Maximizing Performance in Phased Arrays with Time Delay Solutions

February 6, 2025
In our previous blog post on True Time Delay Units called **Part 1: True Time Delay: What It Is and How It Works**, we explored how true time delay works in an AESA system and some methods to achieving time delay like MMICs, microstrip and strip-line. The most common way being MMICs due to their compact size and cost-effectiveness.

In modern communication, radar, and phased array systems, time delay units (TDUs) are a fundamental component for achieving precise signal transmission and reception. These units ensure the synchronization of signals across multiple antenna elements, which is crucial in optimizing performance metrics such as beamforming, directivity, and range resolution. In this article, we will explore the role of time delay units in phased array systems, how they relate to antenna performance, and how different design considerations impact system efficiency. The discussion will delve into the integration of TDUs with phase shifters, true time delay techniques, and the relationship between beamwidth, scanning angle, and array size.

Phased Array Systems and Time Delay Units

Phased array systems are widely used in applications requiring directional signal transmission and reception, such as radar, communication systems, and satellite tracking. A typical phased array is constructed using unit tiles, each containing several antenna elements and associated electronics, such as beamforming integrated circuits (BFICs) and RF front-end modules. These tiles are often arranged in configurations like 2x2 square matrices to scale the overall array size and performance as needed, as shown in Figure 1 below.

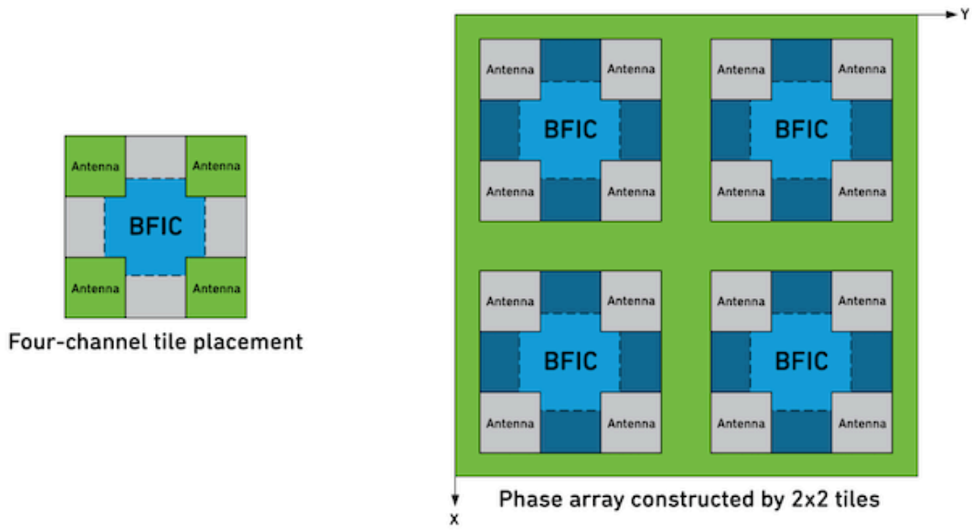


Figure 1: Phase arrays constructed in 2x2 tiles.

The key to effective phased array operation is the ability to control the relative timing of signals received or transmitted by each antenna element. This is where TDUs come into play. They introduce a controlled delay in the signal path to ensure the correct timing of signals across the array, facilitating coherent beamforming and improved signal directionality. Let's first explore the main figures of merit with phased array systems.

Figures of Merit of Phased Arrays: EIRP and G/T

In phased array systems, two key performance metrics are Equivalent Isotropically Radiated Power (EIRP), which measures transmitter power, and Gain-to-Temperature Ratio (G/T), which assesses receiver sensitivity. EIRP measures the effective power radiated by the antenna array in a specific direction, which is critical for achieving a sufficient signal-to-noise ratio (SNR) in the transmission process. G/T, on the other hand, is a measure of the array's sensitivity and is particularly important in the receiving process. Below are the mathematical formulas used to calculate these performance metrics.

