrt peak)	B	D - Directivity (dBi)	η - Efficiency (dB)	$B_{null\text{-}to\text{-}null}$
-13.26	0	18.06	0.0	3.6
-20	0.7386	17.74	-0.32	4.5
-30	1.2762	17.05	-1.01	5.8
-40	1.7415	16.51	-1.55	7.2
-50	2.1793	16.08	-1.98	8.1

Table 1: Values of B for desired sidelobe levels in One Parameter Taylor Distributions

Another characteristic of active antennas is grating lobes, which are primarily affected by lattice spacing — the spacing between elements (variable d). To avoid parasitic grating lobes, which are antenna responses in undesired beam directions, the lattice spacing must follow these rules:

- $d/\lambda o < 1/(1+\sin\Theta)$ for a rectangular lattice (Min. spacing = 0.5 λo at 90 deg scan)
- $d/\lambda o < 1.15/(1+\sin\Theta)$ for a triangular lattice (Min. spacing = 0.575 λo at 90 deg scan)

Where λo is the free space wavelength, Θ is the max scan angle, and d is the spacing between antenna elements. A common value of lattice spacing for active antennas with rectangular lattices is 0.55 lambda.

Figure 9 shows that required lattice spacing is a function of frequency. The graph plots lattice spacing in millimeters vs. frequency of operation. Note that, for lower frequencies, large lattice spacing makes planar active antennas not very challenging. But look what happens at 28 GHz and above: the lattice is rapidly contracting, which leaves very little room for the T/R functions and beam-forming electronics to fit with the lattice. Fitting within the lattice is critical to high-performance active antennas, as it guarantees minimum feed loss, which maximizes EIRP and minimizes receiver Noise Figure (NF).

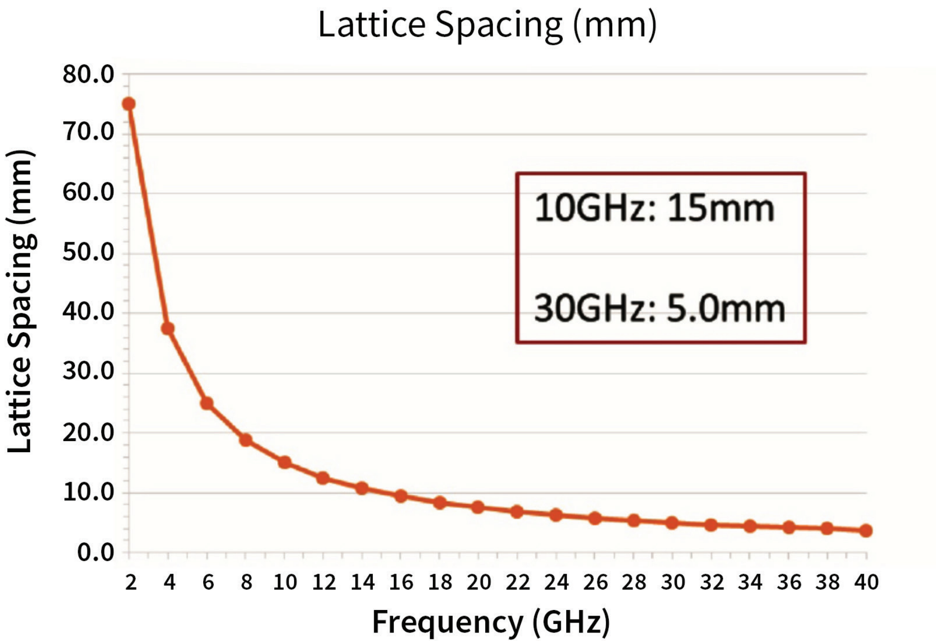


Figure 9: Lattice Spacing Example Calculation

λ/2 lattices at mmWave bands are quite small: 10.3 mm at 14.5 GHz, 5.4 mm at 28 GHz, and 3.85 mm at 39 GHz. This is where the high level of integration with silicon is critical. As mentioned above, the most efficient method to implement planar active antennas at mmWave is to fit the electronics within the lattice using highly integrated silicon ICs, in the same plane as the radiating elements. As shown in Figure 10 below, a four-element IC is optimal for signal routing and other component integration.

