1

TIMED AND PHASED ARRAY ANTENNAS

This chapter briefly introduces antenna arrays and the difference between phased and timed arrays. Not long after the invention of antenna arrays, researchers experimented with moving the main beam by modifying the phase of the signals fed at the elements [1]. Manual beamsteering eventually led to the invention of the phased array where the main beam was electronically steered to a desired direction by applying a pre-calculated phase to all the elements [2]. Phase is a narrow band concept, though. Today's applications of antenna arrays require high data rates and wide bandwidths. The term "timed arrays" applies to several classes of antenna arrays that are becoming more important with the development of new technologies that must be designed, analyzed, and tested in the time domain, rather than the steady-state, time harmonic forms used with phased arrays. One author defined timed arrays as [3] "… timed-domain equivalent of phased arrays, where each radiating element is excited by pulsed instead of narrowband signals." This book adds adaptive arrays, reconfigurable arrays, and other time-dependent arrays to that definition of timed arrays.

1.1 LARGE ANTENNAS

Large antennas collect more electromagnetic radiation than small antennas. They have the potential to detect very faint signals—the reason they are popular for radio astronomy and radar. Consequently, an antenna has gain that magnifies the received

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or transmitted signal in the direction it is pointing. An approximate relationship between the physical size or aperture area (A_p) and gain is given by

$$G = \frac{4\pi A_p}{\lambda^2} \tag{1.1}$$

where λ is the wavelength. Note that this formula assumes the antenna only transmits over a hemisphere. "Large antenna" may indicate its physical size but more often refers to its electrical size: area$/\lambda^2$. For a given aperture size, higher frequency means higher gain.

Antenna arrays are frequently used in communications and radar systems. The power received by a communications antenna is given by the Friis transmission formula:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \tag{1.2}$$

And the power received by a monostatic radar antenna is given by the radar range equation:

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4} \tag{1.3}$$

where P_t = power transmitted (W), σ = radar cross section (m^2), R = distance (m^2), λ = wavelength (m), G_t = gain of transmitting antenna, and G_r = gain of receiving antenna.

Both (1.2) and (1.3) point out that a bigger antenna increases the received power through a higher gain.

Large antennas come in two forms: reflectors and arrays. Figure 1.1 has examples of a large reflector (Green Bank Telescope, GBT) used for radio astronomy and a

(a) (b)

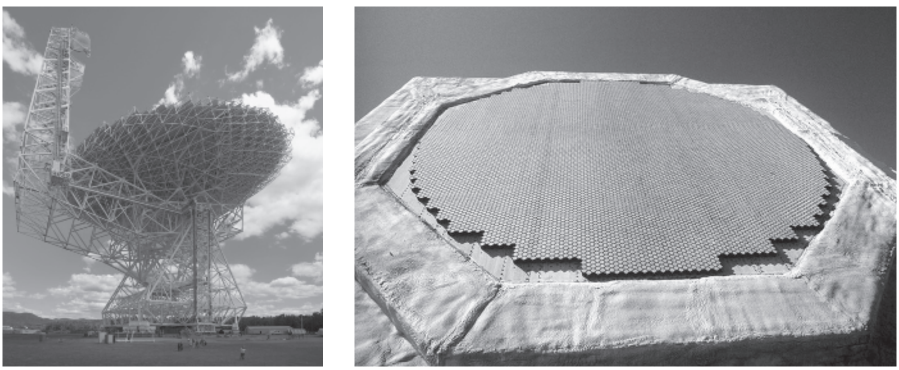

FIGURE 1.1 (a) Green Bank Telescope reflector [4] (Courtesy of NRAO). (b) PAVE PAWS radar [5] (Courtesy of BMDO).

large phased array (PAVE PAWS) used for radar. The Green Bank reflector is a 100 m diameter offset-fed reflector that operates from 0.1 to 116 GHz [4]. The GBT mechanically steers to access 85% of the celestial sphere. The PAVE PAWS radar has two apertures with each covering 240° in azimuth and from 3–85° in elevation [5]. It operates at 420–450 MHz. Each face is 22.1 m in diameter and has 1792 active T/R modules and 885 passive elements resulting in a gain of 37.9 dB with a 2.2° beamwidth. The nominal peak power per face is 600 kW, with a power of 150 kW.

Reflectors and arrays compete to fulfill the role of a large antenna in systems that detect weak signals The reflector is cheap compared to the array, and that is why it is the antenna of choice for commercial activities, such as satellite television. Moving a large reflector in order to locate or track a signal requires gimbals, servomotors, and other mechanical parts that result in a reliability and maintenance problem and leads to significant lifecycle costs [6]. Mechanical steering is too slow for some systems, such as radars on airplanes that need high-speed electronic steering offered by arrays.

