Carnegie Mellon University

Electrical & Computer ENGINEERING

Phased-Array Antennas

ECE-300 Electromagnetics

Final Project

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December 18th, 2020

Abstract

In this text, a conceptual and mathematical explanation of the operation of Phased-Array Antennas will be presented with illustrations and animations. The importance of this antenna topology in recent applications such as SpaceX's Starlink Low-Latency-Internet Satellites will be discussed in some detail. Other areas where Phased-Array Antennas play an important role, such as in 5G technology will be highlighted. To complete the discussion, the technological and potential health constraints these devices encounter are presented.

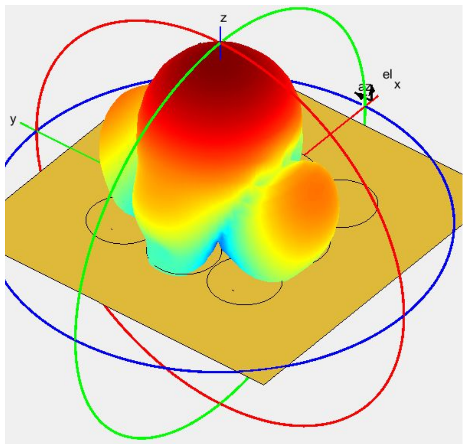

Figure 0. A 3x3 Circular Microstrip Phased-Array Antenna Radiation Pattern

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Introduction - Dipole Antenna

As highlighted in the name, phased-array antennas are constructed by arranging a number of individual antennas to form an array. Figure 1 shows a linear array antenna made up of dipole antennas.

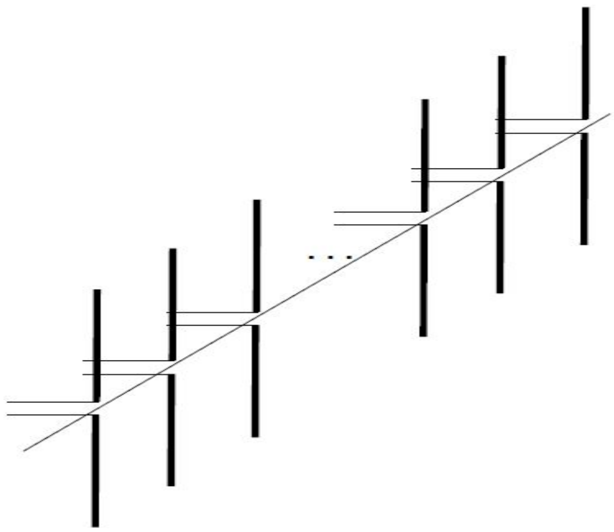


Figure 1. Linear Phased-Array Antenna of Dipoles

Before exploring the nature and operation of phased-array antennas, it is beneficial to review the characteristics of antennas and the operation of a simple, but very common antenna: the dipole antenna. This will provide context and highlight the great advantages of phased-array antennas over any other antenna topology.

If we recall the definition, an antenna is a device that acts as a transducer, converting a guided electromagnetic wave into an unbounded electromagnetic wave, as illustrated in figure 2, or vice versa, depending on the mode of operation: transmitting or receiving.

Abstractly, this concept is simple. Concretizing how the transduction can be achieved, is perhaps more difficult. To provide some intuition to this phenomena, let's take a look at a circuit element we are familiar with: the parallel plate capacitor.

As shown in figure 3(a), when a capacitor is excited by a current in the clockwise direction, the charge and electric field distribution are generated as shown.

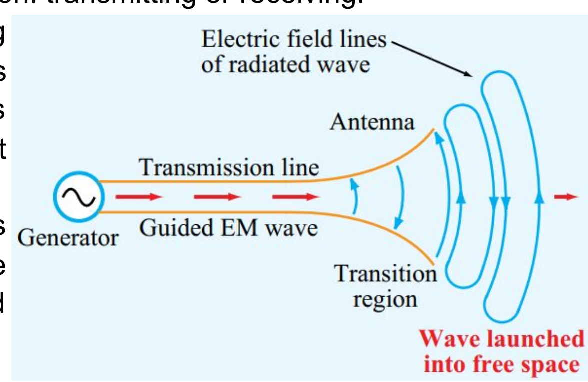
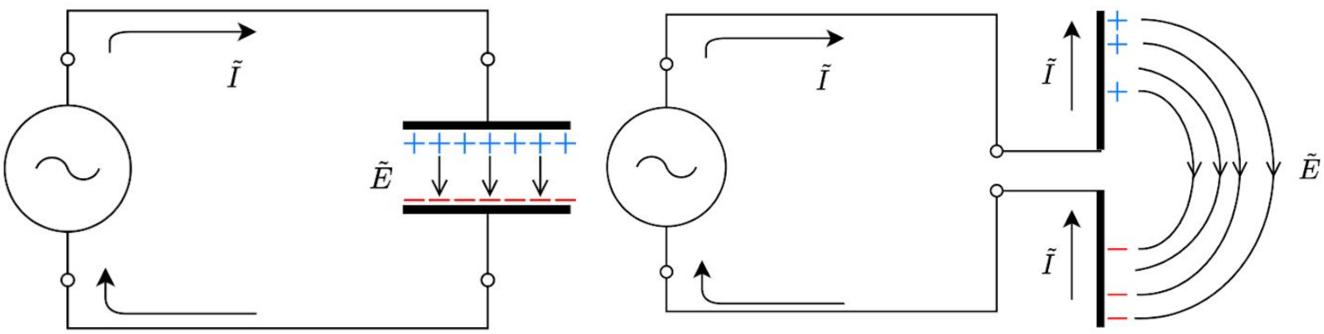


Figure 2. Antenna as wave transducer. [1]

If we make a slight modification to this arrangement and connect the wires to the edges of the capacitor and we fold it up and energize it as in fig. 3(b), we can predict an electric field distribution as shown, where the lines follow a path from positive to negative charges. The charge distribution might be more difficult to predict. Applying the free-electron model of conductors, however, we can explain how at the instant the capacitor is energized, the free electrons in the conductors (wires and plates) will get pushed and drift towards the end of the bottom plate. Henze, more charges are expected towards the edges of the plates and the charge distribution will be lower towards the center of the dipole.

$$\tilde{I} = I_0 cos(\omega t) = \mathbb{R}[I_0 e^{j\omega t}]$$



(a) Parallel Plate Capacitor (b) Dipole Antenna Current and E-field direction

Figure 3. Modifying a parallel plate capacitor into a dipole antenna

It is important to note that the direction of current in both plates is the same. As we will see later, this is important as both currents contribute to the generation of a stronger H-field rather than subtract the contributions of each other. When the polarization of the current flips at the source, there's an instant when the charges have not drifted to the other side quite yet and remain with a similar distribution, but the current is in the opposite direction, as in figure 4.

For the frequency range of operation of dipole antennas, the voltage (or charge) distribution and current distribution may or may not have opposite orientation with respect to each other. In any case, the current drives the charge drift, which responds with a certain delay. As we will see in the discussion in figure 5, this will yield the generation of a forward propagating electromagnetic wave.

