DIPOLE ANTENNAS

A dipole antenna is most commonly a linear metallic wire or rod with a feed point at the center as shown in Fig. 1. Most often, this type of antenna has two symmetrical, aligned, radiating arms. Because of the symmetry of the antenna relative to the xy plane containing the feed point, the resultant radiation is independent of ϕ (rotationally symmetric about the z axis). Dipole antennas and arrays of dipoles are commonly used for high-frequency (HF) and ultrahigh-frequency (UHF) communications, TV, and FM broadcasting, and as electric field probes. This article will describe the basic nature and applications of dipole antennas and some of their variations such as biconical and bowtie antennas, slot dipoles, folded dipoles, sleeve dipoles, and shunt-fed dipoles. The commonly used broadband log-periodic and Yagi–Uda dipole arrays are also discussed.

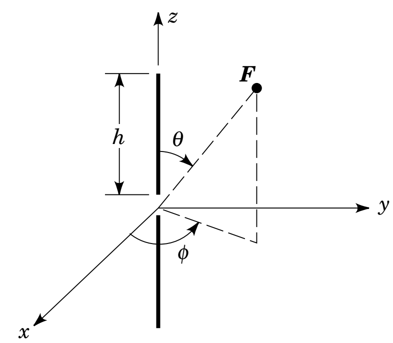


Figure 1. Dipole antenna variations.

INFINITESIMAL DIPOLE (HERTZIAN DIPOLE)

An infinitesimal dipole ($L \ll \lambda$) is a small element of a linear dipole that is assumed to be short enough that the current (I) can be assumed to be constant along its length L. It is also called a Hertzian dipole. The electric and magnetic field components of this dipole are (1)

$$\boldsymbol{H} = \frac{1}{4\pi} IL \sin\theta \, e^{-j\beta_0 r} \left(\frac{j\beta_0}{r} + \frac{1}{r^2} \right) \boldsymbol{\phi} \tag{1}$$

$$\begin{aligned} \boldsymbol{E} = {} & \frac{j\eta_0 IL}{2\pi\beta_0} \cos\theta \left(\frac{j\beta_0}{r^2} + \frac{1}{r^3} \right) e^{-j\beta_0 r} \boldsymbol{r} \\ & - \frac{j\eta_0 IL}{4\pi\beta_0} \sin\theta \left(-\frac{\beta_0^2}{r} + \frac{j\beta_0}{r^2} + \frac{1}{r^3} \right) e^{-j\beta_0 r} \boldsymbol{\theta} \end{aligned} \tag{2}$$

where $\eta_0 = (\mu_0/\epsilon_0)^{1/2}$ is the intrinsic impedance ($= 377\ \Omega$) for free space, and $\beta_0 = \omega(\mu_0\epsilon_0)^{1/2}$ is the propagation constant ($= \omega/c$, where c is the speed of light). The fields decay rapidly ($1/r^3$ variation) very near the antenna, and less rapidly ($1/r$ variation) farther away. The fields with terms $1/r^2$ and $1/r^3$ (the *induction terms*) provide energy that is stored near the antenna. The fields with $1/r$ variation (the *radiation terms*) represent actual energy propagation away from the antenna. The distance away from the antenna where the induction and radiation terms are equal is $d = \lambda/2\pi$. When $d < \lambda/2\pi$, one is in the *near field* of the antenna, and the induction terms dominate. When $d > \lambda/2\pi$, one is in the *far field,* and the radiation terms dominate. In the far field, the wave propagation is in the transverse electromagnetic (TEM) mode, which is characteristic of far-field radiation from finite structures.

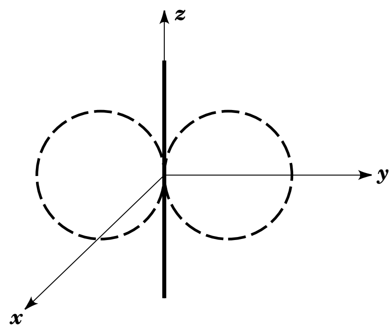


Figure 2. Radiation pattern for an infinitesimal (or Hertzian) dipole.

The far-zone radiated fields of the Hertzian dipole follow from (1) and (2) by retaining the $1/r$ varying terms:

$$\boldsymbol{H} = \frac{j}{4\pi r} IL \sin\theta \, e^{-j\beta_0 r} \boldsymbol{\phi} \tag{3}$$

$$\boldsymbol{E} = \frac{j\eta_0}{4\pi r} IL \sin\theta \, e^{-j\beta_0 r} \boldsymbol{\theta} \tag{4}$$

As expected for TEM wave propagation, the $\boldsymbol{E}$ and $\boldsymbol{H}$ fields are perpendicular to each other and to the outward propagation in the $\boldsymbol{r}$ direction. Also, the ratio $E_\theta/H_\phi = \eta_0 = (\mu_0/\epsilon_0)^{1/2}$, which is the intrinsic impedance of free space.

