Benefits for Phased Array Systems Through Advancements in Surface Mount Components

By Doug Jorgesen

Mechanically steered antennas have given way to phased array architectures in many applications in the last fifty years. Phased arrays benefit applications in the densely populated signal environments that are common in the modern world. These capabilities require a vast increase in the channel count of the underlying RF system, placing pressure on the RF components to be perpetually smaller. In this paper we will discuss phased array architectures and then focus on how advances in technology have led to smaller RF and microwave components that retain exceptional performance specifications in surface mount packages.

PHASED ARRAY BACKGROUND

When multiple antennas radiating at the same frequency are placed close together, their radiation pattern will show peaks and nulls due to interference. By controlling the phase of the radiated signals, the radiation pattern can be controlled dynamically. This is the concept behind a phased array, which dates back at least 100 years [1].

Most phased arrays consist of a linear or triangular array of equally spaced, identical, fixed antennas. The phase between each element is controlled to create a radiation pattern that is focused into a main lobe (called a beam). In addition to the desired beam the radiation pattern will also have undesired radiation sidelobes.

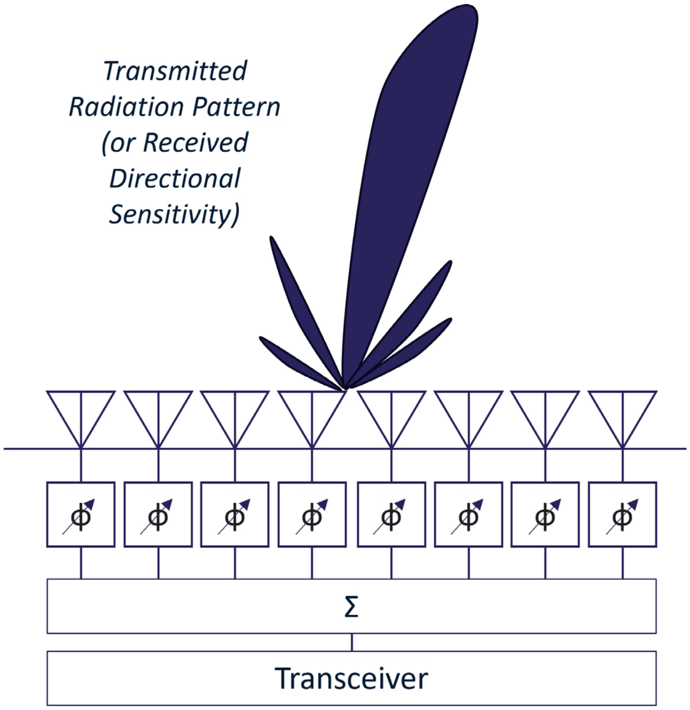


Fig. 1: Operation of a Phased Array Antenna

As long as the phase shift is passive, the structure is reciprocal. The transmitted radiation pattern will be the same as the sensitivity of the antenna to received signals.

The increase in the focus of transmission or reception is described by the antenna gain *G*, and to first order it increases linearly with increasing number of antenna elements *N*:

$$G \propto G_0 \cdot N$$

Further, when individual power amplifiers are used on each element of a transmitter the radiated power increases linearly with *N*, so the effective isotropic radiated power increases as N^2.

$$P_{effective} \propto P_0 \cdot N^2$$

Therefore, the combined system improvement per element is theoretically proportional to N^3 for a combined transmit/receive system with phased arrays on both sides [2].

PHASED ARRAYS VS. MECHANICAL STEERED ANTENNAS

The realistic comparison system for a phased array isn't a single radiating element, but a single parabolic dish antenna with high gain fed by a large transmitting amplifier and receiving with a single low noise amplifier. For the same aperture size, a single antenna has many advantages:

- Fewer Components
- No beamforming network losses
- The gain drops with phased array scanning, but not with mechanical scanning

There are, however, several important advantages to phased arrays that make them extremely common in many applications.

- **Electronic scanning**
  A phased array can be scanned quickly, and can jump discretely from one location to another, allowing applications like tracking multiple simultaneous objects in radars and servicing of multiple simultaneous users in communications
- **Flat or low profile form factor**
  - Critical for any airborne application to reduce drag and mechanical reliability
  - Critical for ground-based military vehicles, as large mechanically scanned antennas make the vehicle a target for enemy fire while phased arrays can be hidden.
- **Reliability**
  - Applications that need to track have significant reliability issues with the motor controllers, which are compounded in terrains that have high sand or dust content.
  - Phased arrays have graceful failure. Losing a small number of elements will not impact the overall array performance.
- **Multi-beam solutions**
  - Using specific implementations of phased arrays, it is possible to support multi beam solutions. This is required for MPAR (multifuncation phased array) for applications such as adaptive search and track solutions and support for multi-user SATCOM.

TYPES OF PHASED ARRAY SYSTEMS

A key consideration in designing a phased array is determining how the tasks of generating the transmit signal and processing the received signal are allocated among the electronic components associated with each radiating element. To better understand this, it's helpful to first examine the operation of a traditional rotating dish transceiver, such as those used in radar systems.

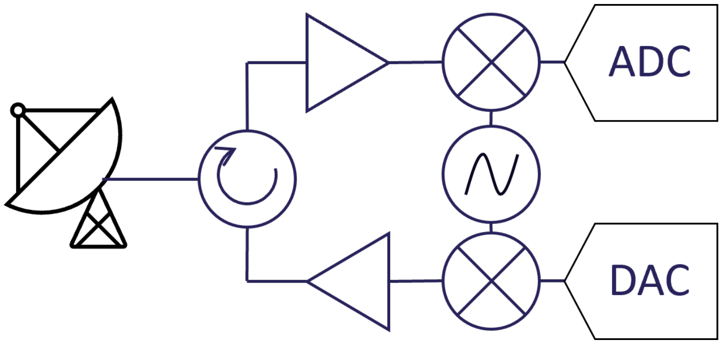


Fig. 2: Core Elements of a Traditional Transceiver

The core elements of the transmit system are a digital to analog converter to generate the transmit signal, an upconverting mixer, a power amplifier, and a duplexer to feed the antenna.