λ/2 lattices at mmWave bands are small: 3.85 mm at 39 GHz. High levels of integration are critical; the most efficient method to implement planar active antennas at mmWave is to fit the electronics within the lattice using highly integrated silicon ICs, in the same plane as the radiating elements. A quad IC is optimal for signal routing and other component integration.

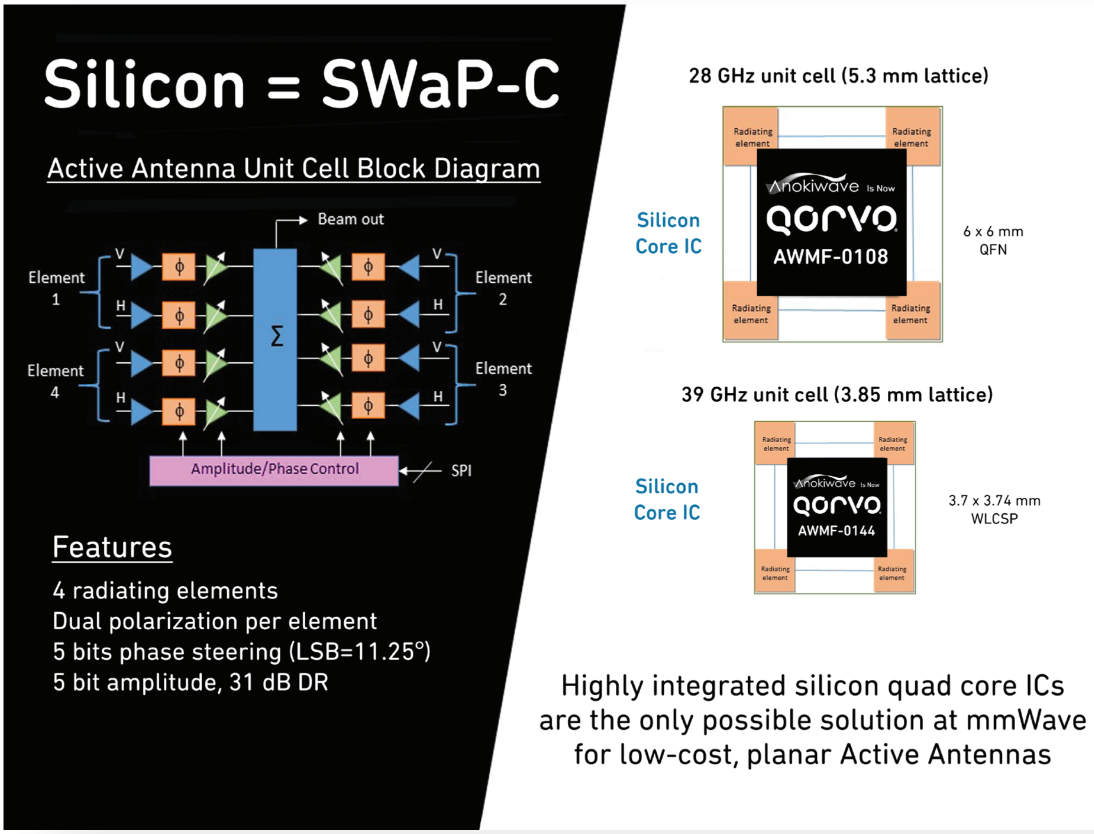


Figure 10: Highly integrated silicon ICs are critical to achieve planar active antennas at mmWave frequencies

Active Antenna Beamforming Considerations

Three general beamforming architectures are used in active antennas: analog beamforming, digital beamforming and hybrid beamforming. This section describes each approach from a high level and then compares the pros and cons of each approach. Note that, in the sections below, the block diagrams all denote receiver diagrams; transmitter block diagrams look similar, just reversed in direction and using DACs instead of ADCs.