The radiation pattern of this Hertzian dipole is shown in Fig. 2, and exhibits the classical symmetry expected of dipole antennas, being both independent of ϕ and symmetric about the xy plane through the center (feedpoint) of the dipole. The magnitude of the total radiated power is $P_{\rm rad} = 40\ \pi^2 I_0^2\ (L/\lambda)^2$. From Eqs. (3) and (4) it is interesting to note that even for this constant-current infinitesimal dipole, the radiated power density is proportional to $\sin^2\ \theta$. Hence, it is maximum for $\theta = 90°$ (i.e. in the xy plane normal to the orientation of the dipole) and zero for the directions along the length of the dipole ($\theta = 0°$ and $180°$). The latter property for zero radiation along the length of the dipole will be seen for all linear dipoles regardless of length. It follows from the fact that a linear antenna may be considered as composed of infinitesimal dipoles do not create $\boldsymbol{E}$ and $\boldsymbol{H}$ fields or radiated power density for the $\theta = 0°$ and $180°$ directions.

LINEAR DIPOLE ANTENNAS

The geometry of a linear dipole antenna of length $2h$ is shown in Fig. 1. The current distribution is sinusoidal and is approximately given by

$$I(z') = \frac{I(0)}{\sin kh} \sin k(h - |z'|) \qquad \text{for} \quad -h < z' < h \tag{5}$$

where $I(0)$ is the current at the feedpoint of the antenna, $h = L/2$ is the half length of the antenna, and $k = \omega(\mu\epsilon)^{1/2}$ is the propagation constant in the material surrounding the dipole. The current distributions for several lengths of dipole antennas are shown in Fig. 3.

The electric and magnetic fields around the dipole are calculated by modeling the antenna as a series of Hertzian or elemental dipoles and integrating the fields from each of these elements. The resultant fields far from the antenna at a distance r_0 are

$$\boldsymbol{E} = \frac{j\eta I(0)}{2\pi r \sin kh} F(\theta) e^{j(\omega t - kr)} \boldsymbol{\theta} \tag{6}$$

and

$$\boldsymbol{H} = \frac{jI(0)}{2\pi r \sin kh} F(\theta) e^{j(\omega t - kr)} \boldsymbol{\phi} \tag{7}$$

where $\eta = (\mu/\epsilon)^{1/2}$, and where the θ dependence $F(\theta)$ of the radiated fields is called the pattern factor and is given by the following:

$$F(\theta) = \frac{\cos(kh\cos\theta) - \cos kh}{\sin\theta} \tag{8}$$

The radiated power density $P(\theta)$ is given by

$$P(\theta) = \frac{\boldsymbol{E}\cdot\boldsymbol{E}^*}{2\eta} = \frac{\eta I^2(0)}{8\pi^2 r^2 \sin^2\ kh} F^2(\theta) \tag{9}$$

Using $\eta = \eta_0 = 120\pi$, this can also be expressed in terms of the total radiated power W [$= I^2(0)R_{\rm a}/2$] and the feedpoint resistance $R_{\rm a}$ as follows:

$$P(\theta) = \frac{30}{\pi r^2}\frac{W}{R_{\rm a}}\frac{F^2(\theta)}{\sin^2\ kh} \tag{10}$$

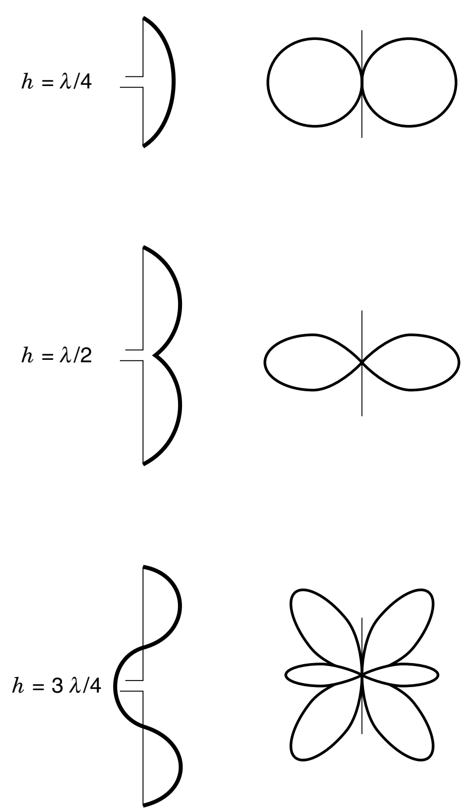


Figure 3. Current distributions and associated radiation patterns for several different lengths of dipole antennas.

