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Research Article

Pulse Dispersion in Phased Arrays

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Phased array antennas cause pulse dispersion when receiving or transmitting wideband signals, because phase shifting the signals does not align the pulse envelopes from the elements. This paper presents two forms of pulse dispersion that occur in a phased array antenna. The first results from the separation distance between the transmit and receive antennas and impacts the definition of far field in the time domain. The second is a function of beam scanning and array size. Time delay units placed at the element and/or subarrays limit the pulse dispersion.

1. Introduction

The demand for high data rates in wireless systems has pushed the technology for wideband communications systems. Figure 1 shows a plot of the bandwidth and data rates associated with the digital wireless standards over time [1]. Up to today, the signals of interest were relatively narrowband, but future systems must process signals with very wide instantaneous bandwidths. These large bandwidths equate to high data rates that significantly impact the design of phased array antennas.

There are usually two definitions for a wideband phased array antenna [2–4]. The first and most widely used is the operational bandwidth. In other words, the array components are wideband, but the array only processes narrowband (low data rate) signals that lie within a wide frequency range. The second definition is based on the signal bandwidth. In this definition, the bandwidth is a function of the array size and beam scan angle [5]

$$\text{BW}\ (\%) < \frac{\lambda}{Nd\sin\theta_s}, \tag{1}$$

where N is the number of elements, d the element spacing, λ the wavelength, and θ_s the scan angle. Large phased arrays with wide scan angles have very narrow bandwidths.

Phased array bandwidth limits are based on two related factors [6]. First, a phased array scans the main beam using a linear phase shift across the aperture that is calculated at the center frequency. Frequencies above and below the center frequency cause the main beams to squint toward or away from broadside, respectively. The array bandwidth is defined by a maximum beam squint bounded by the 3 dB beamwidth of the center frequency main beam as defined in (1). An alternative factor that can be used to define array bandwidth is pulse dispersion or a widening in the pulse width. For the purposes of this paper, we assume that a pulse represents one bit. In this definition, the signal pulse width must be greater than the length of the array which is traditionally defined as aperture fill time [7]. This assumption also leads to the definition in (1).

This paper starts with an overview of pulse dispersion that occurs in a phased array antenna. Pulse dispersion has long been a problem in optical fibers, but until recently, phased array designers rarely worried about wideband signals, unless the array was very large with a large field of view. In Section 3, we explain two causes of pulse dispersion in a phased array. The first occurs in the near field and impacts antenna measurements. The second results from the aperture size and the scan angle. The next section outlines the need for time delay units in array systems with wide instantaneous

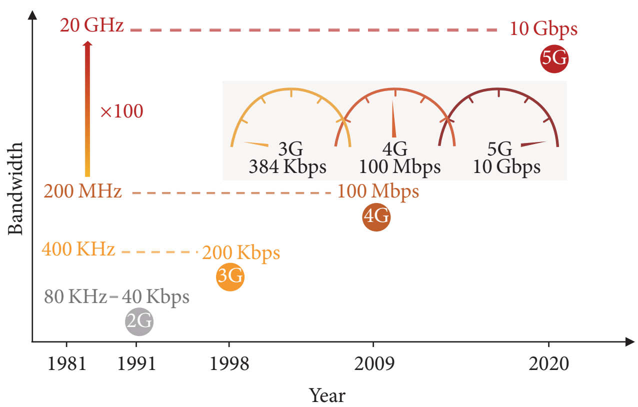

Figure 1: Increase in the bandwidth of the wireless standards over time [1].

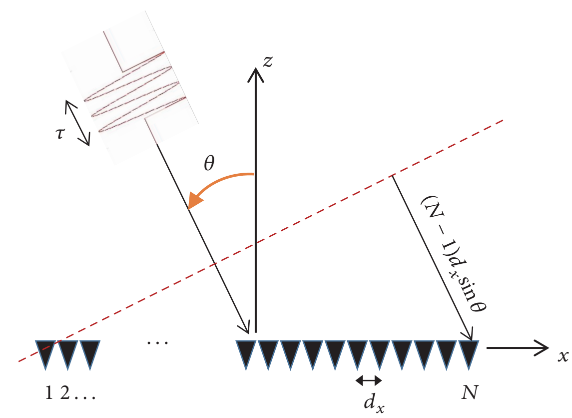

Figure 2: Plane wave incident on a linear array.

bandwidth signals. Time delay aligns signal envelopes and minimizes pulse dispersion.