The core elements of the receive system are again the antenna duplexer, a low noise amplifier to boost the signal above the noise floor, a downconverting mixer, and an analog to digital converter to receive and process the signal.

In addition to these core components, additional components are added to improve the bandwidth and spur free dynamic range of this system and add additional protection. These components might include:

- Limiters to protect the LNA from the high power transmit signal
- Filters to reduce the received noise, transmitted harmonics, remove blockers and interferers, and eliminate spurious products created by the mixer or amplifiers
- Attenuators, equalizers, and additional amplification to set the signal level entering the ADC to maximize its dynamic range
- Couplers to monitor the transmitted or received power levels
- Baluns to convert the differential ADC or DAC signal to a single ended signal

As we’ll discuss later, miniaturization of these components is critical for high channel count receivers. Consider now a phased array implementation of the same system.

PASSIVE BEAMFORMING

The most straightforward way to move to a phased array implementation is to change only the antenna and leave the rest of the system intact. This requires a distribution manifold and a series of phase shifters, as well as radiating elements:

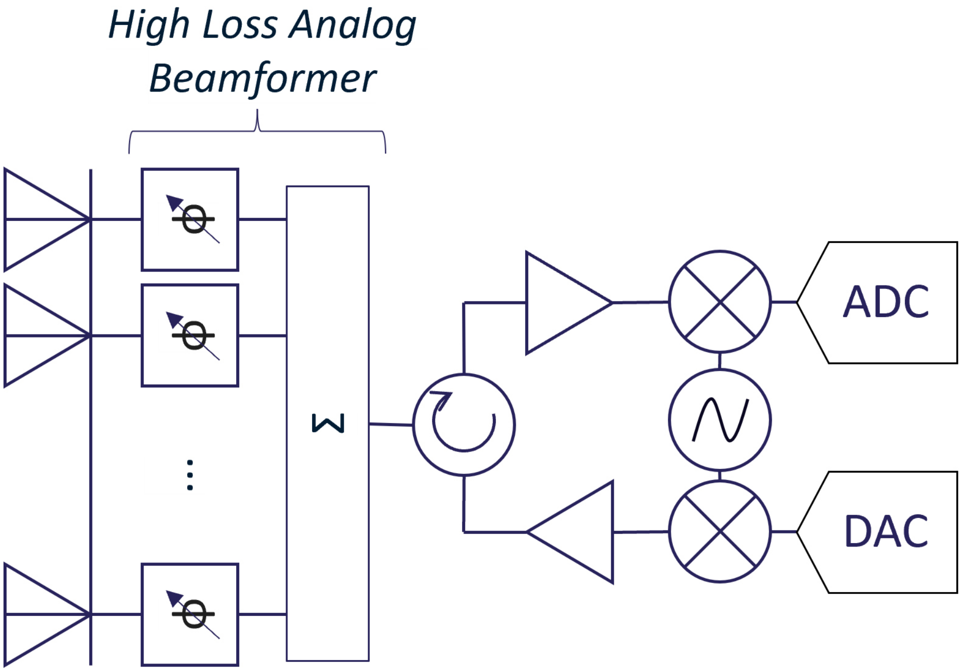


Fig. 3: Passive Beamforming Architecture (after [3])

With the addition of phase shifters, the beam can be steered as quickly as the phase shifters can tune. This is on the order of nanoseconds vs. several seconds for a mechanically steered antenna. This creates the ability to track multiple simultaneous targets nearly instantaneously.

In addition to phase shifters, individual tuning of the amplitude of each radiating element is frequently performed with variable attenuators at each port. By varying the power of each element (more in the middle, less on the outside) the undesired grating lobes of the antenna pattern can be reduced significantly. For the remainder of the paper, it is assumed that each element level phase shifter includes a fixed or variable attenuator to correct the amplitude to the desired level for the required antenna beam.

The major downside of this system is that there are significant excess losses (in addition to the splitting loss) in the beamforming network. While the centralized high-power amplifier can be a very high power tube amplifier, the sensitivity of the receiver is directly reduced by the excess loss of the manifold.

ACTIVE BEAMFORMING

To overcome these losses, we can (if we have the amplifier technology available) place a low noise amplifier on each element to improve the sensitivity. If also available (as it is with GaN technology) we can place a transmit amplifier on each element as well.