$EIRP = P_T - L_C + G_a$

EIRP = output power of a signal when it is concentrated into a smaller area by the antenna

- P_T = output power of the transmitter (dBm)
- L_C = cable loss (dB)
- G_a = antenna gain (dBi)

Antenna G/T (dB/K) = antenna gain (dBi) – [10 log (system noise temperature in Kelvin)]

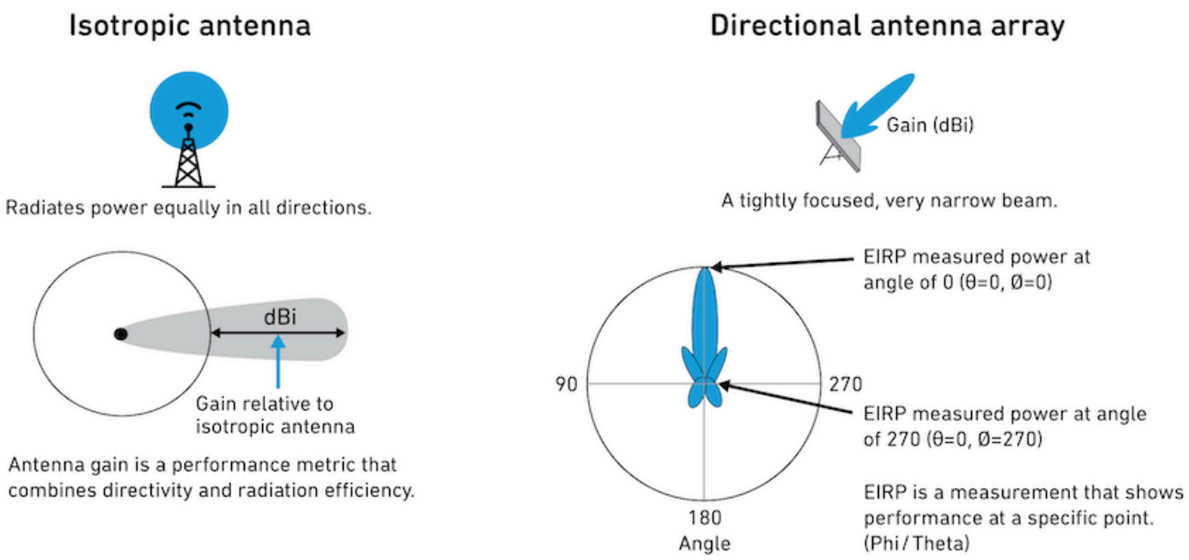
Antenna gain (dBi) = 10 log (I_x/I_z)

- I_x: electromagnetic intensity of the directional antenna
- I_z: electromagnetic intensity of the isotropic antenna

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Decibels relative to isotropic (dBi) is a unit of measurement that describes how much power an antenna transmits in a single direction when compared to an isotropic radiator, which transmits in all directions at once. The difference between the two is called antenna gain, which is represented as a numerical value in dBi.



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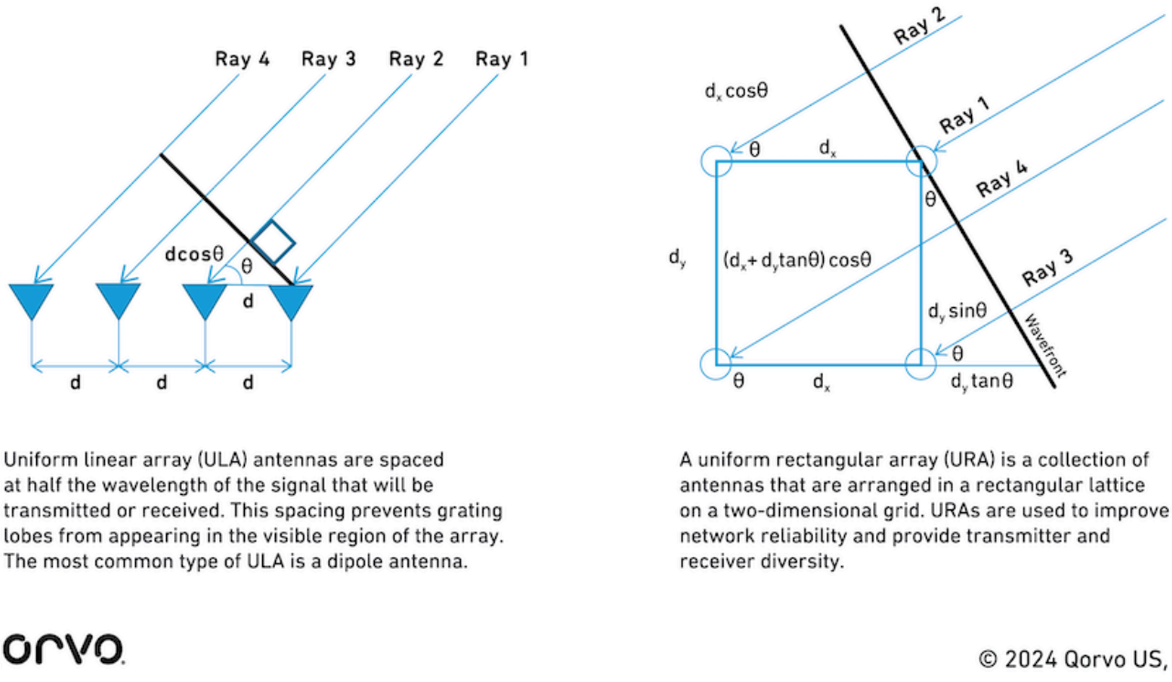
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Figure 2: Isotropic antenna and directional antenna array.