2. Pulse Dispersion

Pulse dispersion [8–10] results when the received pulse has a longer duration than the transmitted pulse. It occurs due to the following:

(i) Multipath: a transmitted signal arrives at the receiver via more than one path. The different path lengths cause different signal delays.

(ii) Polarization: two orthogonal polarizations in an optical fiber travel at different speeds.

(iii) Intramodal: it is also known as chromatic dispersion when the index of refraction changes with frequency inside the material.

(iv) Intermodal: modes travel at different speeds.

(v) Array: arrival times at the elements are different.

The extended pulse width increases intersymbol interference (ISI) in communications system which in turn increases the bit error rate (BER) [11]. This paper only addresses the pulse dispersion created by antenna arrays due to the position of the elements.

Figure 2 shows a signal, $s(t)$, with a pulse of length τ incident at an angle θ_s on an N-element, equally spaced linear array lying along the x-axis. The pulse arrives at element 1 first and then sequentially at all the elements up to the last one. The signal from each element is weighted (w_n), time-delayed, and summed to get the array output

$$S = \sum_{n=1}^{N} w_n s\left[t - \frac{x_n}{c}\sin\theta_s + \tau_n\right]. \tag{2}$$

If the time delay at element n is

$$\tau_n = \frac{x_n}{c}\sin\theta_s, \tag{3}$$

then the signal maximum corresponds to the main beam pointing at θ_s. Steering the main beam in this manner is known as time delay steering.

The output from a linear array that receives a single frequency signal is given by the array factor

$$\mathrm{AF} = \sum_{n=1}^{N} w_n e^{jk(n-1)d_x\sin\theta + \delta_n}. \tag{4}$$

Time is ignored in this steady state scenario, because there is no signal envelope. If

$$\delta_n = -(n-1)\,kd_x\sin\theta_s = -(n-1)\,\frac{2\pi f}{c}d_x\sin\theta_s, \tag{5}$$

then the array output is a maximum at θ_s which corresponds to the main beam pointing in the direction of the signal. Steering the main beam in this manner is known as phase steering. Note that the phase shift needed to point a beam maximum at θ_s increases with frequency.

A phased array uses a phase shifter at each element to align the signal phases in order to coherently add all the pulses. Phase shifters have a constant phase shift across their operational bandwidth. As a result, a constant phase shift over frequency in (5) means that the scan angle changes with frequency. Figure 3 shows the relative timing of the signals arriving at each of the 20 elements of a linear array (d = 30 cm) operating at f_c = 10 GHz with the signal arriving from $\theta = 30^\circ$. The pulse width is set to 0.95 ns to ensure the aperture fill time is satisfied for all elevation scan angles. Phase steering the main beam to $\theta_s = 30^\circ$ results in the coherent addition of the 20 signals as shown by the plot at the bottom of Figure 3. The 0.95 ns transmitted pulse spreads into a 1.43 ns received pulse.

Pulse dispersion is a function of the arrival and scan angle as shown in Figure 4. At broadside, the received pulse has the same shape and duration as the transmitted pulse. When the pulse arrives at 30 degrees and the array is phase scanned to 30 degrees, then the pulse expands by about 1.5 times. Increasing the angle of arrival and the phase scan to 60 degrees expands the pulse even further. At this angle the 0.95 ns pulse has

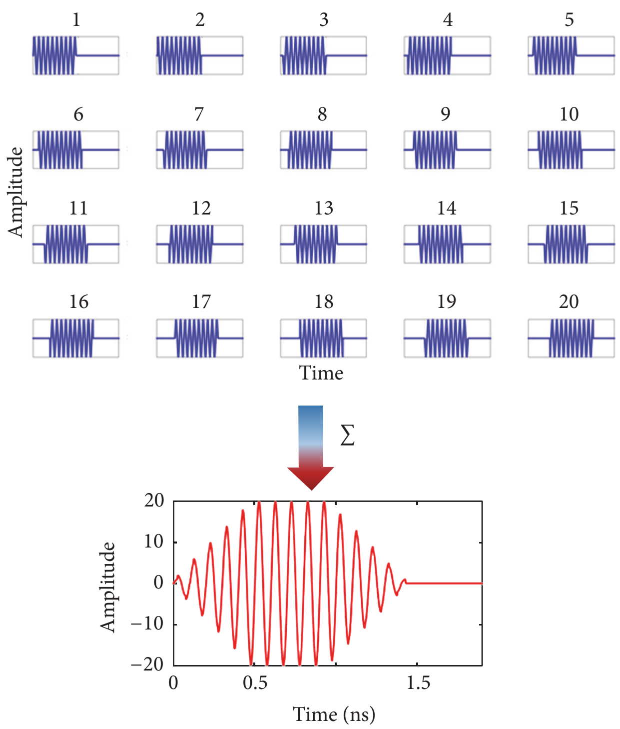

Figure 3: Signal dispersion in a 20-element linear phased array steered to $\theta_s = 30^\circ$.