An array makes many performance promises for a price. Some potential advantages of an array over a reflector antenna include the following [7]:

1. Fast, wide-angle scanning without moving the antenna
2. Adaptive beamforming
3. Graceful degradation in performance over time
4. Distributed aperture
5. Multiple beams
6. Potential for low radar cross section

Reflectors have the following advantages:

1. High G/T
2. Wide bandwidth
3. Relatively low cost

The mission and budget drive cost/performance trade-offs in the antenna design. Hybrid reflectors are a compromise between the array and reflector. Hybridization may be in the form of arrays of reflectors or an array feed of a reflector. Major research and development efforts are devoted to lowering the cost/element of an array.

1.2 COLLECTION OF ELEMENTS

Antenna arrays are collections of smaller antenna elements situated to produce a desired gain and response as a function of angle (antenna pattern). Elements either sample (receive) or create sample (transmit) signals. These samples are weighted and then combined to form desired beams. The element configuration determines the spatial sampling rate of the transmit or receive signal.

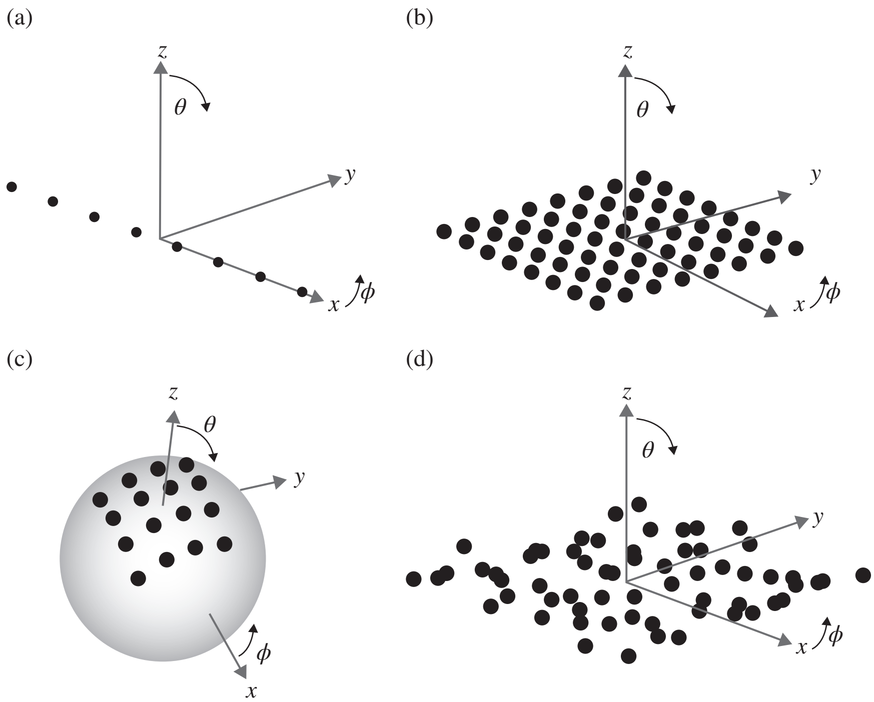

FIGURE 1.2 Four different geometrical layouts of an array: (a) linear array, (b) planar array, (c) conformal array, and (d) random array.

Four common categories of arrays are determined by the element configuration: linear, planar, conformal, or random arrays based on the element layout. The linear array has all of its elements lying along a straight line as shown in Figure 1.2a. Unequally spaced elements lead to an aperiodic or nonuniformly spaced array. The array in Figure 1.2b is planar. The element grid is either periodic or aperiodic. When the elements are placed on a curved surface, then the array is called conformal. A diagram of an array that conforms to a spherical surface is shown in Figure 1.2c. Finally, a random array is shown in Figure 1.2d. The elements in this array follow no pattern in the x, y, and z directions. The minimum element spacing is limited by the area occupied by the element.

Moving far from an antenna creates the illusion that the radiation comes from a single point—much like the light from a star. The phase of the radiated signal on the surface of any sphere having this point as the center is constant, because phase is just distance time the wavenumber, $k = 2\pi/\lambda$. The black dots in Figure 1.2 represent the physical locations of these phase centers of the elements. An element phase center is the point from which the radiation appears to originate (Fig. 1.3). Actual antenna elements occupy a much larger region than the phase centers indicate. These phase centers are also called point sources. In a receive configuration, the point source

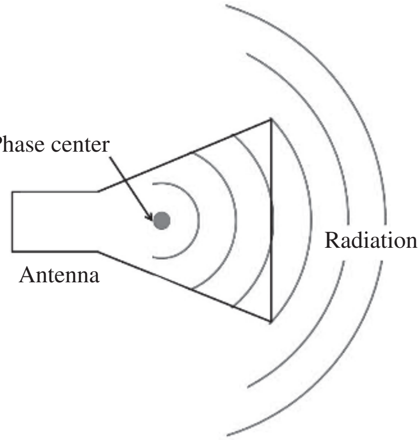

FIGURE 1.3 Concept of an antenna phase center.