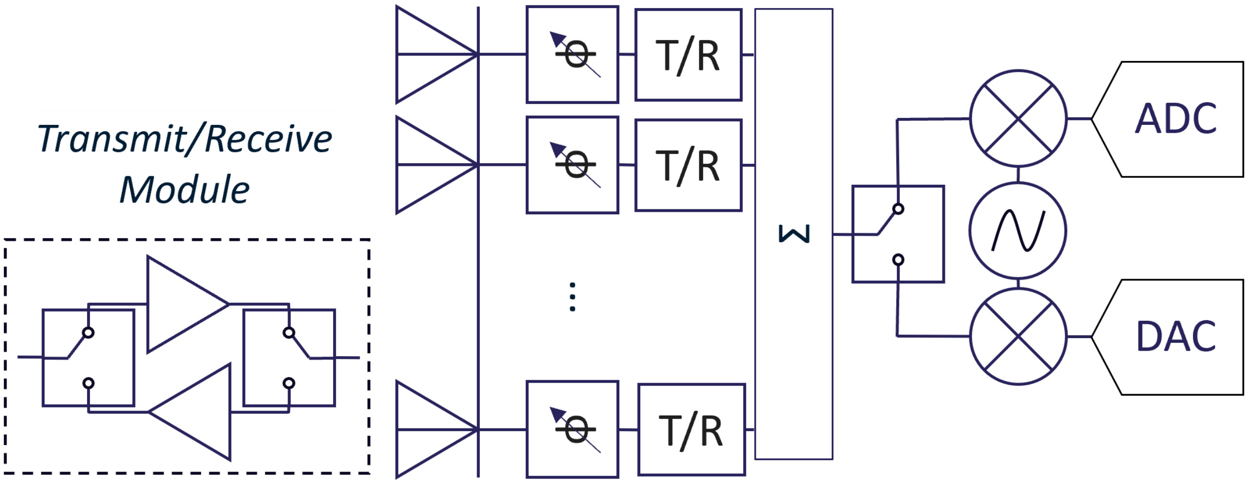


Fig. 4: Active Beamforming Architecture (after [3])

This is referred to as active beamforming, since there is an active amplifier on each element, as opposed to passive beamforming. Since the loss of the beamforming manifold directly degrades the sensitivity of the receiver, these manifolds were large, heavy, expensive waveguide components. Putting the LNA before the manifold significantly reduces the loss requirements on the manifold and a simple power splitting/ combining network can be used. The cost, in terms of going from a single RF front end to one RF front end per element, depends largely on the cost of the RF front end components, particularly the transmit power amplifier.

Sidenote: RF, IF, and LO Beamforming

Instead of applying the phase shift to the signal directly at the RF frequency, it is also possible to downconvert each element and apply a phase shift to the LO instead, with an amplitude shift at baseband. This is called *LO Beamforming*. The phase and amplitude shift can also be applied at baseband instead of at the RF frequency, which is called *IF Beamforming* [4].

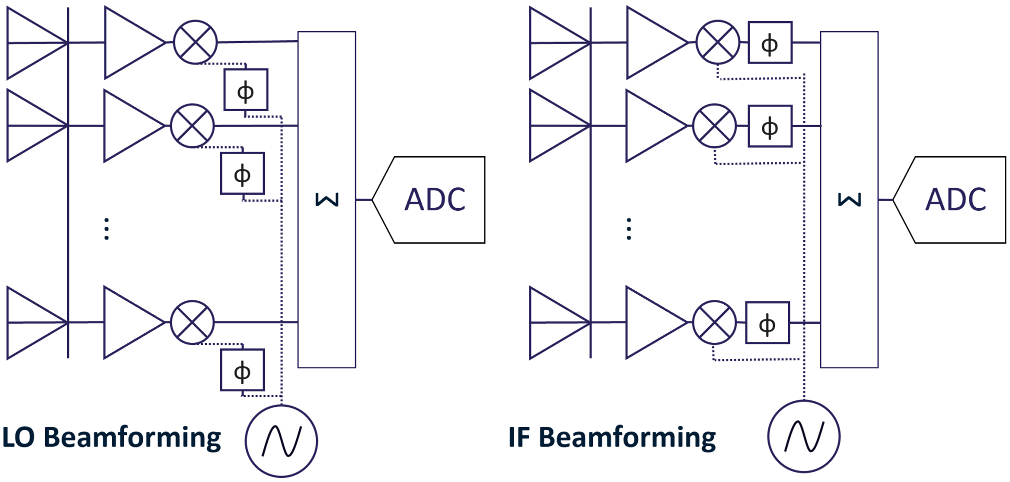


Fig. 5: IF and LO Beamforming Receiver Architectures (after [4])

RF beamforming has the best signal integrity of these options, since the beamforming occurs prior to the mixer. Additional interfering signals in the mixer create spurs that must be subsequently filtered. Therefore, RF beamforming is the most linear option.

DIGITAL BEAMFORMING

Active beamforming has one major drawback: it is very difficult to realize multiple simultaneous beams. Each beam pattern requires a different setting of the analog phase shifters and variable amplifier/attenuators. While the transmit function may be able to scan to different locations, this is a major limitation for the receive function. For applications like electronic warfare where determining the location of unknown incoming signals is the main function, this temporary blindness is unacceptable.

Resolving this issue requires processing the same incoming signals, but with different amplitude and phase weightings to resolve different beams. This is possible by using an ADC on each channel instead of a single ADC for the entire array. The same input signal to each ADC can be processed using different weightings in digital signal processing to resolve different locations. These calculations are performed simultaneously in a high-speed FPGA fed by the ADC output.

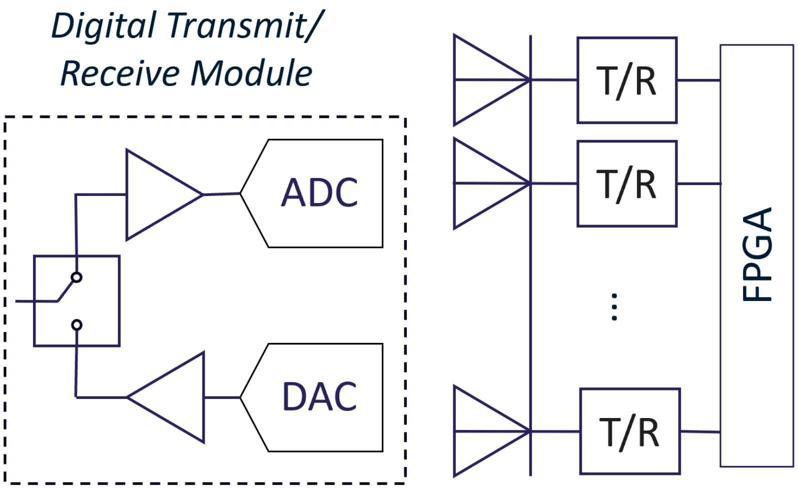


Fig. 6: Digital Beamforming Architecture (after [3])

By receiving the data directly into an ADC and applying the phase and amplitude weighting digitally it is possible to resolve multiple incoming array patterns. Instead of the limitations being in analog hardware, the limitations are now in the analog to digital conversion and digital signal processing. This amplitude and phase modulation can be performed at baseband after a conventional downconversion, but it will be subject to the limitations of IF beamforming mentioned above. It can be performed immediately after the antenna element if a sufficiently capable (high frequency and high resolution) ADC is within the power and cost budget of the system.