Analog Beamforming

All discussion thus far has addressed analog beamforming, where a phase shift is applied to each element in the array followed by coherent power summation. Included in the diagram (Figure 11) is a suitable frequency downconverter and ADC to complete the system.

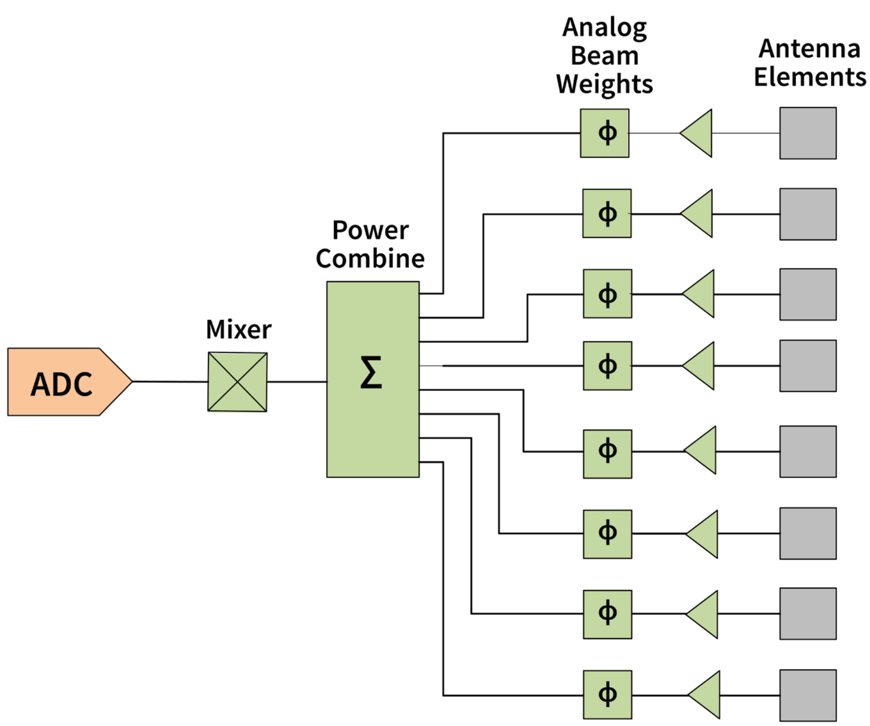


Figure 11: Analog Beamforming Block Diagram

Analog Beamforming Advantages	Disadvantages
Simplest hardware implementation	Single Beam
Hardware can fit within the lattice at high frequencies	Number of beams is fixed by hardware and cannot be changed
Beam benefits from the full array gain	
Lowest system DC power	

Table 2: Analog Beamforming Considerations

Digital Beamforming

In digital beamforming, the beams are formed using complex digital weights, rather than with analog phase shifters (Figure 12). To do this, a full receiver chain from antenna element to digits is required at every element in the array. This is practical only at low frequencies, such as S-band, where the lattices are large and there is plenty of room to place the required hardware on the array. This approach is not practical at mmWave frequencies, since inadequate real estate exists with the tight lattices.

Other significant challenges include high DC power consumption, especially if large bandwidths are to be digitized, signal routing complexity, where multiple bits of I and Q lines must be routed off the array to the digital processor (imagine routing 8 bits of I and 8 bits of Q times the number of elements in the array!) and LO signal routing within the array. On the plus side, if these challenges can be addressed, then this architecture is the most flexible, since multiple beams and nulls can be formed dynamically, with no change in hardware required, and each beam benefits from the gain of the full array.