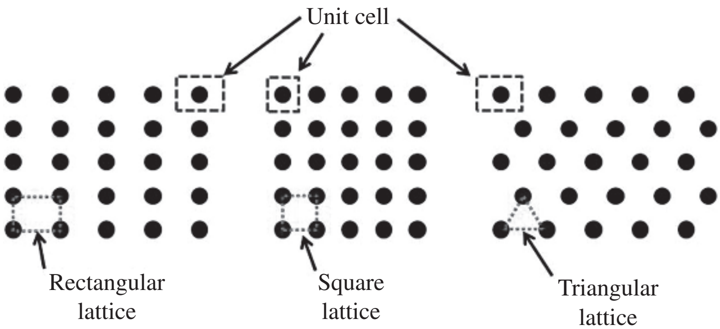

FIGURE 1.4 Three different element lattices and corresponding unit cells.

represents the point in space where the signal sampling occurs. The location of the phase center on an antenna is a function of frequency, polarization, and angle, so placing the phase center at a single point in space is only an approximation.

Elements in a planar array lie in either a rectangular or triangular lattice (Fig. 1.4). A rectangular lattice has equal spacing in the x direction (d_x) that is different from the equal spacing in the y direction (d_y). If the spacing in the x and y directions are the same, then it is a square lattice. Triangular spacing has every other row offset by half the element spacing as shown in Figure 1.4. The triangular lattice is important, because for a given gain (aperture size), it has fewer elements than are needed than for a rectangular lattice [8].

The unit cell is the maximum area that that an element can occupy and is defined by the element spacings

$$A_{uc} = d_x d_y \tag{1.4}$$

Unit cells for the different element lattices are shown in the top row of elements in Figure 1.4. For an N element array, the physical area of the aperture is N times the unit cell area, so the gain of a planar array in (1.1) becomes

$$G = \frac{4\pi N A_{\mathrm{uc}}}{\lambda^2} \tag{1.5}$$

Thus, the gain of a planar array is proportional to the number of elements in the array. This formula works when the elements spacing is small enough to prevent grating lobes (see Chapter 3).

1.3 OVERVIEW OF AN ARRAY ARCHITECTURE

Figure 1.5 shows a diagram of the array architecture considered in this book. Other important parts of an array, such as control, cooling, and radome are ignored (although they are very important). The components in Figure 1.5 are critical pieces of either a phased or timed array.

The elements or small antennas that sample the field take various forms. Selection of the antenna element depends on the frequency, polarization, and bandwidth requirements. These components are examined in detail in Chapter 4.

Amplifiers take the form of power amplifiers (PAs) in transmit or low-noise amplifiers (LNAs) in receive. A transmit/receive (T/R) module combines both functions in one package. T/R modules provide the last amplification of transmitted signals and the first amplification of received signals in an array. They typically have phase and amplitude controls to steer the beam, calibrate the signal path, and control the sidelobes. Arrays have many T/R modules, so the module cost needs to be low. Chapter 6 is dedicated to T/R modules.

The beamforming network takes the signals from all the elements and coherently combines them to form a beam in the receive mode. In the transmit mode, the feed

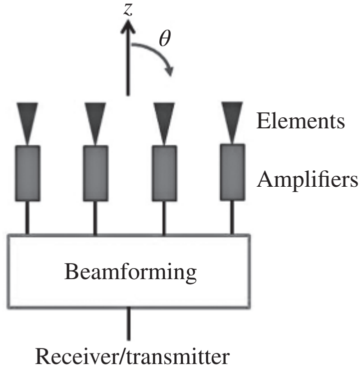

FIGURE 1.5 Generic array architecture.

network distributes the signal from the transmitter to the elements to form a beam. Sometimes, the beamforming network creates multiple beams. For instance, a monopulse tracking radar has simultaneous sum and difference beams. Beamforming is covered in Chapters 3, 5, 7, and 8.

1.4 TRANSIENT VERSUS STEADY STATE

Steady state implies that a system's properties do not change with time. In mathematical terms, the partial derivative of any property with respect to time is zero. Steady-state signals have a finite number of Fourier components contained in a small bandwidth. There are no transients or short duration signals with high bandwidths. A steady-state system is linear time invariant. A steady-state array implies the signals are continuous wave, and the array components do not change with time. Students learn about antenna arrays from this narrow band, steady-state point of view. Even books devoted to phased arrays spend most of their content addressing narrow band, steady-state issues [9–12].