The advent of GHz frequency ADCs and DACs with 10+ bit resolution has made this capability a reality, although at the expense of significant power expenditure and cost. Requiring a high speed, high dynamic range ADC in front of every element in an array with hundreds or even thousands of elements is clearly cost prohibitive for many applications. Additionally, the power consumption of the FPGA network required to combine all of the high speed outputs from these elements contributes further cost and power consumption.

HYBRID BEAMFORMING

The most common implementation of phased arrays for many applications is a compromise between active beamforming and element level digital beamforming referred to as hybrid beamforming. In a hybrid system there are both digital beamforming elements as well as analog beamforming elements.

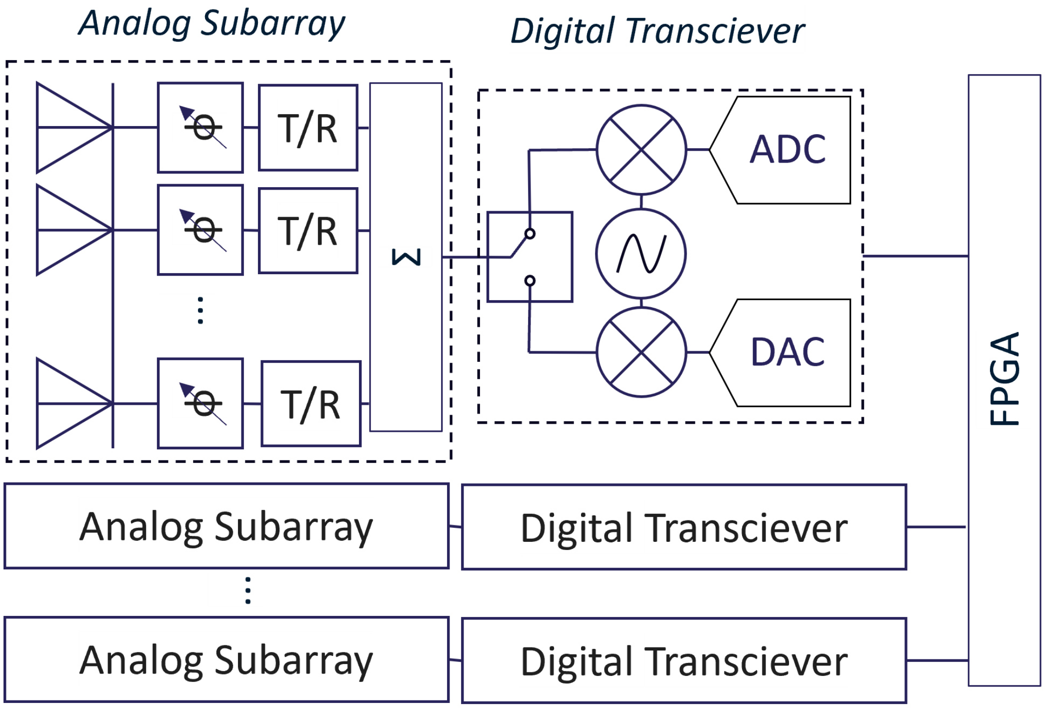


Fig. 7: Hybrid Beamforming Architecture (after [3])

In essence each analog subarray acts as a radiating element, and the digital beamformers process the data from these subarrays to detect signals from multiple different directions. The benefit of this is clearly that the cost and power consumption of the ADC and FPGA are reduced by the number of elements in each subarray. For example, a 32x32 element array (1024 total) may be divided into 8x8 elements subarrays (64 elements per subarray) for a total of 16 subarrays. Each element will require its own analog phase shifter and variable amplifier/attenuator. Only 16 DAC/ADCs are required instead of 1024, reducing the power consumption by 90%.

Again, the digital beamforming can be performed at either the RF or IF frequency, but the linearity of a subarray can after downconversion can be much better than the linearity of a single element since there is some rejection of interferers and jammers. This provides more flexibility and further cost and power reduction.

COMPONENT MINIATURIZATION AND PHASED ARRAYS

The capability and cost of both digital and analog electronic components used to realize a phased array system form a critical part of the engineering tradeoffs in designing a system. Another critical factor for phased array systems is the size of the components. The sidelobes that are created in addition to the main beam in a phased array are called ‘grating lobes’, and they limit the highest frequency (or minimum spacing) possible in an array. This is given by

$$D_{max} = \frac{c}{f_{high}(1+\sin\theta_{max})}$$

where D_{max} is the maximum antenna spacing, c is the speed of light, f_{high} is the maximum operating frequency, and θ_{max} is the maximum scan angle [5]. For a full scan angle of 90° this is the same as half the wavelength (in free space) at the highest operating frequency. For a 12-18, 6-18, or 2-18 GHz receiver then this is always the same 8mm array spacing.