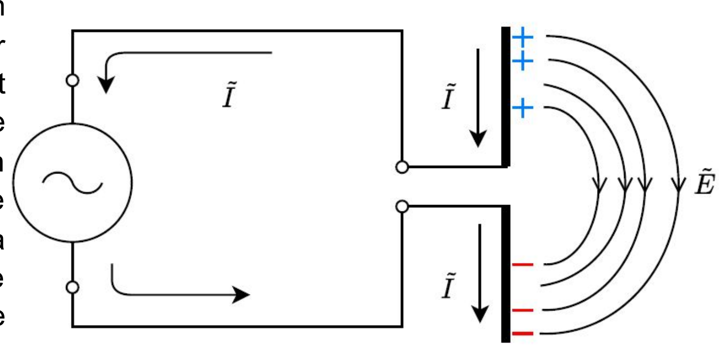
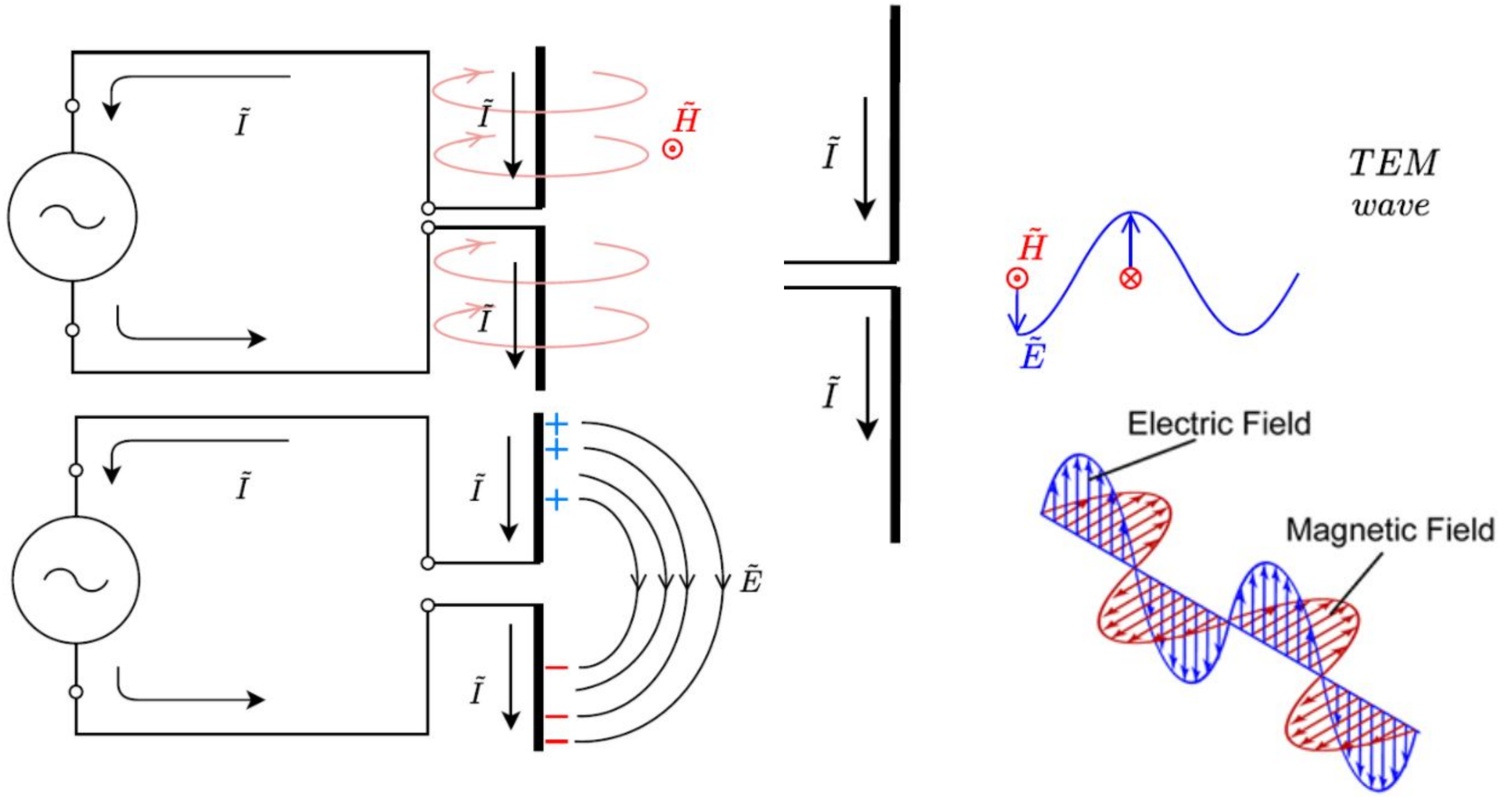


Figure 4. Alternate current and charge distribution.

Applying the right hand rule, as in figure 5(a), we obtain an H-field coming out of the plane on the right hand side of the dipole. With the E-field lines almost straight at the center of the dipole, we can approximate these two field lines around the center of the dipole to generate the electromagnetic wave in figure 5(b).



(a) E-field and H-field lines (b)Forward traveling TEM electromagnetic wave [2]
Figure 5. Transverse Electromagnetic Wave generation from dipole antenna.