Both EIRP and G/T are directly related to the array's radiated power and gain, which in turn depend on amplifier performance, antenna design, and beamforming techniques. The antenna array and beamforming improve the system's directivity, but as directivity increases, the beamwidth narrows, which introduces challenges for maintaining sufficient instantaneous bandwidth. This is where engineers must carefully evaluate system-level trade-offs to optimize their design.

Beamforming and Array Design Trade-offs

Antenna arrays are typically designed using a Uniform Linear Array (ULA) or a Uniform Rectangular Array (URA) configuration, where the antenna elements are evenly spaced along one or two axes, respectively. Beamforming improves the directionality of the array by focusing the transmitted or received signals in a specific direction, referred to as the Direction of Arrival (DOA).



Uniform linear array (ULA) antennas are spaced at half the wavelength of the signal that will be transmitted or received. This spacing prevents grating lobes from appearing in the visible region of the array. The most common type of ULA is a dipole antenna.

A uniform rectangular array (URA) is a collection of antennas that are arranged in a rectangular lattice on a two-dimensional grid. URAs are used to improve network reliability and provide transmitter and receiver diversity.

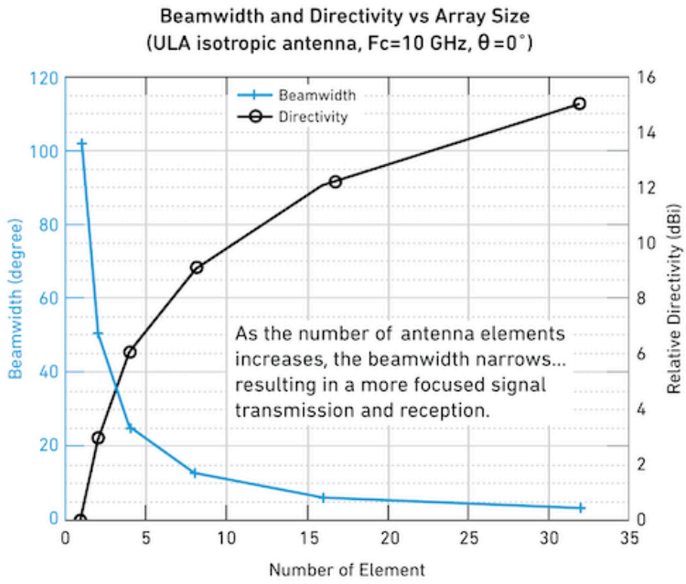
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Figure 3: Comparison between uniform linear and uniform rectangular arrays.

One of the main design trade-offs in phased array systems is between beamwidth and directivity. The array size and the number of antenna elements play a key role in this trade-off. As the number of elements increases, the beamwidth becomes narrower, improving directivity and gain. However, a narrow beamwidth can limit the array's ability to capture signals across a broad range of directions without significantly reducing the system's instantaneous bandwidth.

The minimum beamwidth of an antenna array must ensure that the instantaneous bandwidth is greater than the desired signal bandwidth to maintain signal integrity and performance. The beamwidth of the antenna array is influenced by both the array size and the maximum scanning angle. As the size of the array increases, particularly as the number of antenna elements doubles, the beamwidth narrows, resulting in more focused signal transmission and reception. This increased focus enhances the array's directivity, with the directivity approximately doubling or increasing by 3 dB, as illustrated in Figure 4. This relationship is crucial for achieving optimal performance in phased array systems, where beam shaping and signal directionality are essential.



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Figure 4: Graph showing beamwidth vs. elements vs. relative directivity.

Instantaneous Bandwidth and Beamwidth

The instantaneous bandwidth of an antenna array must be larger than the desired signal bandwidth to ensure that the array can accommodate the entire signal without significant degradation. For example, in a radar system, the pulse width (Td) determines the desired signal bandwidth (Bs), with shorter pulse widths providing better range resolution but reducing the maximum detection range. Therefore, a shorter pulse width improves range resolution, allowing targets that are close to each other to be more easily and accurately distinguished.