Considering that standard component sizes range in the 3-6mm sq size range, this is too small to accommodate conventional discrete electronic components. There have been two primary solutions to this problem, one for high cost systems and one for high volume systems.

GAAS ASICS AND MULTI-CHIP MODULES

For ultra-high-performance systems (major radar and electronic warfare systems) which cost millions of dollars the solution has been to create application specific semiconductors in GaAs and multi-chip modules that can be tightly integrated. This technique has several limitations. Integration of multiple functions in GaAs leads to suboptimal component performance metrics as compromises must be made between the optimal process (HBT, power pHEMT, high frequency pHEMT, PIN diode, etc) to enable integration on a single die. These tradeoffs are eliminated in multi-chip modules, which allow a system designer to pick and choose individual components with the highest performance for their application.

The issue with multi-chip modules is the assembly cost. Bare die components are not environmentally robust, so they must be assembled into an environmentally protected package. The assembly process is intrinsically serial, using specialized equipment. It can be automated and companies that have the required processes can produce multi-chip modules in high volumes at reasonable costs, but the capabilities are not widely available. In contrast surface mount assembly is a low cost, parallel process that is widely available from many contract manufacturers. For this reason surface mount assembly is the preferred implementation for many modern RF and microwave systems in both high and low volume production.

SILICON AND SIGE BEAMFORMERS

The obvious choice for small size, small cost electronics is integration in silicon. Indeed, silicon beamforming products have proliferated in recent years (as of 2024), and many products are available from numerous companies. These chips integrate a power amplifier, LNA, phase shifter, variable amplifier, power splitting, sometimes up/downconversion, and other functions in a single chip. As with GaAs ASICs, however, integration leads to degradation of performance specifications. This is more pronounced in Silicon as the fundamental RF performance of Silicon is inferior to III-V compounds for most functions. Integration also leads to limited flexibility, so many systems that would benefit from a phased array implementation will be unable to utilize the Silicon chips due to operating frequency, bandwidth, or performance limitations. Development of a custom silicon beamformer requires many years and millions of dollars.

For applications where a Silicon chip is available and meets the performance requirements, it is the obvious choice. An additional III-V power amplifier and low noise amplifier are almost always preferred, and other discrete components are required to meet system level performance specifications. There is still a need to miniaturize the discrete components in the system *without* sacrificing the performance advantage provided by these components. Fortunately, component manufacturers continue to make advances in size reduction while maintaining electrical specifications.

THE CHIP SCALE PACKAGE FOR HIGH PERFORMANCE DISCRETE COMPONENTS

Industry standard QFN packages have provided significant size reductions from previous generations of microstrip carrier packages. Construction of a QFN consists of a monolithic microwave integrated circuit (MMIC) die wirebonded to transition pads to the bottom of the package. This wirebond – pad transition adds parasitic inductance, capacitance, and significant extra size to the package, especially for small die. Marki Microwave's chip scale package eliminates the need for these wirebonds and places the landing pads under the MMIC die, enabling significant size reductions.

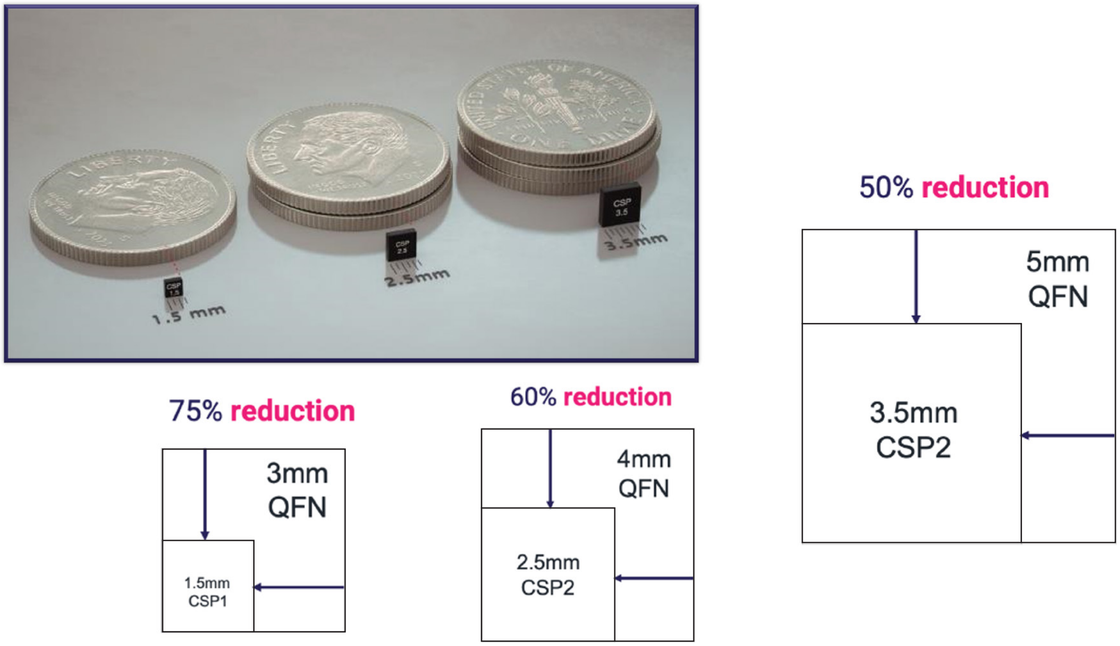
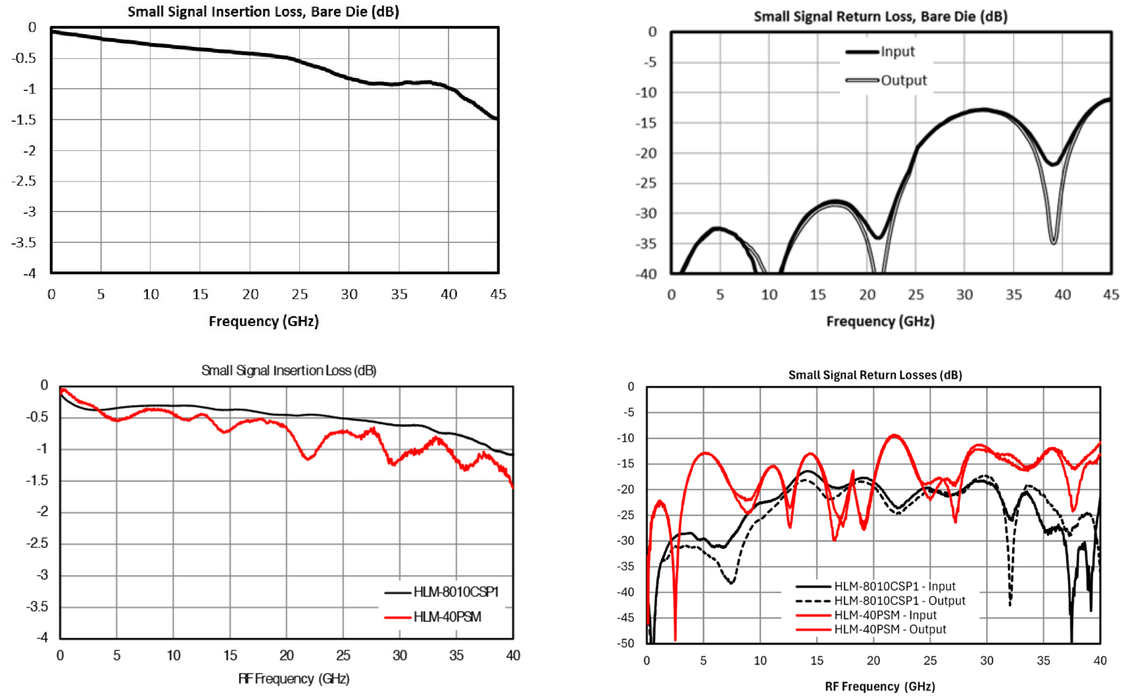