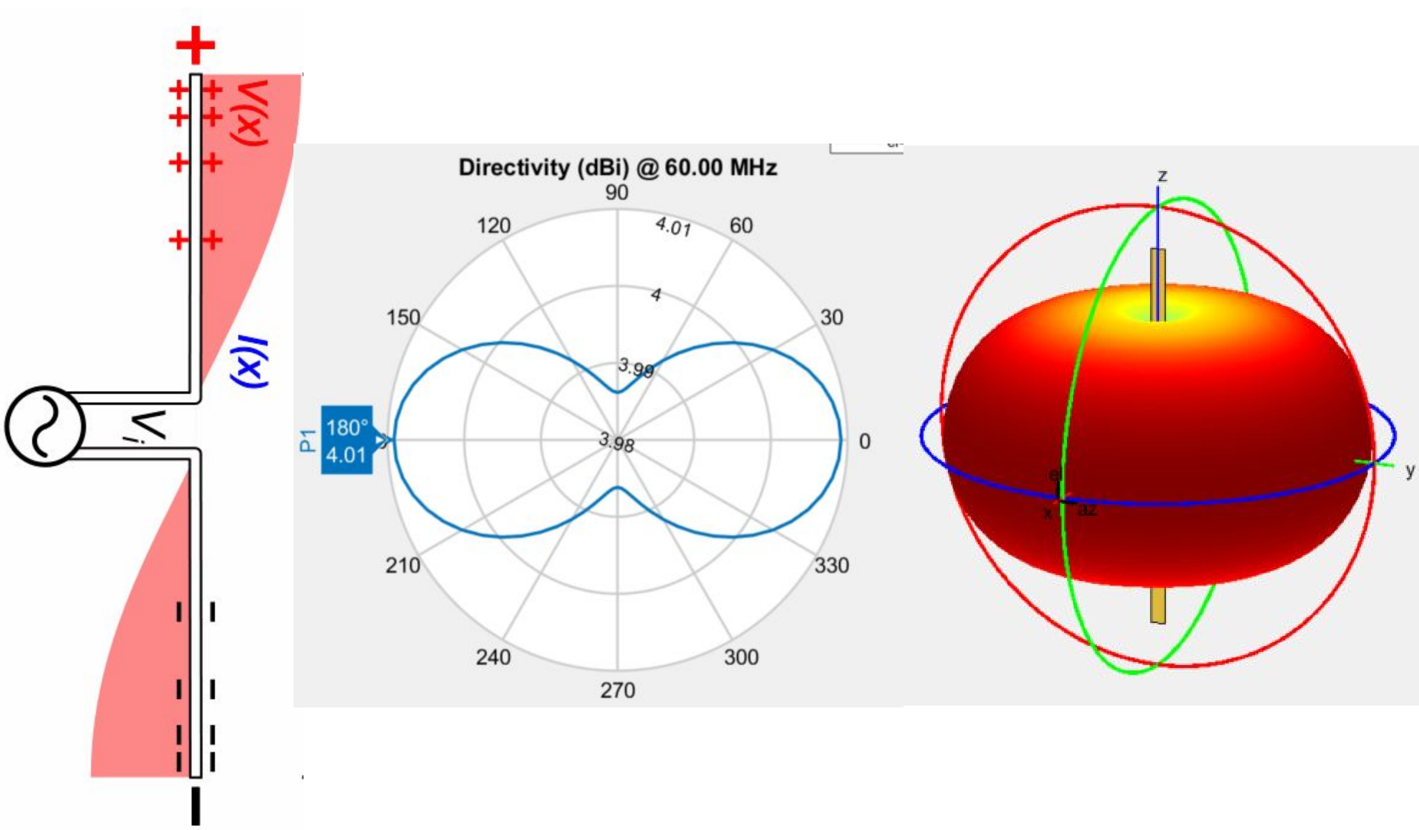
Power Propagation - Radiation Pattern

Currently, there is still ongoing investigation on the study of models that can more accurately describe the charge and current distribution of dipole antennas as well as many other antennas. For the purposes of this text, and the overall standards in industry, the existing theory describing the nature of dipoles is in line with the explanation presented above and available in the dipole Wikipedia page. Borrowing an animation from this page of the half-wave dipole antenna −name given because its length is half a wavelength− we proceed to investigate its output radiation pattern.

As shown in figure 6(a). The voltage and current distribution are exactly opposite to each other. When the current is maximum the voltage is zero and vice versa. The polarities are always opposite as well, when the current is positive, the voltage is negative and vice versa. This is important, because when evaluating the propagation of power within a medium, we use the time-average Poynting Vector, given in equation 1.

$$S_{av} = \frac{1}{2}\mathbb{R}[\tilde{E} \times \tilde{H}^*] \quad \text{(Eq. 1)}$$

Assuming time harmonic fields, to calculate the propagating power S_{av}, we cross-multiply the phasor electric field, $\overline{E}$, times the conjugate of the phasor magnetic field, $\overline{H}$. From the animation, we can predict the power propagation being higher towards the center of the dipole compared to the edges. Using MATLAB's App: Antenna Designer, we obtain figures (b) and (c), which provide an exact illustration of the radiation pattern of a half-wavelength antenna at 60MHz.



(a) [animation]   (b) yz-cross section of radiation pattern   (c) 3D radiation pattern

Figure 6. Radiation Pattern of Half-Wave Dipole Antenna at 60MHz.

The same analysis can be performed on different antenna topologies: a helix antenna (fig. 7) or a horn antenna (fig. 8), for example. As shown in these illustrations, the radiation patterns vary in shape and intensity. If a team of RF engineers is to select an antenna for a specific application, they would have to evaluate the desired radiation pattern. If an omnidirectional pattern is desired, as in AM radio for example, the half-wave dipole will work well. If instead, more directivity is needed, as in weather tracking or satellite TV, a helix or horn antenna might be more appropriate. Among these antennas, despite the differences in the radiation pattern, they all have a common feature: their radiation pattern is **fixed**. The RF engineer, or antenna designer, can do very little to modify the shape of the pattern without compromising other performance parameters. It is precisely for restrictions in radiation pattern versatility where phased-array antennas offer an outstanding advantage: the ability to control the radiation pattern, to a certain degree, and to do it so *on-demand.* We will see how in the next section.

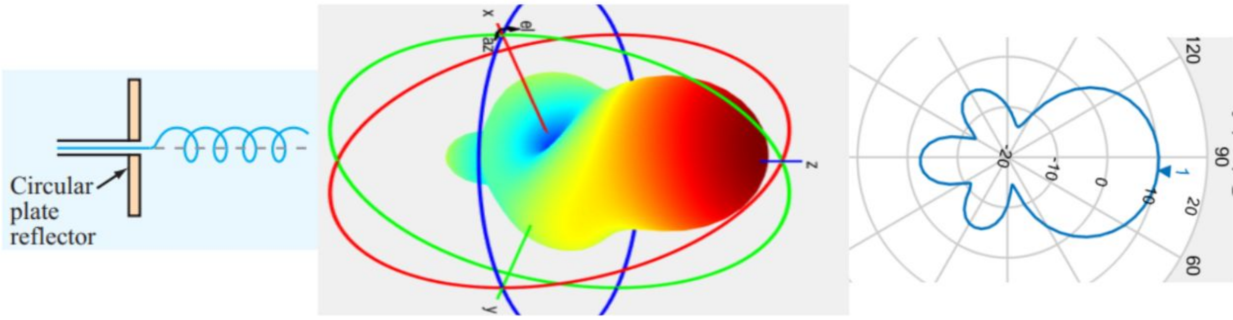


Figure 7. Radiation Pattern of a Helix Antenna

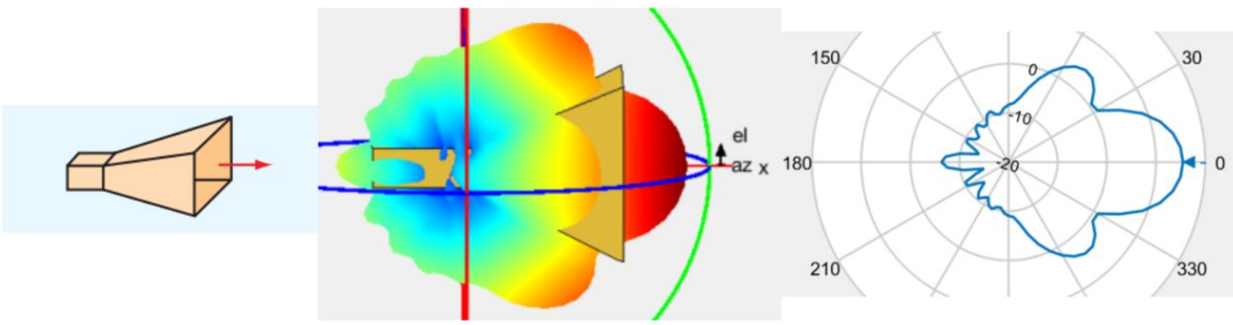


Figure 8. Radiation Pattern of a Horn Antenna

Phased-Array Antennas

The physical principle behind a versatile radiation pattern is **wave interference**. The interference phenomena in waves was discovered a long time ago and the concept of combining individual antennas to form a phased-array antenna is also not novel. How come this antenna topology is now revolutionizing the field? As with many other fields in engineering, the recent advances in mixed-signal hardware and novel digital signal processing (DSP) algorithms has allowed for the closed-loop implementation of phased-array antennas into back end systems, such as transmitter and receiver systems. Without these improvements, the implementation of these antennas was limited to complex projects with great resources, such as the AN/FPS-85 Phased Array Radar facility in Florida. Nowadays, one can find phased-array antennas in devices as small as a cell-phone.