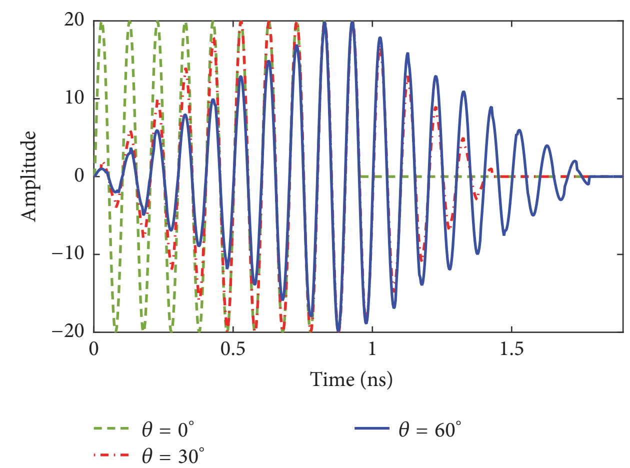

Figure 4: Pulse dispersion at scan angles of 0, 30, and 60 degrees.

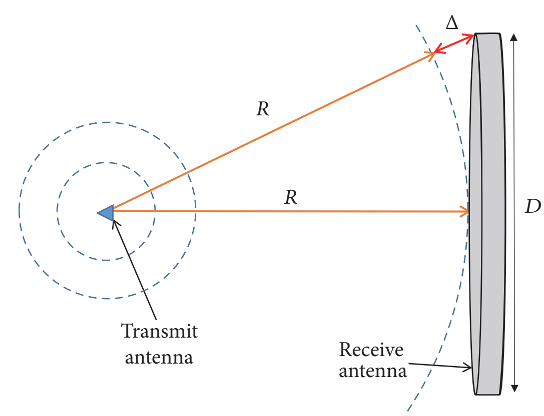

Figure 5: Time delay in the near field of an antenna.

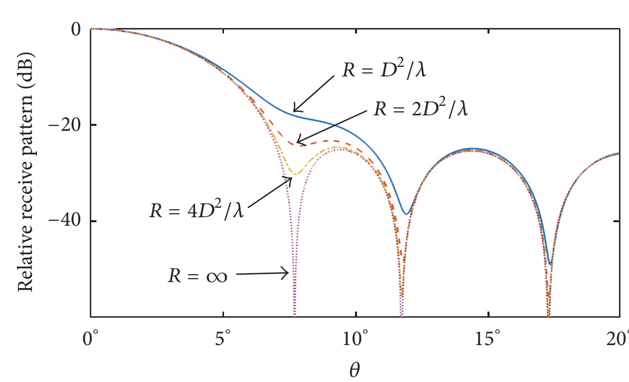

Figure 6: Far field patterns as a function of separation distance between the transmit and receive antennas.

spread to 1.78 ns or 1.87 times its original length. This plot shows that ISI will increase between consecutive pulses as the scan angle increases. Also, the increased ISI will result in a higher BER.

3. Pulse Dispersion in the Near Field

The far field of a receive antenna occurs when the wave from the transmitter is approximately a plane wave. Figure 5 shows a spherical transmitted wave impinging on the receive antenna. This spherical wave arrives at the edge Δ/c seconds after arriving at the center. Since the antenna aperture receives the pulse at different times across its extent, dispersion occurs.

In antenna measurements, the far field starts when the distance from the transmit antenna to the receive antenna edge $(R+\Delta)$ exceeds the distance to the center of the antenna (R) by $\Delta \le \lambda/16$ or $\pi/8$ radians. Using this value for Δ, the IEEE antenna standard defines the far field in terms of the receive antenna diameter (D) [12]

$$R^2 + \left(\frac{D}{2}\right)^2 = (R+\Delta)^2 \Longrightarrow \qquad (6)$$
$$R \ge \frac{2D^2}{\lambda}.$$

This approximation manifests itself as errors in the sidelobes of the far field pattern close to the main beam as shown in Figure 6 for several values of R. Decreasing R results in phase errors that distort the nulls and sidelobes close to the main beam.