Fig. 8: Size Reduction of CSP vs. QFN Packages

While QFN packaging typically compromises the performance of the MMIC die inside (particularly for high frequency or low loss components), CSP components offer performance nearly identical to the comparable MMIC die.

CHIP SCALE PACKAGE PERFORMANCE

As an example, consider various limiter options available. A limiter is a component placed before the LNA in a receiver to protect it from the high power transmit signal. Insertion loss of a limiter directly degrades the sensitivity of the receiver. Poor return loss in a limiter will cause signal degradation due to reflections between the limiter and the antenna.


Small Signal Insertion Loss, Bare Die (dB)

Small Signal Return Loss, Bare Die (dB)

Small Signal Insertion Loss (dB)

Small Signal Return Losses (dB)

Fig. 9: Small signal performance of bare die, QFN, and CSP packaged limiters

The HLM-40CH bare die limiter has excellent performance to 40 GHz, with insertion loss below 1 dB and return loss below 12 dB. When placed into a QFN (as the HLM-40PSM) the parasitic capacitance and inductance cause reflections that appear as degraded return loss and insertion loss. When this limiter is modified into the CSP package (as the HLM-8010CSP1), the insertion loss and return loss return to the same or even superior performance compared to the bare die version. At 1.5mm sq the HLM-8010CSP1 is 7x smaller than the HLM-40PSM, which is critical in an 8mm grid spacing. The CSP package brings bare die performance and size to customers and projects that require surface mount packaging.

COMPONENT PERFORMANCE PARAMETERS AND ARRAY ARCHITECTURE

We have shown now that the CSP package reduces the footprint of high performance electronic components enough that they can be used within the spacing of a microwave phased array system. To understand how this capability can be used we need to consider various system level architectures. In doing so we will understand the importance of various component performance parameters and their impact on system level performance.

For simplicity we will only consider broadband receivers. In the following architectures it is assumed that each receiver is a hybrid beamforming network where each block of 8 antenna elements would actually represent an analog subarray that would be combined with other subarrays using digital beamforming to create a receiver that can simultaneously receive signals from multiple different directions with beamsteering and adaptive nulling.