A transient state has quickly changing properties and occurs prior to steady state. Any sudden change in a signal is a *transient*. Transients have an infinite number of Fourier components and a very wide bandwidth. Some books are devoted to one special aspect of phased arrays in the time domain like adaptive nulling or wideband arrays [13, 14].

1.5 TIME VERSUS PHASE

Phase is the narrow band term describing the argument of a sine wave. Phase has units of radians or degrees. Two sinusoids of the same frequency are in phase when their arguments have the same value. Consider a wave described by

$$\cos\left[2\pi f(t+T_{\mathrm{d}})+\delta_{\mathrm{s}}\right] \tag{1.6}$$

If the frequency (f) remains constant, then the argument of the cosine function depends on the time delay, T_{d}, and the phase shift, δ_{s}. As such, the time delay converts to phase via

$$\delta = 2\pi f T_{\mathrm{d}} \tag{1.7}$$

Since phase is modulo 2π, there is not a direct conversion of phase to time at a given frequency which means that a phase shift converts to an infinite number of possible time delays given by $2\pi f T_{\mathrm{d}}, 4\pi f T_{\mathrm{d}}, 6\pi f T_{\mathrm{d}}, \ldots$. This nonreciprocal relationship between time and phase becomes critical when a system is time varying and wideband instead of steady state.

Figure 1.6 shows two sinusoidal signals (steady state) adding in and out of phase. Summing the in-phase signals results in a similar signal having twice the amplitude. Changing the phase of the second signal by $3\pi/4$ moves the two waves relative to each other. Adding these two signals together results in a lower amplitude sinusoid of

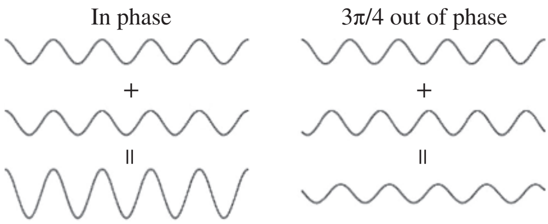

FIGURE 1.6 Two signals adding in and out of phase.

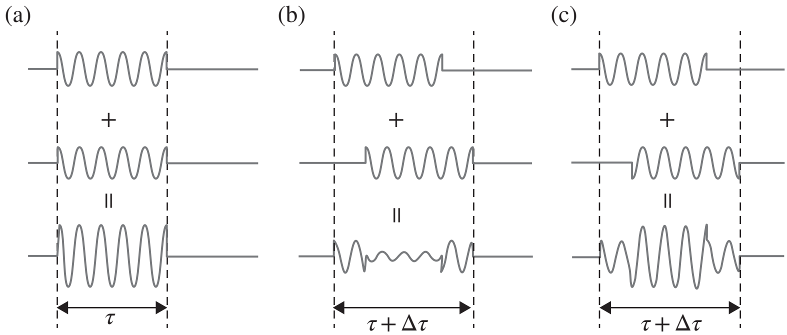

FIGURE 1.7 Pulse dispersion: (a) Two identical pulses (coherent) added together. (b) Two identical pulses (not coherent) that start at different times added together. (c) Two identical pulses (coherent) that start at different times are added together.

the same frequency. The amount of movement of the signal can only be distinguished by $\pm\pi$, even if the phase differential is over 2π. Distinguishing the phase by over 2π is not important for a cosine function, so the difference between time and phase for a sinusoid is not important.

A clear distinction between phase shift and time delay occurs with wideband signals. Adding two identical wide band signals (in this case pulses) together results in a similar signal that has twice the amplitude and has the same start and stop times (Fig. 1.7a). If the start time of the second signal is delayed, then summing the signals causes pulse dispersion (pulse period increases by $\Delta\tau$) as well as destructive interference (Fig. 1.7b). Aligning the phase of both signals before summing them together eliminates the destructive interference but not the dispersion or pulse spreading (Fig. 1.7c). The moral of this story is that phase shifting helps with the coherent addition of two signals but does not help with the pulse dispersion.

1.6 BOOK OVERVIEW

The term "phased array" implies a narrow band approach due to the term "phased." Thus, this book title replaces "phased" with "timed" and concentrates on any aspect of an antenna array that must be viewed from a time perspective. A timed perspective is needed when wideband signals are important. Phase shifters no longer sufficiently align the signals when adding them together. This book explains a variety of issues related to the use of time delay in arrays. Time is also important if the array changes states such as for adaptive arrays or reconfigurable arrays. In these cases, components change array properties in order to meet some performance standard.

The next two chapters introduce signals and the mathematics associated with array theory. From there, a chapter is devoted to each of the array components shown in Figure 1.5. The final chapters describe how to place time delay in an array and introduce adaptive and reconfigurable arrays.

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