The array beamwidth is related to the number of elements in the array (N) and the scanning angle (θs). For a ULA operating at a maximum frequency of 10 GHz and a signal bandwidth of 1.5 GHz, the array can support up to 16 elements with a maximum scanning angle of 60 degrees without significant signal degradation. The array's beamwidth can be further calculated as a function of wavelength (λ), array size, and scanning angle.

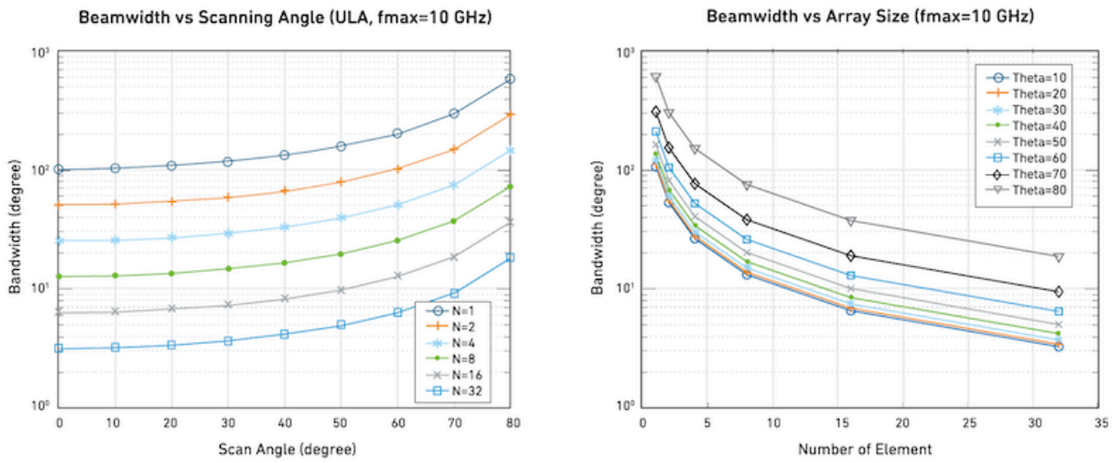
$$\frac{1}{T_d} = B_s = \frac{c}{Ndsin\theta_s}$$

For example, in a ULA with a maximum frequency at 10 GHz, Bs = 1.5 GHz, the maximum scanning angle (θs, max) = 60˚ - this antenna can have up to 16 array elements without significant signal degradation.

Also, the array's beamwidth can be defined by

$$\theta_B = 0.886 \frac{\lambda}{Ndcos\theta_s}$$

Using these above equations. We can define the relationship between the beamwidth of different array sizes and scanning angles as shown in the figures below.



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Figure 5: Beamwidth with varying array sizes and scanning angles.

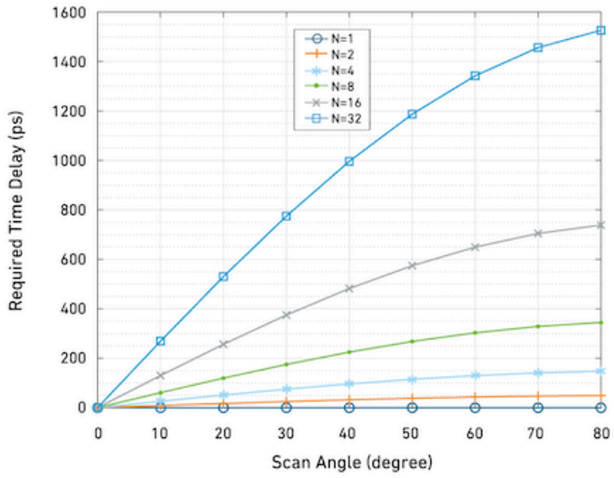
Now we have the data to determine the required bandwidth, array size and maximum scanning angle to meet our systems' requirements.

Determining True Time Delay in a ULA System

In beamforming systems, both phase shifters and time delay units are used to control the signal path across the array elements. Phase shifters alter the phase of the signal to steer the beam in a particular direction, while time delay units introduce an actual delay in the signal, enabling more precise control, particularly over wide bandwidths.

The minimum beamwidth of the antenna array must have an instantaneous bandwidth larger than the desired signal bandwidth. This requirement becomes critical as the array size increases and the scanning angle widens. The use of TDUs, which introduce actual time delays rather than phase shifts, allows for more accurate beam steering, especially for wideband signals.