In order to understand why and how these antennas are revolutionizing the area of communications, we will start analyzing what is the interference phenomena (figure 9). Recall that when an isotropic wave source generates omnidirectional waves and these hit a wall with narrow openings, or slits, these become sources of waves themselves. The waves coming from the two slits, will interact and produce the resulting intensity pattern some distance away at the screen.

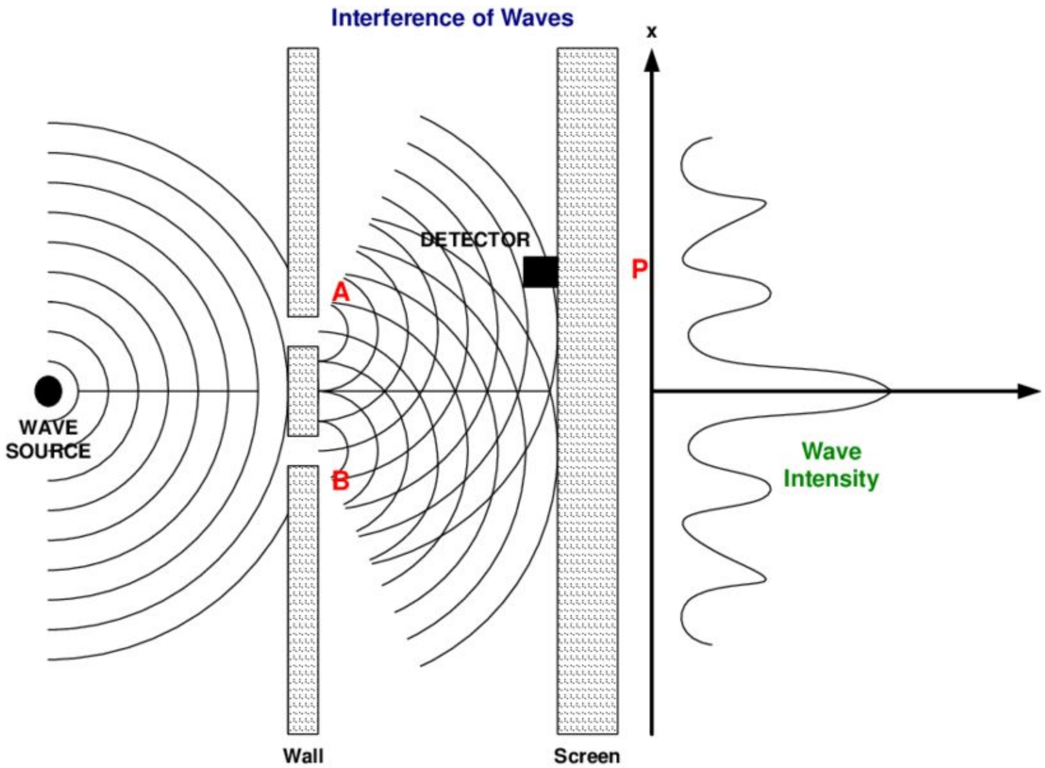


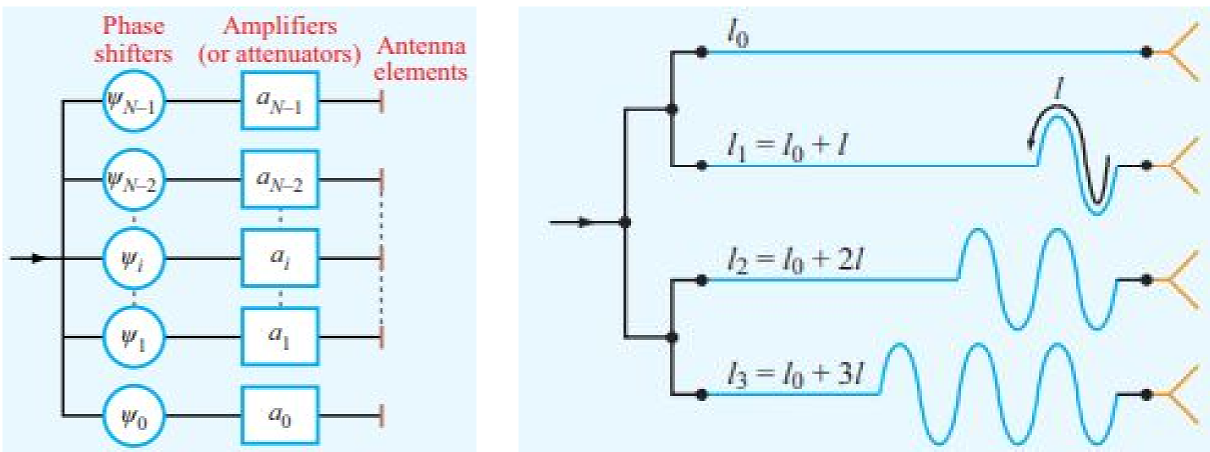
Figure 9. Double-slit experiment illustrating the interference phenomena. [4]

Because at different points in the screen, one of the waves has traveled a different length than the other, there is a relative phase difference between the two waves. The two waves coming together at different points in the screen will interfere constructively or destructively, depending on the relative phase, to produce a *sinc* function intensity pattern shown in figure 9.

Exploiting this concept, we can replace the slits in the wall by any desired number of physical antennas and utilize the interference phenomena to our advantage. The objective here is to control certain parameters of the signals feeding the antennas and obtain a desired radiation pattern.

Steering

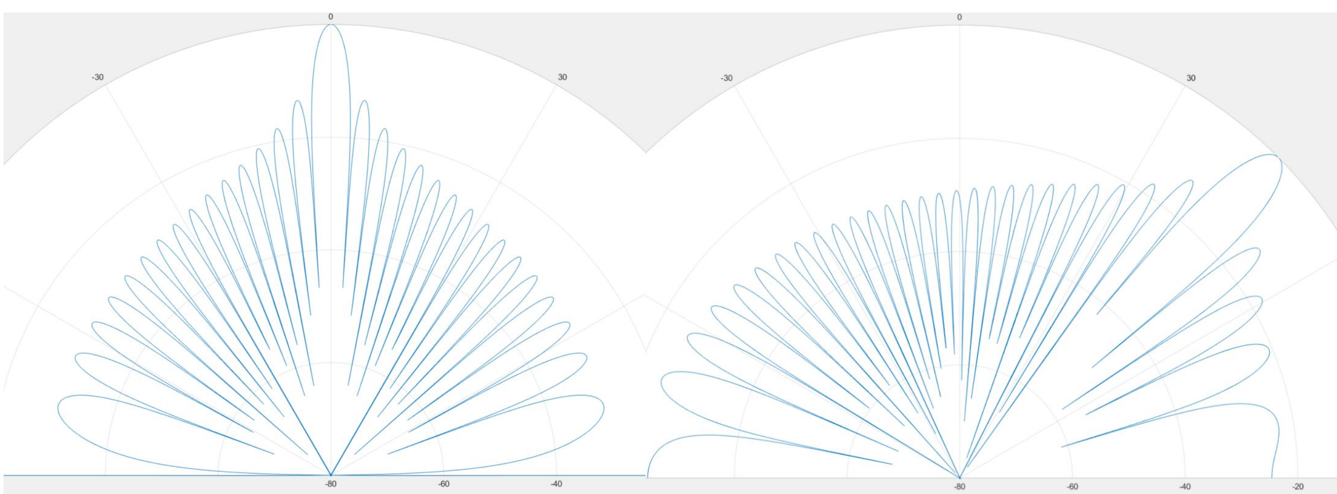
Two parameters of a signal that can be controlled in a circuit are the magnitude and the phase (fig. 10(a)). Amplifiers, power divider circuits or attenuators can be used to control the amplitude. IC phase shifters or true-time delay circuits can be used to control the phase. A true-time delay circuit can be as simple as routing a longer path to different antennas and controlling the specific length the signal has to travel. If the signals are fed from the same feeding point, a different path-length will result in a relative phase difference in the signals reaching the antennas, as shown in fig. 10(b).