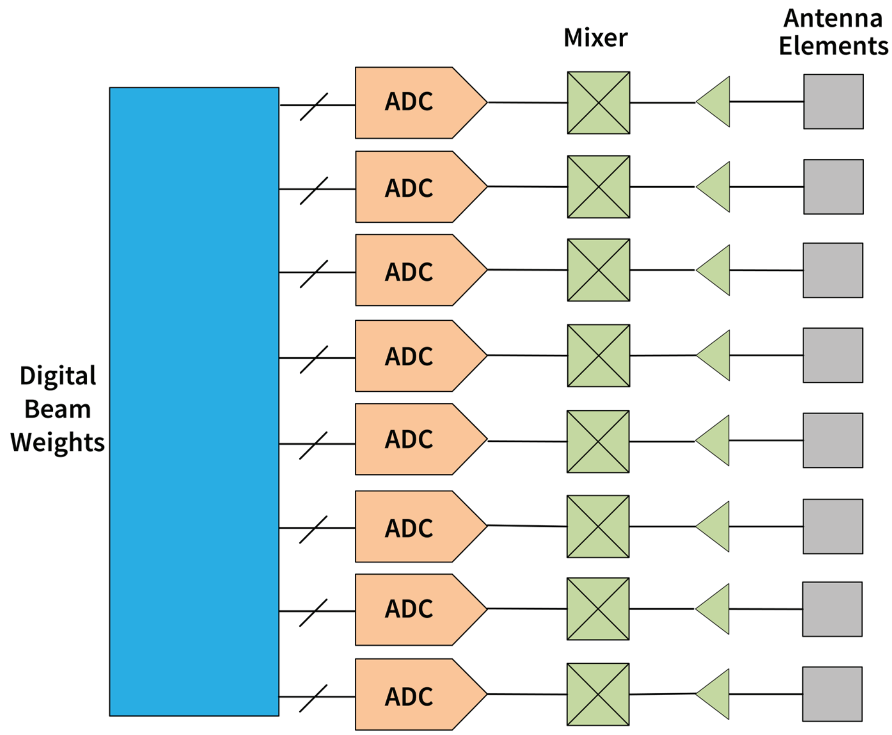


Figure 12: Digital Beamforming Block Diagram

Digital Beamforming Advantages	Disadvantages
Extreme flexibility with number of beams and nulls	Highest DC Power
Can provide high number of beams	I/Q signal routing complexity
Number of beams can be changed dynamically with no change in hardware	LO signal routing complexity
Each beam benefits from the full array gain	Highest hardware complexity - full RF chain per element in the array
	Hardware cannot fit the lattice at high frequencies

Table 3: Digital Beamforming Considerations

Hybrid Beamforming

Hybrid beamforming is a cross between analog and digital beamforming. The beam concept (Figure 13) involves the formation of analog (sub-array) beams from a portion of the full array. In Figure 14, the wide black beam represents the embedded element's gain, the red beam is the analog sub array beam, and the two blue beams are the digital beams. Only two digital beams are shown for simplicity but, in fact, many beams can be formed.