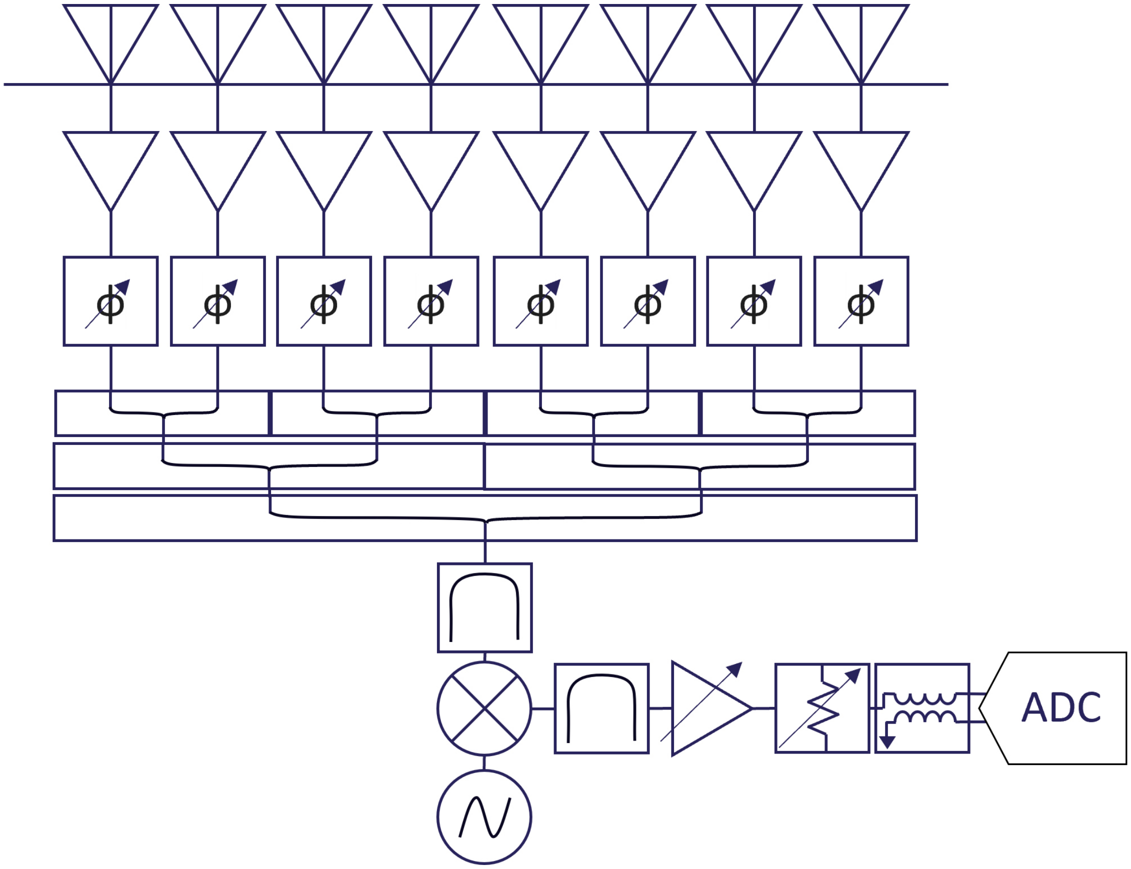


Fig. 10: Maximum Sensitivity Receiver Architecture

In the first architecture each receiving antenna element feeds directly into a low noise amplifier to set the noise figure and maximize the sensitivity. A variable phase shifter and attenuator tuned to the desired beamshape follow the LNA. Three sections of power combiners and a filter precede a mixer which downconverts the signal. The IF the signal is filtered to remove spurs and amplitude conditioned with a variable amplifier and attenuator to compensate losses and maximize the dynamic range before passing through a balun into the ADC.

Benefits:

- Putting the LNA first means no loss contributes to the noise figure, so very low level signals can be detected
- Since the LNA sets the noise figure, the losses of the phase shifter, power combining network, and filter are not critical specs as long as the gain of the LNA is sufficient

Drawbacks:

- No protection for the LNA, so nearby transmitters can permanently damage the LNA
- The spatial discrimination of the phased array does not occur until after the LNA, so interfering signals

from undesired directions can saturate the LNA and create two tone intermodulation that will obscure the desired signal.

- Other than the antenna frequency response, no frequency filtering occurs before the LNA. Signals at undesired frequencies can also damage, saturate, or cause intermodulation in the LNA.

This architecture trades everything for sensitivity. It is best for narrowband applications where low signal levels are expected, such as communications links in sparsely populated areas. The burden for electrical performance specifications is placed squarely on the LNA, which must be both highly linear and robust to damage from interfering signals. While these LNAs may be available, the power consumption, heat management, and cost of putting such an LNA on each antenna element may be prohibitive for many systems.

The electrical performance specifications for the remaining components are relieved, but the requirements for size remain. All the electronics must fit into the spacing of the antenna array. This is particularly challenging for the power combiners, since N-1 are required for an N element array.