(a) Controllable Elements (b) True-time delay circuit

Figure 10. Array elements with individual amplitude and phase control. [1]

With the idea of wave interference in mind, we can visualize how controlling the relative phase of the antennas can result in steering the main beam to a desired direction, as shown in figure 11, or in the following animation.



(a) Main beam at boresight (b) Main beam at 45°

Figure 11. Main beam steering by control over the relative phase of each antenna.

Electrically steering the main beam offers the advantage of eliminating a mechanical structure, saving costs, complexity and providing resilience to mechanical failure. The rates at which the beam can be steered are much faster than a rotational system. While the ability of steering the main beam electrically offers great advantages, the shape of the radiation pattern still remains as a sinc-type function, with unwanted side lobes with high power levels.

Shaping

We saw that steering can be achieved with phase-shifters, but the shape remained practically the same. In this section we will show how controlling the amplitude weights (fig. 12) of the antenna elements can result in changes in the shape of the radiation pattern.

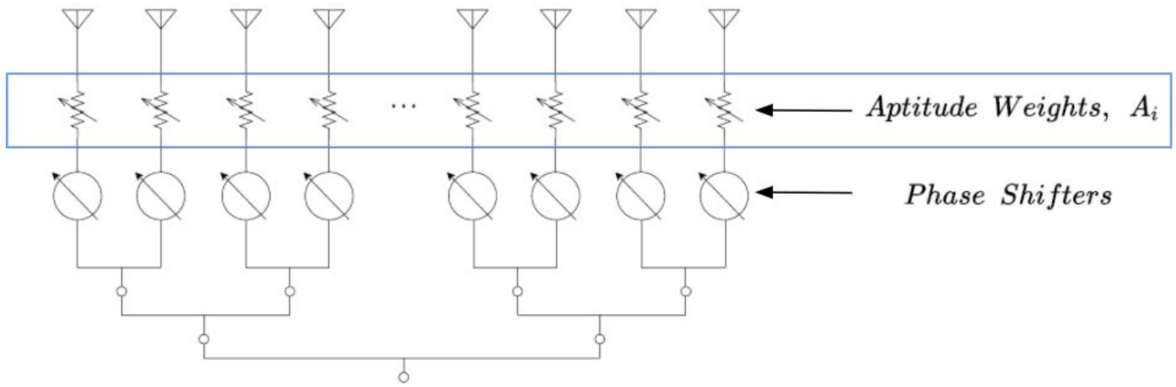
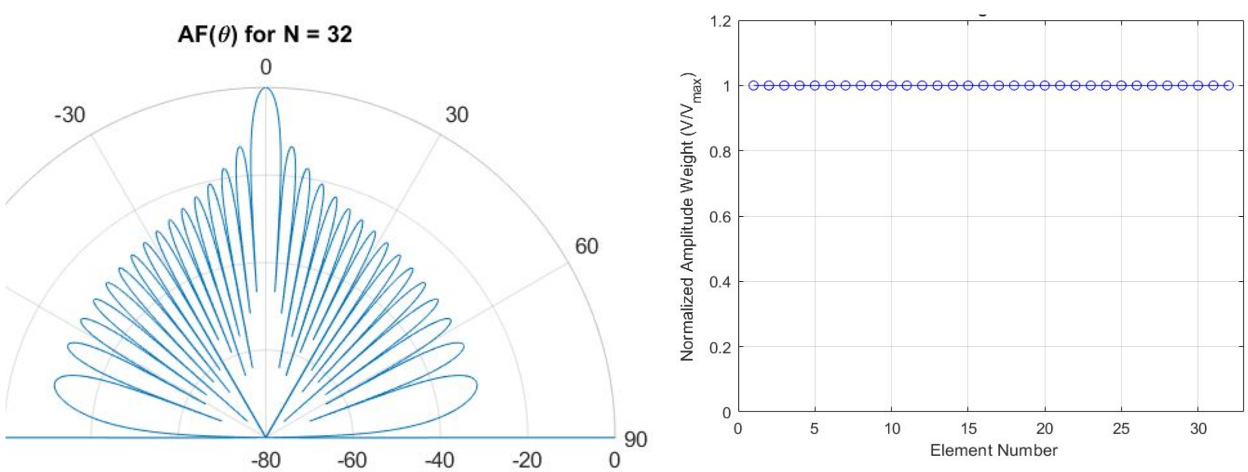


Figure 12. Phased-Array Illustration

Uniform Weights

The radiation pattern in figure 11(a) assumed a uniform weight distribution on all the antennas, as shown in figure 13.



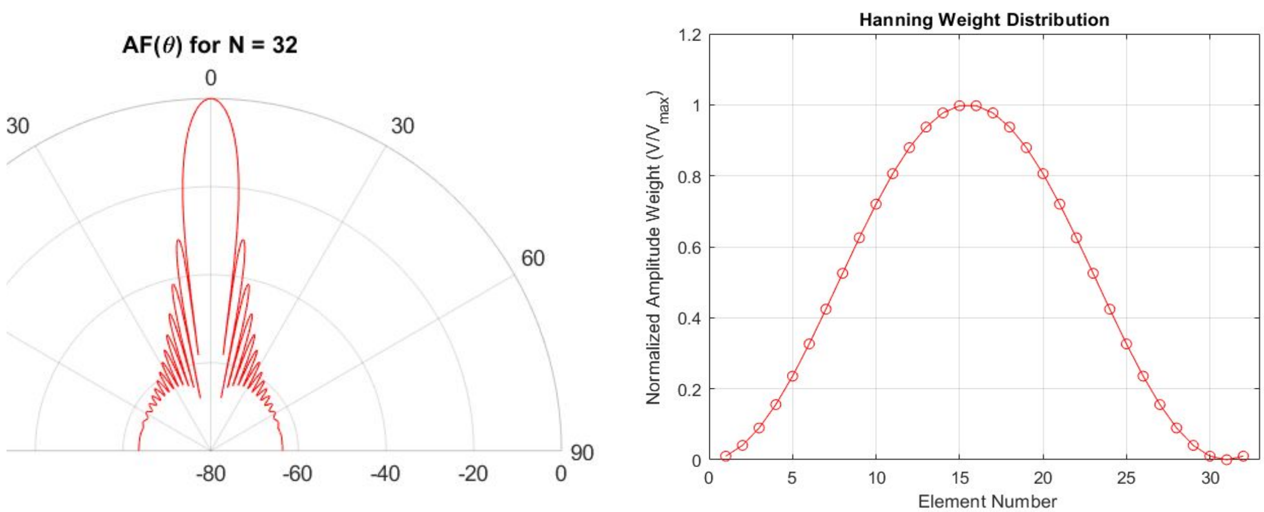
(a) Radiation Pattern (polar coordinates) (b) Uniform weight distribution

Figure 13. Radiation pattern in polar coordinates from a uniform weight distribution.