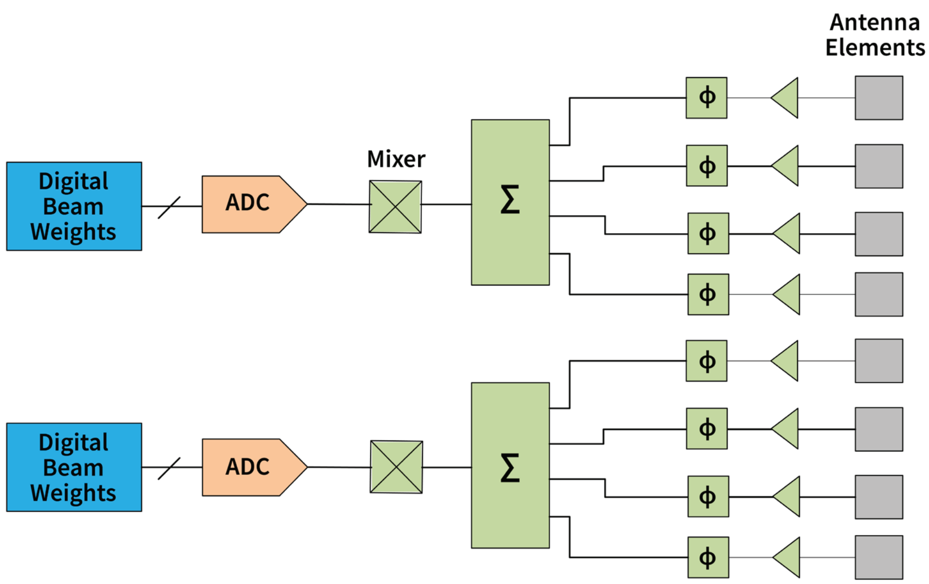


Figure 13: Receive Hybrid Beamforming Block Diagram

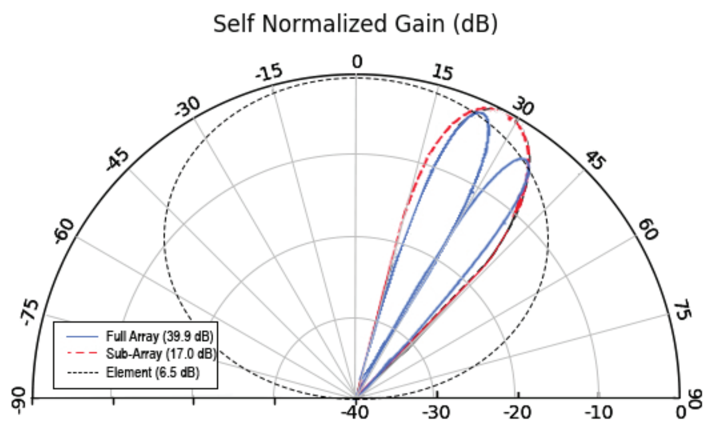


Figure 14: Hybrid Beamforming Beam Illustration

The full array is broken into sub-arrays, with an individually steerable analog beam assigned to each sub-array. Then, digital beamforming is used to form many beams within the analog beams. The beauty of this approach is that it can be used at mmWave frequencies, it provides the digital flexibility to dynamically form many beams and nulls with no change in hardware and it does not require a full RF chain per element, only a full RF chain per sub-array. With the many advantages that this approach offers, it is no wonder that this is the most popular beamforming approach used in emerging mmWave communications systems today.

Hybrid Beamforming Advantages	Disadvantages
Extreme flexibility with number of beams and nulls	Digital beams can only be formed within the analog beams
Can provide high number of beams	
Number of beams can be changed dynamically with no change in hardware	
Hardware can fit within the lattice at high frequencies	
No complex signal routing	
No LOs to distribute in the array	

Table 4: Hybrid Beamforming Considerations

Optimal mmWave Solutions

Qorvo offers the industry’s broadest portfolio of mmWave products and is dedicated to enabling OEMs stay one step ahead, using key innovations to provide critical market solutions.

Qorvo's goal is to enable radio manufacturers and antenna manufacturers to successfully build active antennas in a quick and cost-effective way at a mass scale by providing insights, knowledge, expertise and tools to our customers.

Scalability

Both SATCOM and 5G systems have very different use cased in each of their respective markets. SATCOM systems see varying EIRP (Effective Isotropic Radiated Power, an indication of transmit power) and G/T (Rx antenna gain/system noise temperature, a measure of the quality of the receiver) requirements, while 5G systems see varying use cases (small cell, GNodeB, consumer) that also drive EIRP.