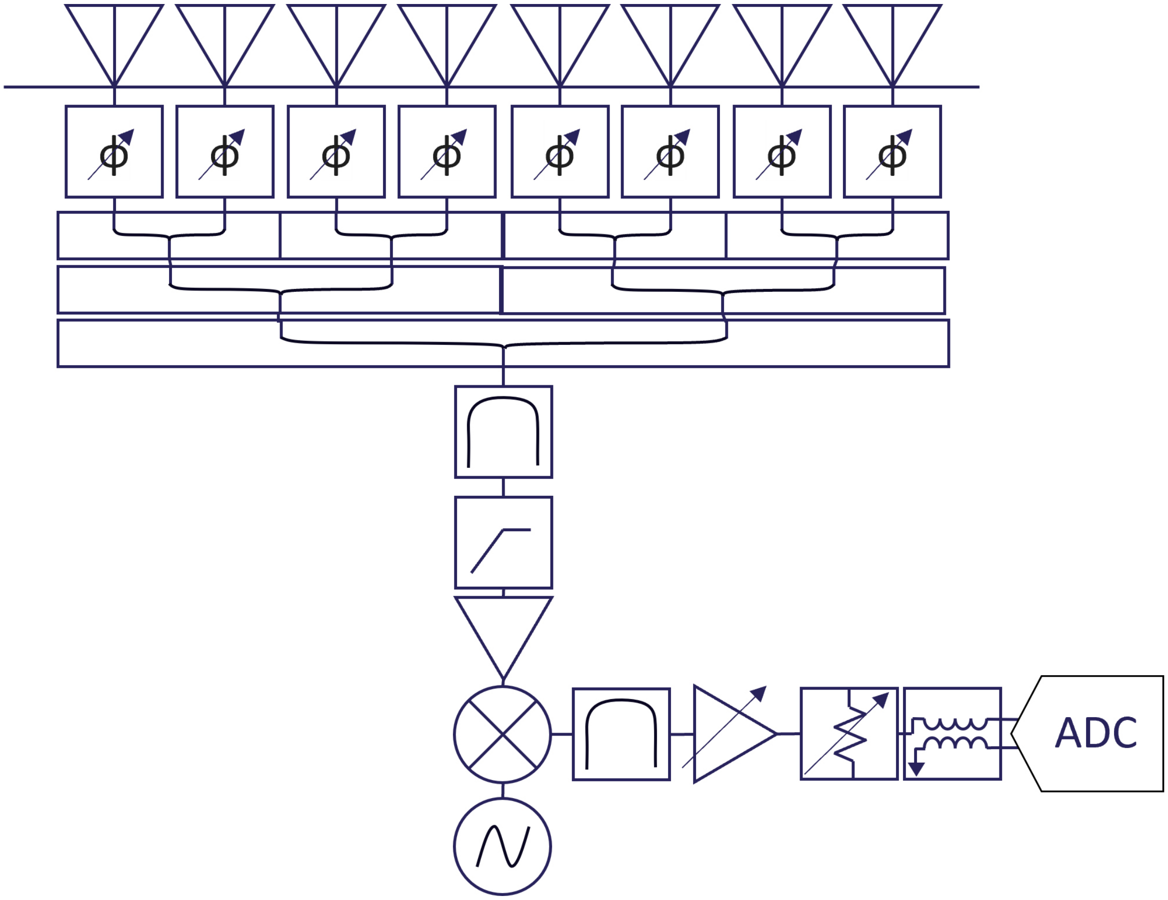


Fig. 11: Maximum Linearity Receiver Architecture

In this architecture undesirable jamming and interfering tones are eliminated in several ways before the low noise amplifier. The phase and amplitude shifters and power combining network provide gain to the desired spatial direction and null undesired jamming locations, a filter removes undesired frequencies, and a limiter protects the LNA from destructive level jammers.

Benefits:

- Signals from undesired directions are fully suppressed prior to the LNA.
- Signals at undesired frequencies are filtered prior to the LNA, reducing distortion and risk of damage from these interferers
- The LNA is protected from damage by a limiter

Drawbacks:

- The loss of all elements preceding the LNA (phase/amplitude shifter, power combining network, filter, and limiter) contributes directly to the noise figure of the receiver, degrading the sensitivity.

This architecture trades everything for linearity. It is best for wideband systems operating in dense signal environments, such as electronic warfare and communication in crowded environments. The burden for component performance is placed on the phase/amplitude shifter, power combiners, filter, and limiter.

Real systems are unlikely to follow either the maximum sensitivity or maximum linearity scenarios but make individual tradeoffs depending on the required system level specifications for sensitivity, immunity to jamming signals from undesired directions or frequencies, and protection from high power transmitters. These tradeoffs will depend on the performance parameters available for small form factor components, which we will consider now on an individual component basis.

Power Combiners – Desired signals will be in-phase when they meet in the power combiners, so they will only be subject to the *excess insertion loss* of the combiner. This is what will contribute to the noise figure of the receiver, so it should be as low as possible. Undesired signals will be terminated by the *isolation* of the power combiners, so this should be as high as possible. Both desired and undesired signals will reflect from each level of the power combining network, so *return loss* must be excellent or the signal will be distorted by reflections. Again, the size of each combiner must be small enough to fit into the antenna grid spacing. Marki Microwave offers a full line of high performance CSP power splitter/combiners in both 2- and 4-way combinations from 400 MHz to 50 GHz.

Filters – Filter requirements vary widely by application. For a communications link this is likely to be a relatively narrowband filter that requires sharp rejection, low loss, and good return loss again to prevent degradation in sensitivity and signal distortion. For a wideband electronic warfare system this may be a switched filter bank, a tunable filter, or some other adaptive filter. Loss and return loss remain important components. Size is particularly critical for filters, as conventional filter technologies (such as laminate or thin film) are prohibitively large for use within phased array antenna spacing. Marki Microwave offers a full line of MMIC CSP bandpass, lowpass, and highpass filters with sizes as small as 1.5 x 1.5 mm and frequency coverage to 70 GHz. Additionally custom filter designs are available with short lead times.

Limiters – The flat leakage of the limiter must be below the damage threshold of the LNA, the power handling sufficient to handle the combined effect of the power combined array input, and the linearity sufficiently higher than the LNA so as not to degrade the system linearity. As with previous components loss and return loss must be excellent to prevent sensitivity degradation and signal distortion. Marki Microwave offers CSP limiters with sizes as small as 1.5 x 1.5 mm, various flat leakage and power handling values, instantaneous recovery time, and no spike leakage. These small, lower power limiters are ideal for phased array applications where transmit power levels are lower than in traditional systems with very high power traveling wave tube amplifiers.

CHALLENGES OF MULTI-CHANNEL DAC/ADC CHIPS

In addition to the stringent size requirements imposed by the phased array antenna spacing, modern RF and microwave systems use multi-channel ADC/DACs that feed directly to FPGAs to perform the complex calculations required for digital beamforming and other digital signal processing such as digital downconversion and filtering. These chips may have 16 or more microwave channels in a ball grid array package with a pin-to-pin pitch of less than 1mm. This means that the size of each analog signal processing component must be narrower than 3mm to fit all components in a linear array in front of the ADC. Size is a constant concern in high channel count systems regardless of the implementation of the antenna.

CONCLUSION

Phased array technology is a useful tool for many applications. How it is implemented depends on the desired tradeoffs in terms of size, power, cost, and system performance goals such as sensitivity to blockers, ability to detect low power signals, and antenna scanning range. Advancements in surface mount technology from Marki Microwave (such as the chip scale package) enable system designers the flexibility to maintain high performance signal receivers while adding the advanced capabilities of high element count, high channel count arrays.

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