Hanning Distribution

If instead of a uniform weight distribution, we apply a Hanning distribution (fig. 14(b)) following equation 2, where the antennas in the center of the array receive stronger signals than the antennas at the edges, we can predict a pattern with a *pointier* profile, as shown in figure 14(a).

$$A_n = \frac{1}{2}\left(1 - cos\left(2\pi \frac{n}{N-1}\right)\right)$$
$$for \;\; n = 1, 2, \ldots, N \qquad \text{(Eq. 2)}$$



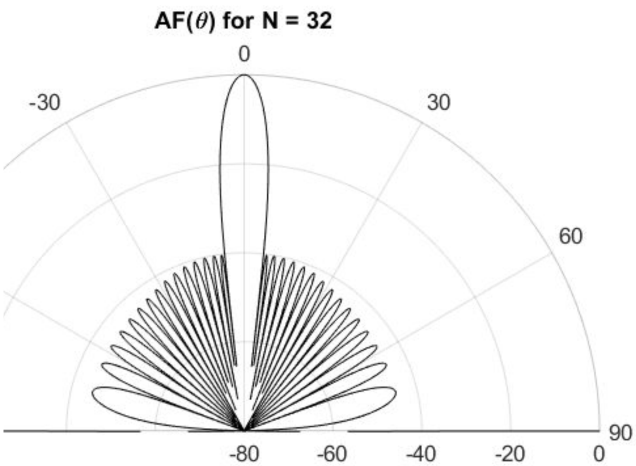
(a) Radiation Pattern (b) Hanning weight distribution

Figure 14. Radiation pattern in polar coordinates from a Hanning weight distribution.

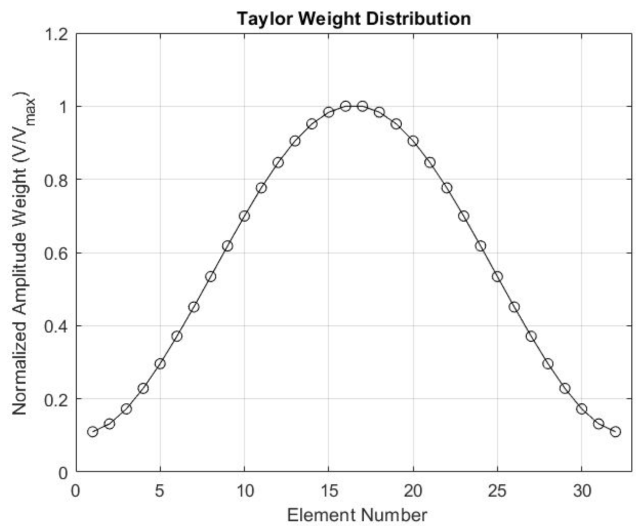
Applying a weight distribution following the Hanning function in equation 2 will provide a much higher directivity and the power dissipated in the side lobes will be significantly reduced.

Taylor Function

Implementing the Hanning weight distribution, however, is not easily realizable. Instead, a taylor distribution function is commonly used. This DSP algorithm can be accessed via multiple sources. In MATLAB, the function `taylorwin(N, nbar, sll)` returns a weight distribution for `N` elements, `sll`, the desired dB level of nearest sidelobes, and `nbar` the number of nearest side lobs with the `sll` value.



(b) Radiation Pattern



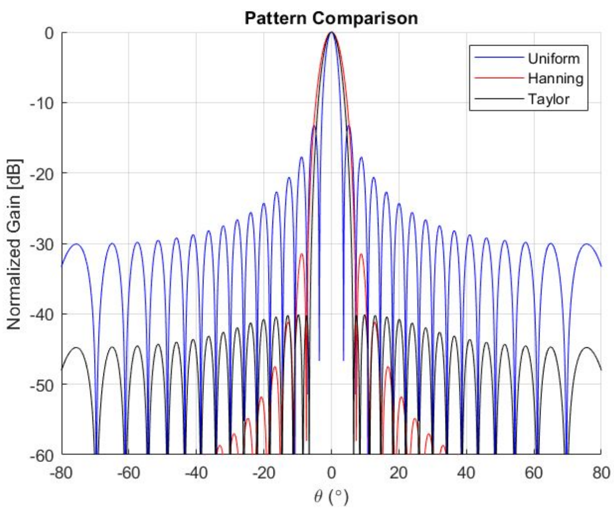
(b) Taylor weight distribution `taylorwin(32, 6, -40)`

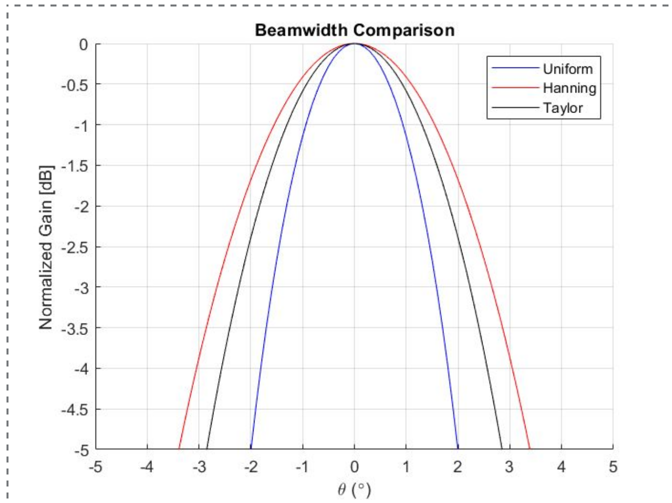
Figure 15. Radiation pattern in polar coordinates from a Taylor weight distribution.

With a similar weight distribution as with the Hanning function, the shape of the radiation pattern has a slightly different profile, but the same desired characteristic: lower side lobe levels.