Phased array antennas are naturally a good technical solution as they are inherently scalable in size with the right design implementation. This is achieved through scalable sub-array building blocks to design systems that can be easily sized based on the application requirements

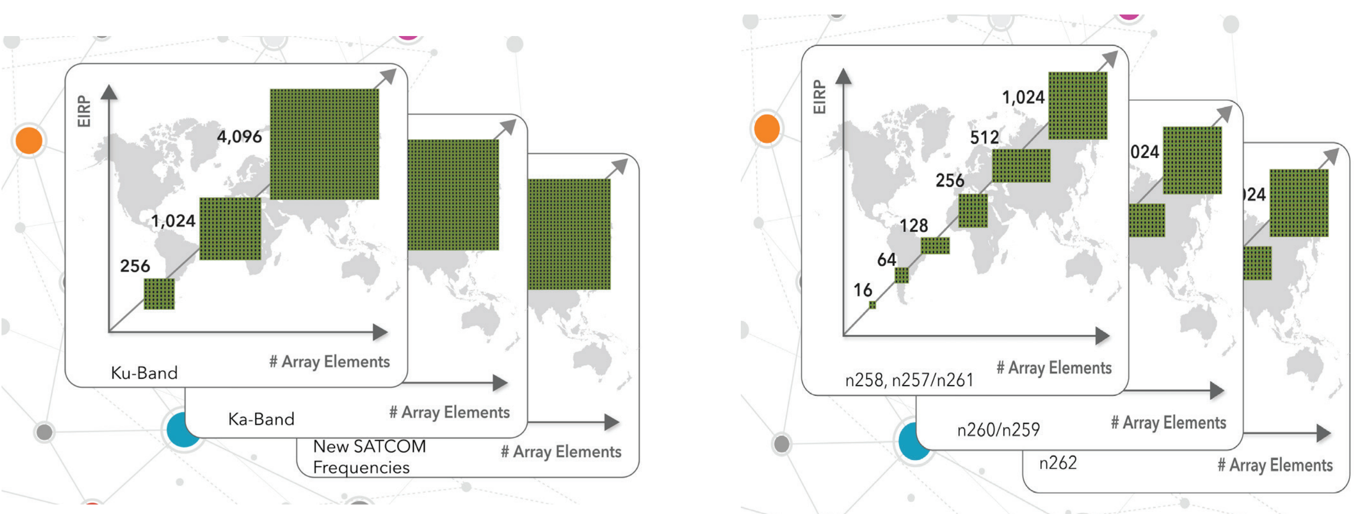


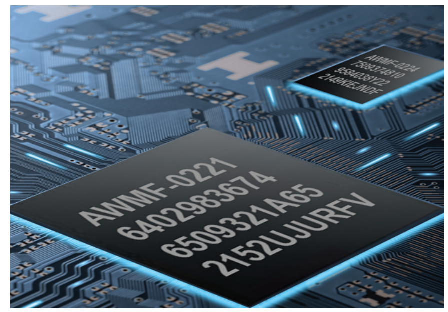
Figure 13: Qovo's quad architecture allows customers to rapidly design arrays in relation to any given use case within a scalable platform.

Performance

Qorvo's all silicon-based smart antenna solutions provide the lowest cost and highest performance to meet commercial market demand. These products, which have been optimized through multiple generations since their initial release, leverage state-of-the-art, unique architecture allowing manufacturers to build scalable arrays with EIRP ranging from 30 dBmi to 70 dBmi.

Some of the performance advantages we bring to the manufactures through our innovations include:

- Kinetic Green™: Lowers energy consumption through dynamic array control and fast attenuator control, turning off elements and rows to shape beams and reduce DC power - supporting the 5G industry's sustainability goals.
- ZERO-CAL®: (Patented): Enables each IC to self-align to prescribed performance levels while reducing the need for array calibration.
- Digital pre distortion (DPD): Improves system efficiency through a higher linear EIRP, lower DC power, minimized heat sink and other innovative methods.
- Ultra Fast Beam Steering (Patented): Enables the antenna to quickly change beam direction consistent with 5G timing protocol.
- Variable Maximum Linear Power (vMLP): Is the ability to flexibly adapt the amount of power in a system while avoiding interference for different requirements.
- Smart Arrays: Defined by the digital core included in the ICs that allows users to monitor IC performance in array operation and apply critical corrections real-time.
- Polarization Flexibility: In SATCOM antennas, the ability to generate and to control any polarization is imperative to support the varied system requirements.