The far field definition in (6) is for the antenna pattern at a single frequency, so it applies to narrowband signals that do not exhibit pulse dispersion. Using the diagram in Figure 5, a time domain version of (6) can be derived by assuming

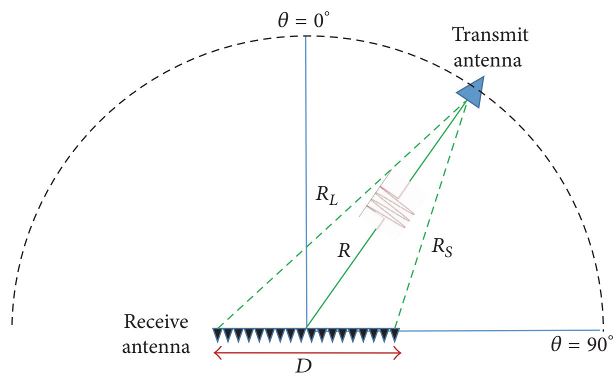

Figure 7: The transmit antenna moves in a circle about the receive array.

$\Delta = \tau c$, where τ is the pulse width. With this assumption, the time domain version of the far field definition in (6) is given by [13]

$$R^2 + \left(\frac{D}{2}\right)^2 = \left(R + \frac{\tau c}{16}\right)^2 \Longrightarrow$$
$$R \geq \frac{2D^2}{\tau c}. \quad (7)$$

This equation is independent of wavelength. Instead, the separation distance depends on the pulse width as well as the antenna size.

In order to quantify the effects of pulse dispersion on the separation distance between a transmit antenna and a receive array, assume that the receive antenna is stationary and the transmit antenna moves in a circle centered on the receive antenna as shown in Figure 7 [14]. For $0 \leq \theta \leq 90^\circ$ the time delay between when the pulse hits the first element and when it hits the last element is given by

$$\Delta t = \frac{R_L - \min\{R, R_S\}}{c}, \quad (8)$$

where R_L and R_S are the longest and shortest paths the pulse takes to the edge elements which are given by

$$R_L = \sqrt{R^2 + RD\sin\theta + 0.25D^2},$$
$$R_S = \sqrt{R^2 - RD\sin\theta + 0.25D^2}. \quad (9)$$

Note that at broadside

$$R_L = R_S = \sqrt{R^2 + 0.25D^2}, \quad (10)$$

and at endfire

$$R_L - R_S = D. \quad (11)$$

The longest distance is always from the transmitter antenna to the last element on the far edge. The closest element, however, depends upon θ. At broadside, the closest element is at the center of the array, while at endfire, the closest element is at the nearest edge.

Figure 8 has plots of the total time delay given by (8) across an array of diameter D at a distance R from the transmitter for several values of θ. At broadside, the shortest delay time occurs from the transmitter to the center of the array with the largest delay time from the transmitter to the edges. Time delay increases with increasing D and decreases with increasing R. As θ increases, the time delay due to the separation distance between the transmitter and the receive array decreases until at $\theta = 90^\circ$, it disappears. The near field time delay dominates at angles close to broadside while the scan angle time delay dominates everywhere else.

4. Pulse Dispersion versus Scan

The last section introduced pulse dispersion in linear phased array antennas primarily due to the separation distance between the transmit and receive antennas. This section presents results for pulse dispersion only due to angle of incidence on a receive phased array when the transmitter is at $R = \infty$ [15, 16]. In general, the spatial delay across the aperture is many wavelengths which corresponds to a phase greater than 2π. This delay is not a problem for narrowband signals, because phase shifters easily align the signals at the elements. The compensating phase provided by the phase shifter is up to one phase cycle or period which is insufficient for wideband signals.

Consider that a 0.95 ns rectangular pulse centered at 10 GHz is incident on a 20-element linear array with a 25 dB Taylor taper. Pulse dispersion is zero at broadside, because the signal hits all the elements at once as shown in Figure 9(a).

Off boresight, the signal no longer coherently adds and the pulse spreads out in time. When the pulse enters the sidelobes, it experiences increased dispersion the further it is from broadside. Scanning the beam to 30 and 60 degrees to receive the pulse at those same angles shows that the resulting received pulse entering the main beam experiences significant dispersion that intensifies as the scan angle increases (Figures 9(b) and 9(c)).