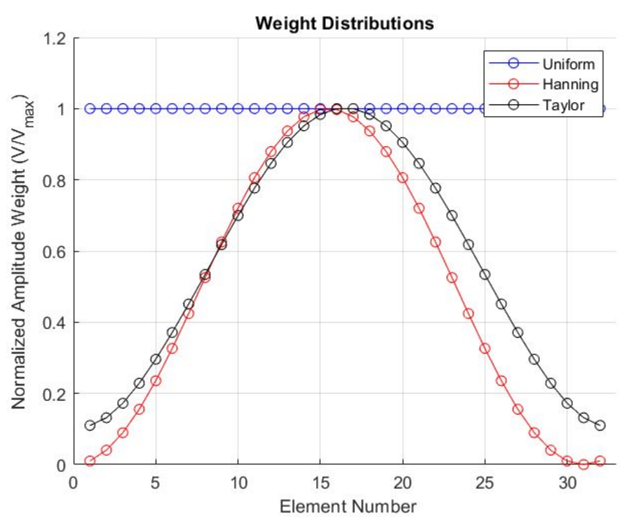
Comparison

Comparing the three weight distributions, we see the differences in the radiation patterns and the main beamwidth. Depending on the constraints of the application, the widening of the beamwidth might need to be considered as a design parameter. In either case, controlling the weights of the signals feeding the individual antennas can provide a variety of desired radiation patterns depending on the application.





(a) Superimposed Radiation Patterns . (b) Close-up picture of the Beamwidth



(c) Superimposed Weight Distribution Functions.

Figure 16. Three-way comparison between Uniform, Hanning and Taylor Weight Distributions.

Drawback - Grating Lobes

As with any other featured technology, there are always tradeoffs one should be aware of and manage well. The versatility in direction and shape of phased-array antennas do not come with zero costs. Grating lobes, as shown in figure 17 are unwanted and sometimes present in phased-array antennas due to signal aliasing. Grating lobes are not found in individual antennas as they are a consequence of array arrangements.

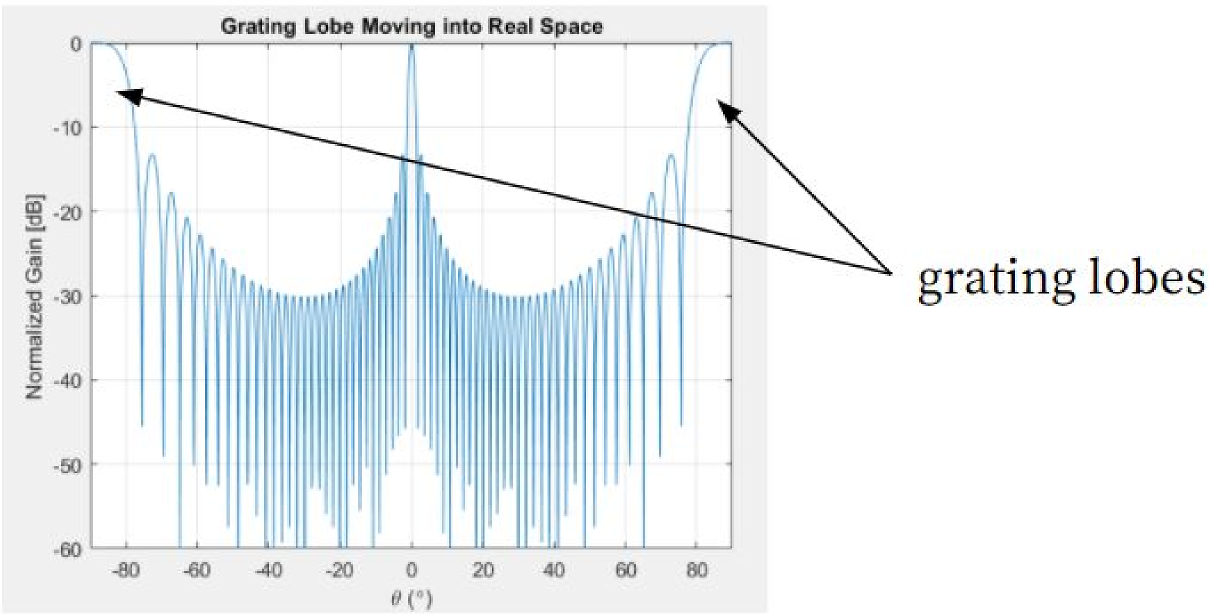


Figure 17. Grating Lobes present in a radiation pattern.

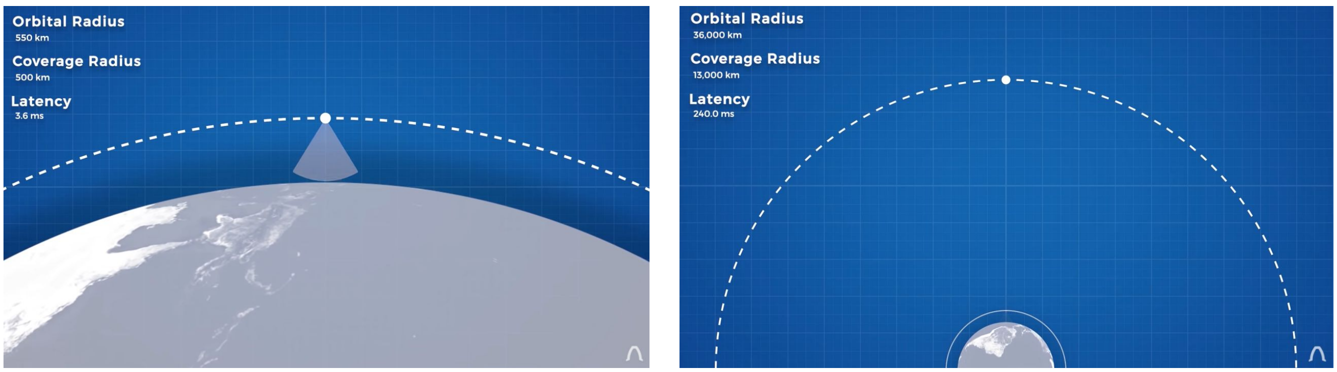
The precise explanation behind Grating Lobes is beyond the scope of this text, since it involves advanced topics in the field of signal processing and the constraints of discrete processing and algorithms. A high level understanding can be obtained using the Nyquist Theorem in the time domain as an analogy. As the Nyquist, or sampling, theorem states: the sampling frequency needed to reproduce an incoming signal must be 2 times higher than the frequency of the signal. Otherwise, aliasing occurs and the output signal gets distorted.

Using the same concept, but in the space domain, if two neighboring antennas are located too close together or too far apart, the scanning of signals will not result in an optimal scan given the relative phases in the signals received and the overall radiation pattern will get distorted, in the form of grating lobes. To avoid grating lobes in a linear array, the distance between neighboring antennas should be between half and a full wavelength, as in eq. 3

$$\lambda/2 < d < \lambda \qquad \text{(Eq. 3)}$$

Recent Application - SpaceX's Starlink

One of SpaceX's latest missions is to provide low-latency-satellite-internet worldwide. In order to do so, they have launched and continue to launch thousands of satellites to Low Earth Orbit (fig. 18(a)). To date, this is the first deployed project of this size with the objective to provide worldwide internet. Common satellites providing internet are placed in Geosynchronous Orbit, where they can service the specific region the satellite is pointing to (fig. 18(b)), as it will rotate synchronously with Earth.



(a) Low Earth Orbit (b) Geosynchronous Orbit

Figure 18. Comparison between low earth orbit and geosynchronous orbit. [5]

A satellite placed in low earth orbit, however, will rotate faster than the Earth to keep its orbit, hence servicing different areas as it moves. To achieve constant service, a constellation of Starlink satellites orbiting around the earth covering the desired areas at all times is needed, as shown in figure 19.