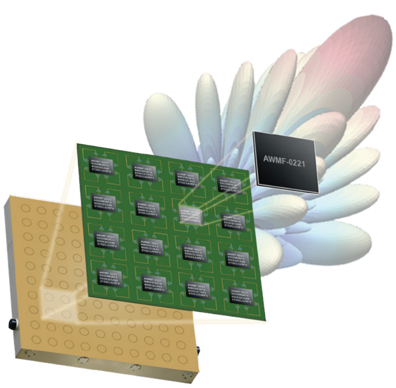
Over the 20+ years of delivering commercially deployed beamformer ICs, Anokiwave, now Qorvo, has the experience and understanding of nuances of commercially deployable mmWave phased array antennas, unlike any other company, and is proven by the unique features of the ICs that make our customers successful.

Cost

In multi element arrays, the cost of GaAs and GaN per mm^2 drives unaffordable solutions for high volume mmWave applications. Highly integrated silicon beamformer ICs provide a compatible size for easy integration within the array lattices at a cost that can be scaled to large volumes. Combined with new printed circuit board (PCB) material/ manufacturing capabilities, lower cost is achievable and more importantly mass production is possible. Newer architectures based on commercially viable multilayer PCBs with radiating elements on one side and surface mounted ICs on the other side have shown cost and performance viability because they are manufactured using existing technologies that are in place to build high volume commercial cell phone and WiFi access point products.

The underlying IC architecture enables a single IC to support dual polarization feeds of four antenna elements. With features such as a single low voltage supply with integrated logic control, these ICs are easily integrated into phased array antenna terminals. Fabricated on a commercial silicon process designed for volume production ensures the perfect combination of performance and low cost.

Over its history, Anokiwave, now Qorvo, has delivered millions of ICs with more than 95% cost reduction. The ICs meet various AESA antenna requirements with proven performance in commercially deployed SATCOM terminals and 5G systems.



Anokiwave, now Qorvo, invented the quad BFIC architecture, which allowed symmetric implementation of phased array antennas with high volume/ low-cost scalability, that are used in mmWave systems enabling a much lower cost point.

Conclusion

We have shown the key performance metrics for mmWave beamforming with active antennas.

To build and manufacture truly planar active antennas for mmWave systems, all of the required beamforming and beam steering electronics must be integrated in the plane of the antenna and fit between the radiating elements. This becomes increasingly difficult at mmWave frequencies due to the shrinking dimensions of the lattice, which is an inverse function of the wavelength. A single IC with all requisite beam forming functions for multiple elements is the most efficient way to achieve this functionality in a very small size.

Qorvo, today, has multiple generations of mmWave SATCOM, Defense and Aerospace and 5G products utilizing silicon ICs with a quad architecture, in volume production.

The ability to service multiple market segments enables us to bring innovations from each market and apply them to our products. This allows us to continuously leverage developments in all market segments and to bring those developments into newer market segments, repurposing them for newer applications.

Qorvo mmWave ICs enable phased array antennas with high-performance, cost-effective solutions for SATCOM user terminals, 5G networks and Defense and Aerospace systems that are available in high volume today.

Anokiwave Is Now Qorvo

About Anokiwave

In 2024, Anokiwave was acquired by Qorvo. Anokiwave's innovative portfolio of active antenna ICs, combined with Qorvo's complementary products, global scale, and significant market reach, provide new options for high integration and high-performance that will democratize phased array active antennas.

The two companies' technologies enable a unique combination of innovation + commercial scale + reputation to deliver with proven commercial success across mmWave 5G, SATCOM and D&A markets.

- mmW Silicon ICs
- Intelligent Array IC Solutions®
- mmW Algorithms to Antennas®

Endnotes

1 - Millimeter Wave Technology Market Set to Soar Past USD 29.85 Billion by 2030. SkyQuest latest global research. January 30, 2024

Article Link

2 - Phased Array Antenna Handbook, Second Edition by Robert J. Mailoux, Copyright 2005. ISBN:9781580536899 Artech House.