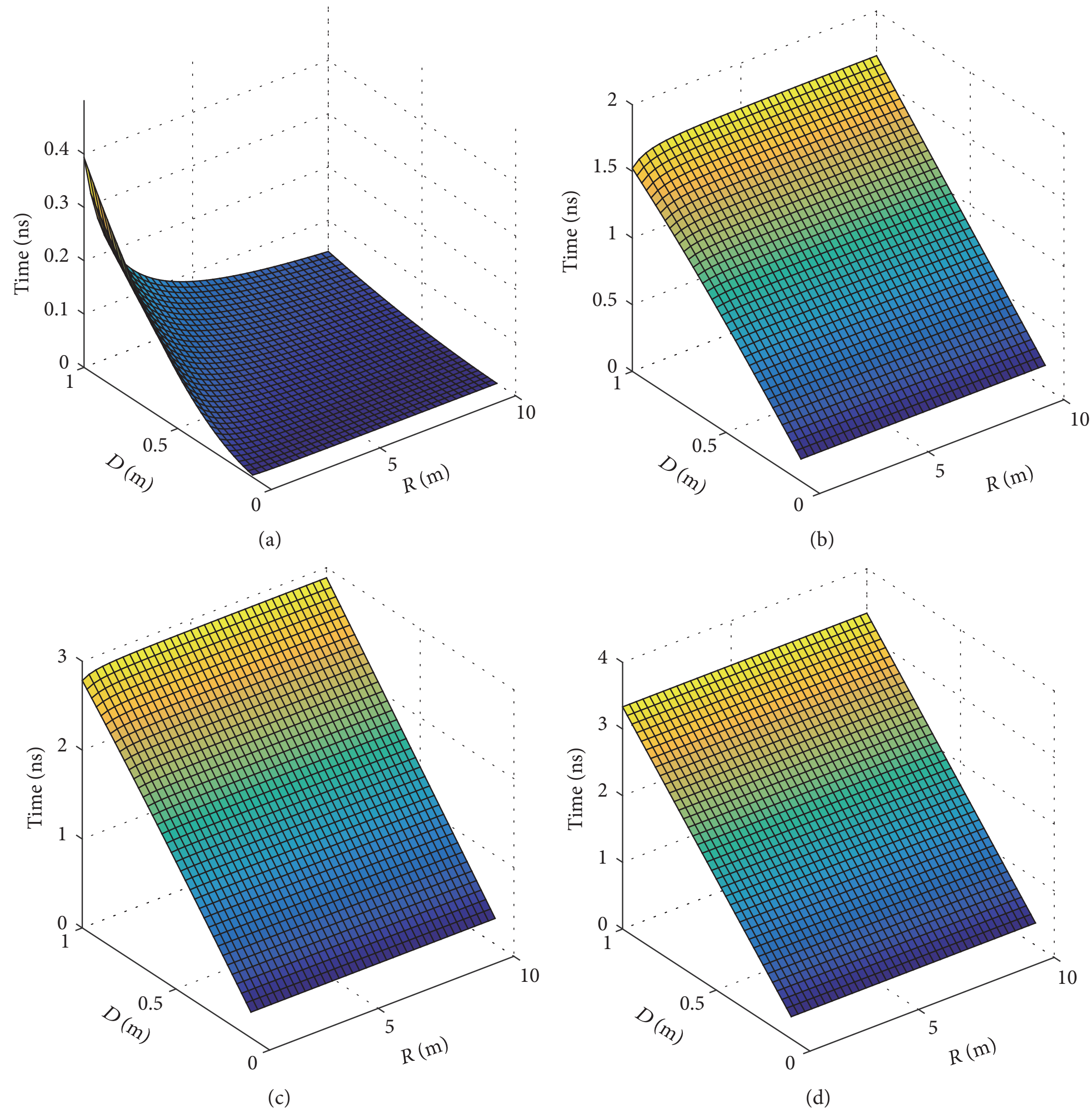

Figure 8: Time delay for antenna separation distance versus receive antenna diameter: (a) $\theta = 0^{\circ}$, (b) $\theta = 30^{\circ}$, (c) $\theta = 60^{\circ}$, and (c) $\theta = 90^{\circ}$.

5. Time Delay Steering

Time delay units compensate for the pulse dispersion and beam squint experienced by an antenna array. Replacing phase shifters at the elements with time delay units allows the array to steer the beam in a way that aligns the signal envelopes as well as the signal phases as predicted by (2).

Figure 10 shows the output of a 20-element linear array with a 25 dB Taylor taper when a 0.95 ns rectangular pulse centered at 10 GHz is incident at three different angles. The broadside case is identical to the broadside case for phase steering, because no time delay or phase shift is needed to coherently add the signals at each element. No pulse dispersion occurs when the signal and timed-delay steering correspond to $\theta_s = 30^{\circ}$ and $\theta_s = 60^{\circ}$. Signals entering the sidelobes do experience a large spreading. Since these signals are not important, their dispersion is not a problem.