Using the graph in the below Figure 6, we can determine the time delay required for a ULA system.



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Figure 6: Beamwidth with varying array sizes and scanning angles.

The last significant bit (LSB) of a typical 6-bit phase shifter is 5.625°. Approximately τ min = 75ps (picoseconds) LSB time delay would be required to replace a 5.625 LSB phase shifter for a 10GHz ULA. As per the above Figure 6 and the equation below, for 16 elements of a ULA with a 60° maximum scanning angle a total time delay or 650ps would be required. Multiple TDUs can also be cascaded to achieve the necessary delay for larger arrays or wider scanning angles.

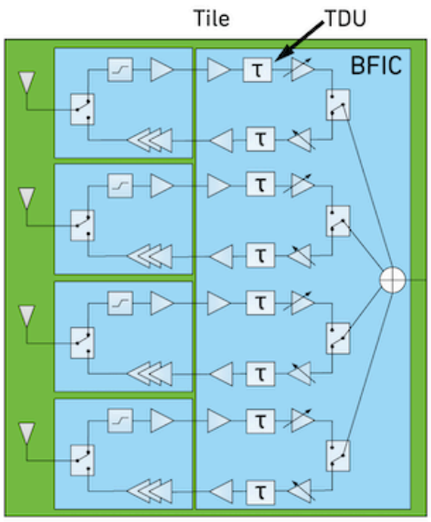
$$\tau_{max} = \frac{(N-1)dsin(\theta_s)}{c}$$

Types of Time Delay Units in Beamformer IC Configurations

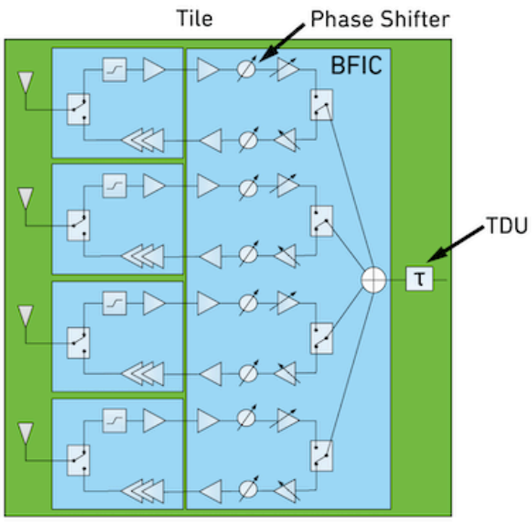
AESA antennas can steer signal beams using either phase shifters or TDUs, each with distinct trade-offs. TDUs are preferable for systems with larger instantaneous bandwidths, as they prevent beam distortion (squinting) by maintaining a constant phase slope across the frequency range. In contrast, phase shifters maintain a constant phase but may result in different beam steering angles for different frequencies, making them better suited for systems with narrower bandwidths.

Phase shifters approximate time delay and steer the beam optimally at the center frequency but can cause understeering at higher frequencies and oversteering at lower ones. While phase shifters are more cost-effective and widely implemented, they may introduce squinting in wideband applications.

Some architectures incorporate both TDUs and phase shifters to mitigate this issue, combining their strengths, as shown in Figure 7 on the right. Engineers must consider system requirements, such as array size and bandwidth, when deciding between these approaches. In some cases, a hybrid solution with phase shifters at the elements and TDUs behind a subset of elements may be sufficient, while larger arrays or wide bandwidth applications might require TDUs at every antenna element.



Time delay unit in each transmit and receive path in the unit tile.



Hybrid method to utilize both phase shifter and time delay unit in the unit tile.