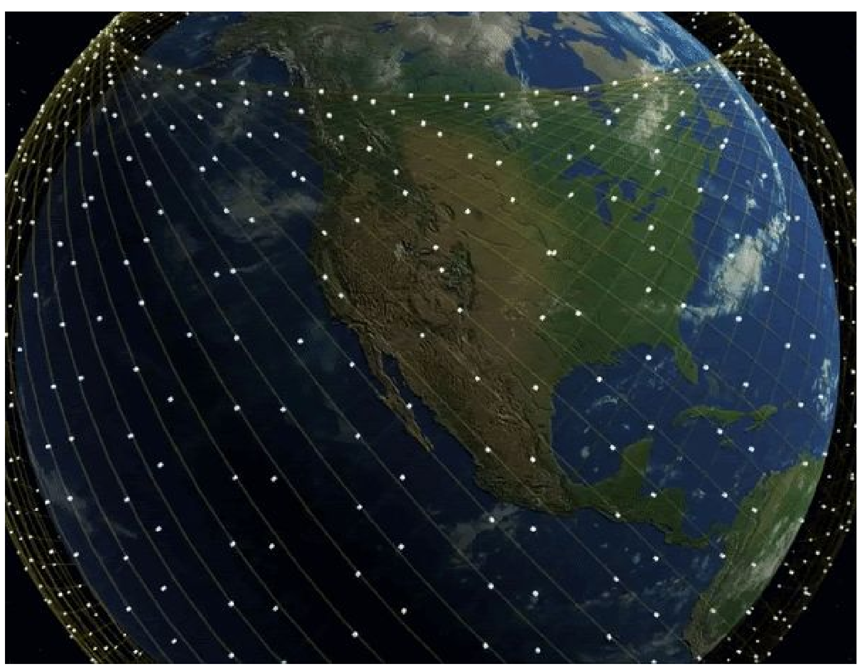


Figure 19. Starlink Satellite Constellation [5]

There is one more caveat. The signal sent to earth from the satellites should reach the location of receiver stations, while the satellite rotates. To accomplish this, the signal must be steered as the satellite moves. As you probably guessed right, Starlink’s satellites have on board 4 phased-array satellites for signal transmission, as shown in figure 20.

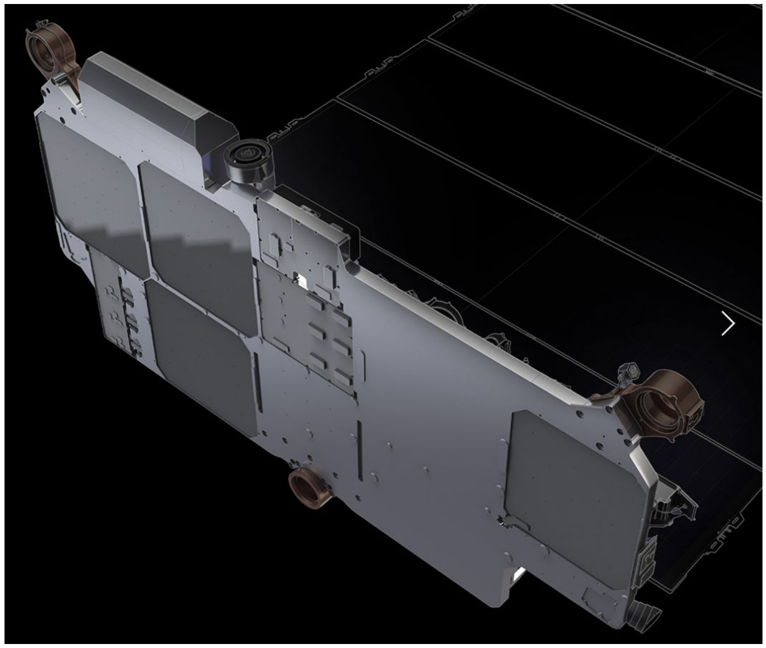
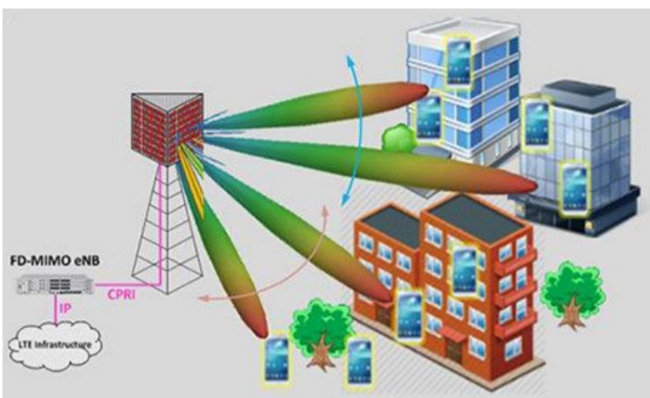


Figure 20. Starlink Satellite with four phased-array antennas. [6]

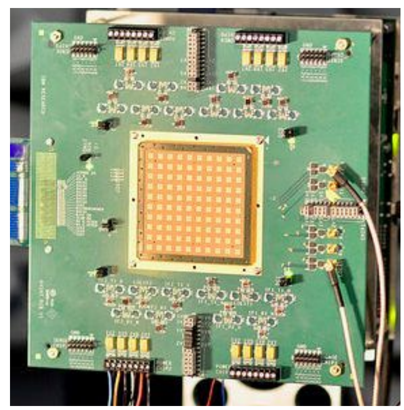
Final Remarks

In this text, we investigated the advantages of phased-array antennas over other individual antenna topologies, which can be highlighted as providing versatility and control over the radiation pattern. We also covered the main disadvantage unique to this antenna topology: Grating Lobes. Finally we presented a current application of phased-array antennas with SpaceX's Starlink satellite constellation.

Before concluding this text, it is worth mentioning that phased-array antennas are at the heart of 5G and Internet of Things (IoT) technologies. In addition to the versatility highlighted in this text, phased-array antennas support massive MIMO (multiple-input, multiple-out) communication capabilities as illustrated in figure 21(a). These antennas are also highly present in the new upcoming mmWave architectures (fig. 21(b)), with big companies investing large amounts of resources and time in research and development of phased-array antennas (fig. 21(c) and (d)). Phased-array antennas are providing a great architecture for the advancement in communication systems.

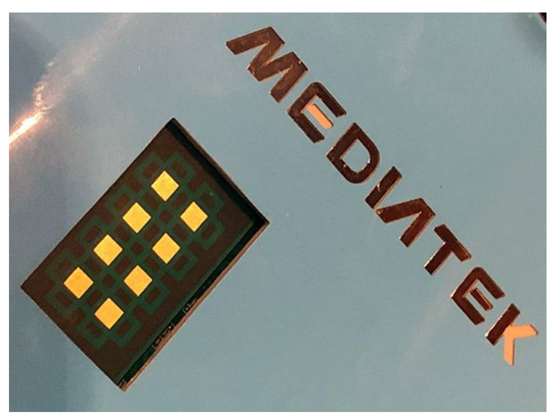


(a) Massive MIMO illustration [10]



(b) IBM + Ericsson mmWave prototype [8]

(c) Qualcomm's 5G project antenna [9]



(d) Mediatek cell phone device antenna [7]

Figure 21. Various applications of phased-array antennas

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