To gain a better understanding on how time delay differs from phase shift, we show the phase-shifted and time-delayed signals for a center element (element number 10) in the 20-element array example. Figure 11 shows a comparison between how these two beam steering techniques operate. With the phase shift approach, the signal is aligned in phase within its envelope. On the other hand, with a time delay the envelope of the signal is shifted which ultimately resolves all issues associated with pulse spreading. Time delay units are needed to steer the beam of a large, wideband array.

If all the time delay bits are placed at the element, then the beam pointing and sidelobe levels are minimally perturbed. Time delay units become larger and more expensive as the number of bits and physical size of the bits increases [17, 18]. Some of the time delay bits must be placed at the subarray levels in the corporate feed network to minimize the cost of the time delay units (Figure 12) [19]. Also, time delay

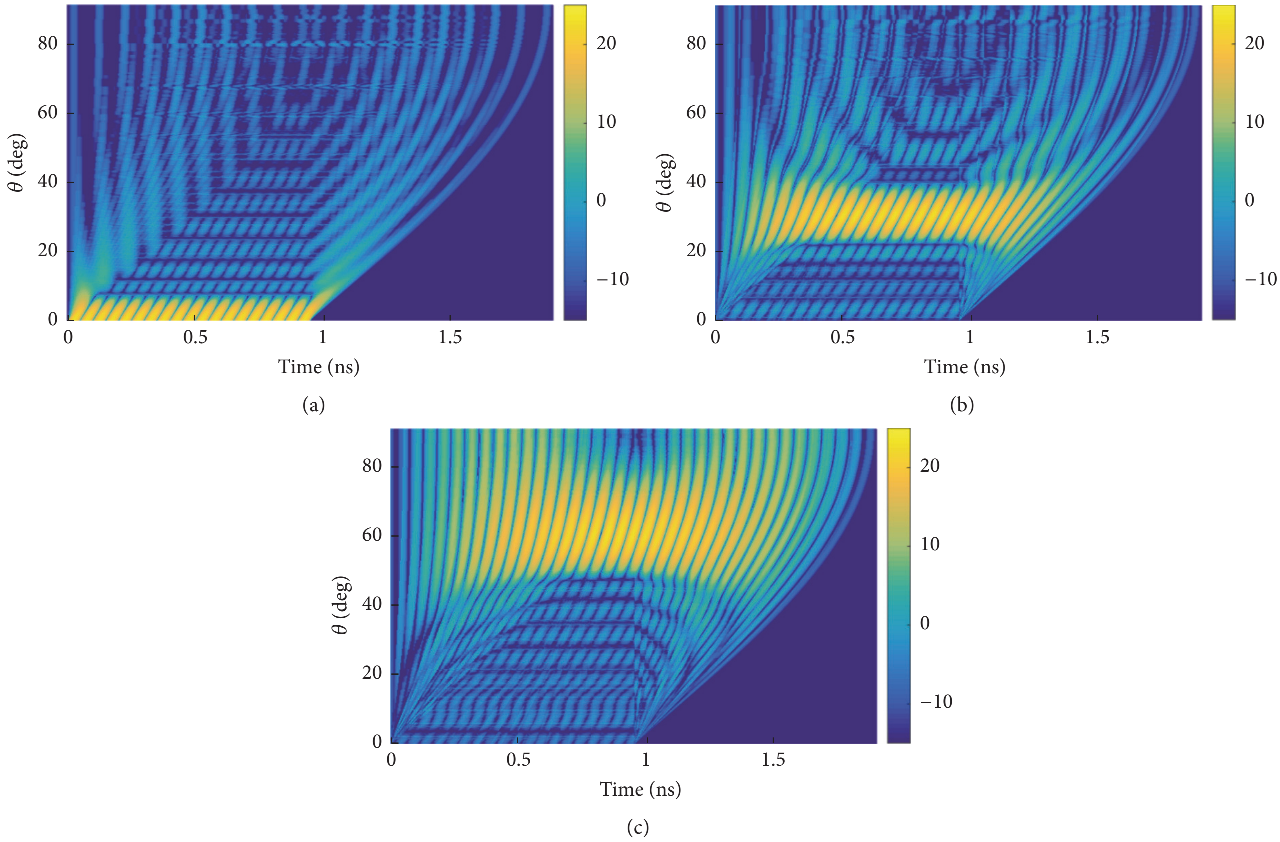

FIGURE 9: Pulse dispersion in a 20-element linear phased array as a function of angle when the angle of incidence equals the scan angle: (a) $\theta_s = 0^\circ$, (b) $\theta_s = 30^\circ$, and (c) $\theta_s = 60^\circ$.