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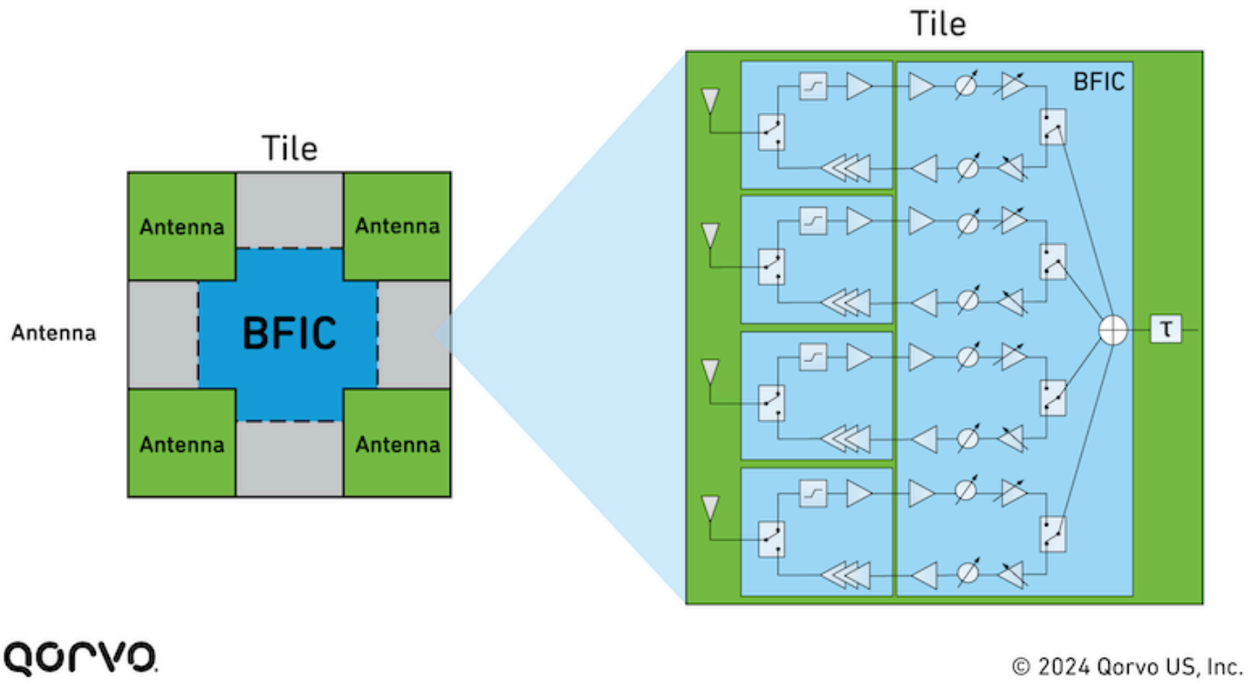


Figure 7: Four channel AESA tile.

Time Delay Unit Topologies

There are various methods to implement time delay units, including switched delay lines, transmission lines and inductance (L) and capacitance (C) components. The designer will consider all tradeoffs and pick the best topology to meet the design requirements. The choice of topology depends on the specific requirements of the system, including the required range of delays, precision, and the physical size of the array.

$$\tau = n\sqrt{LC}$$

TDUs are built with multiple stages, represented by bits, which control the time delay. Switch-based TDU designs offer lower noise and loss but require larger die sizes, sometimes up to three times bigger than Artificial Transmission Line (ATL) designs. However, ATL designs tend to introduce more noise and loss due to their artificial construction.

In radar applications, scanning angles play a critical role in determining whether the system is optimized for detecting near or distant objects, depending on the application's needs. TDUs are used to adjust pulse width and thus influence detection range. For example, a 2ps (picoseconds) time delay accommodates shorter pulse widths, making it suitable for detecting closer objects, while a 4ps time delay works with longer pulses, allowing for the detection of farther objects. The below table shows how each bit represents a delay time in picoseconds in fine and coarse mode. Each application will require a specific time delay, for example, in the fine mode, TDU offers 2ps min time delay and 254ps maximum time delay. In the coarse mode, TDU can offer up to 508ps maximum time delay.

TDU Bit	Time Delay (ps) Fine Mode	Time Delay (ps) Coarse Mode
1	2	4
2	4	8
3	8	16
4	16	32
5	32	64
6	64	128
7	128	256

ps = picoseconds

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Table 1: Bits versus time delay (fine vs coarse mode).

Conclusion

Time delay units are essential components in modern phased array systems, providing the precise control needed for accurate beamforming and improved system performance. Whether used in isolation or in combination with phase shifters, TDUs play a critical role in achieving the desired beamwidth, directivity, and signal bandwidth in applications such as radar, communication systems, and satellite tracking.

The design and implementation of time delay units involve several trade-offs, including array size, scanning angle, and bandwidth. By carefully selecting the appropriate TDU topology and configuration, system designers can optimize performance while meeting the demands of increasingly complex wideband applications.

About the Authors

Our authors bring a wealth of technical expertise in developing and optimizing radar solutions for advanced technologies. With a deep understanding of customer needs and industry trends, they collaborate closely with our design teams to drive innovation and deliver cutting-edge solutions that support industry-leading products.

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