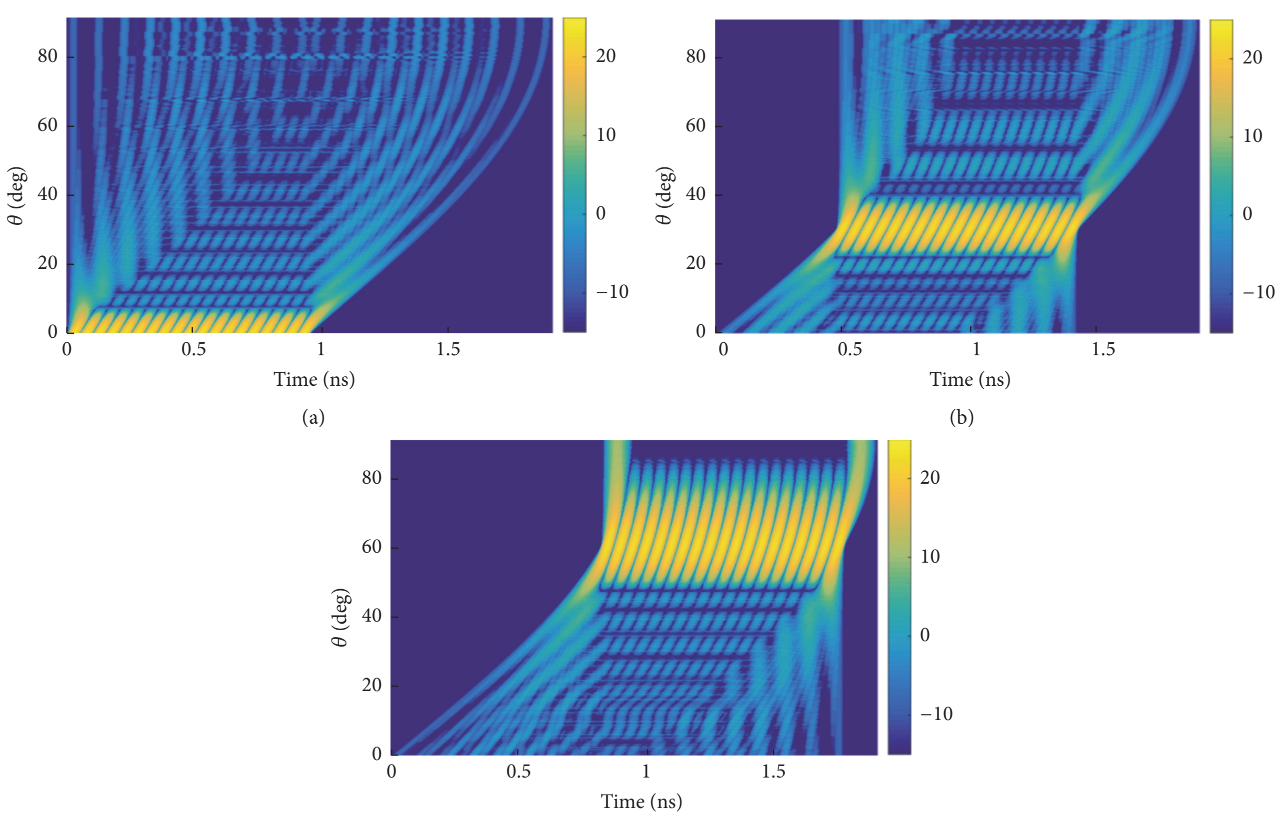

FIGURE 10: Pulse dispersion in a 20-element linear timed array as a function of angle when the angle of incidence equals the scan angle.

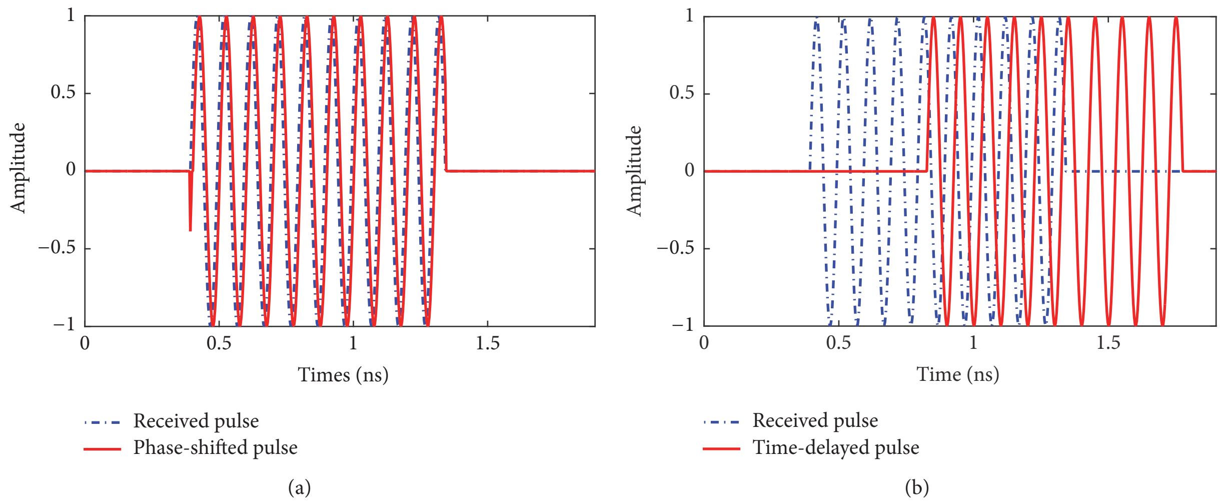

Figure 11: The received pulse at element 10 of a 20-element array is (a) phase-shifted and (b) time-delayed.

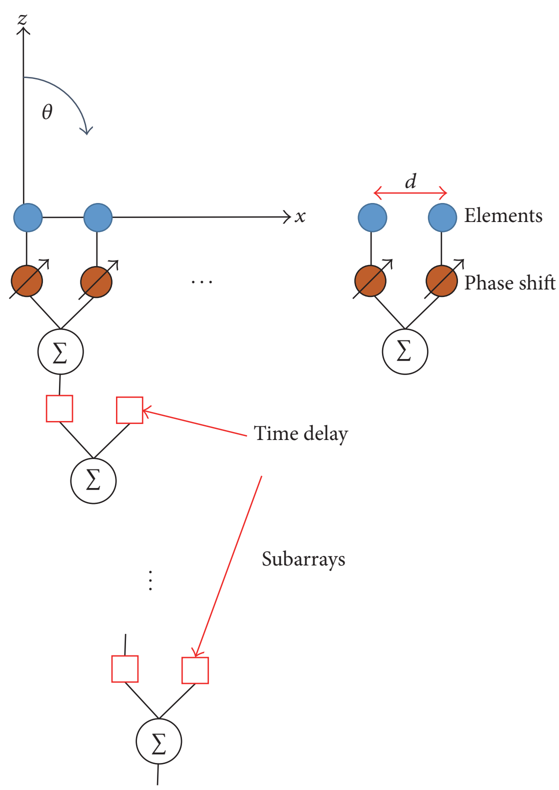

Figure 12: Time delay is typically placed at the subarray level.

units that exceed a few nanoseconds of delay occupy a large physical area and do not easily fit behind an element [20]. When their area exceeds an element unit cell they are placed at the subarray ports. As the bits are moved back in the feed network, time delay quantization increases and produces errors in the array factor [21]. Large bits need to be carefully placed in the subarray structure in order to avoid large quantization lobes that are of the magnitude of the main beam. At least one bit must appear at each level between the element and the highest level, or quantization lobes appear. In order to lower costs and not sacrifice much performance, phase shifters are used at the element levels and time delay is distributed at the subarray levels.

6. Conclusions

Pulse dispersion is a serious issue when designing antenna arrays for receiving and transmitting wideband signals. The elements of a phased array receive the transmitted signal at different times depending upon the distance from the transmitter, the angle of incidence, and the size of the array. When the antenna is in the near field, the spherical wavefront from the transmitting source causes time of arrival differences at the array elements which results in pulse dispersion. Normally, the far field is defined in terms of a phase error for narrowband antennas. A similar time domain far field definition is possible as well. A wideband pulse coming from the far field at an angle off broadside arrives at the elements at different times based upon the angle of incidence and the size of the aperture. Contour plots of the pulse dispersion for scanning arrays were presented that show the extent of the dispersion over the main beam and sidelobes. Time delay units are needed to correct pulse dispersion. This added expense can be mitigated by placing them at the subarray levels.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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