Table 1. Wire Lengths Required to Produce a Resonant Half-Wave Dipole for a Wire Diameter of 2*a* and a Length *L*

Length-to-Diameter Ratio, $L/(2a)$	Shortening Required (%)	Resonant Length, L	Dipole Thickness Class
5000	2	0.49λ	Very thin
50	5	0.475λ	Thin
10	9	0.455λ	Thick

The normalized radiation patterns are shown in Fig. 3(b) for several different lengths of dipoles.

The directivity of a dipole antenna related to the maximum power density that an antenna can create at a distance r_0 is given by

$$D = \frac{P_{\max}}{P_0} = \frac{F^2(\theta)_{\max}}{\frac{1}{2}\int_0^{\pi} F^2(\theta)\sin\theta\, d\theta} = \frac{120}{R_a}\frac{F^2(\theta)_{\max}}{\sin^2 kh} \tag{11}$$

where $P_0 = W/(4\pi r_0^2)$ is the isotropic power density that would have been created at the field point if the antenna had a directivity of one and radiated isotropically for all angles (clearly a mathematical possibility though not physically realizable).

The input resistance R_a of a center-fed dipole antenna of length $L = 2h$ is twice that of an end-fed monopole antenna of length h. This may therefore be obtained by using the graphs given in the related encyclopedia article on MONOPOLE ANTENNAS.

The ohmic losses of a dipole antenna [given by $I^2(0)R_{\text{ohmic}}/2$] are quite small, particularly for $h/\lambda > 0.1$. The resultant antenna radiation efficiencies [given by $R_a/(R_a + R_{\text{ohmic}})$] are on the order of 90% to 99%.

Two effects make physical dipoles act slightly different than ideal dipoles. The first is that realistic antennas have some finite thickness, and the second is that the ends of the dipole couple capacitively to air, effectively making the dipole electrically longer by 2% to 9% than its physical length. For a half-wave dipole ($L = 2h = \lambda/2$), for instance, the physical length must be slightly shortened in order to create a resonant-length antenna ($X_a = 0$). Table 1 shows the wire lengths required to produce a resonant half-wave dipole. This shortening varies from 2% to 9%, depending on the thickness of the dipole.

Since a dipole antenna is a physically resonant structure, its feedpoint impedance (particularly the reactance X_a) varies greatly with frequency. Thus, these antennas have a fairly narrow bandwidth. The voltage standing-wave ratio (VSWR) of a dipole antenna as a function of frequency and wire thickness is shown in Fig. 4 for an antenna that would be half-wave resonant at 300 MHz. Using a criterion for "usable bandwidth" that the measured VSWR should be less than 2 : 1, this antenna has bandwidths of $310 - 262 = 48$ MHz for the thicker wire and $304 - 280 = 24$ MHz for the thinner wire. As fractions of the design frequency (300 MHz), the bandwidths are 16% and 8%, respectively (2).

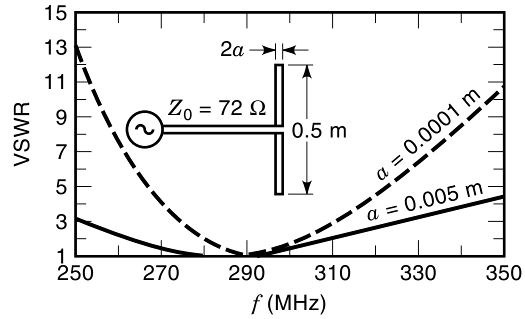


Figure 4. VSWR of a dipole antenna as a function of frequency and wire thickness (from Ref. 5).

SLOT DIPOLE

The slot dipole antenna is dual to the linear dipole antenna. The radiation pattern of a slot antenna is identical to that of the linear dipole of the same length (see Fig. 3) except that the orientations of ***E*** and ***H*** are interchanged. Also, the feedpoint impedance Z_s of a slot antenna is related to that of the dual linear antenna by the following equation:

$$Z_s = \frac{\eta^2}{4Z_a} \tag{12}$$

where Z_a is the impedance of the dual linear antenna.

BICONICAL DIPOLES

A biconical dipole, as shown in Fig. 5(a) is commonly used for broadband applications when the flare angle θ is between 30° and 60°. The exact flare angle is not critical, so it is generally chosen so that the impedance of the dipole nearly matches the impedance of the feeder line to which it is connected. The impedance of the biconical dipole varies as a function of wavelength and flare angle, with a relatively flat impedance response for wide flare angles. Hence the broadband nature of this antenna.

Some variations of this method of using flaring to increase bandwidth are the flat bowtie antenna (which may be built on a printed circuit board) and the wire version of the biconical antenna shown in Figs. 5(b) and (c), respectively.

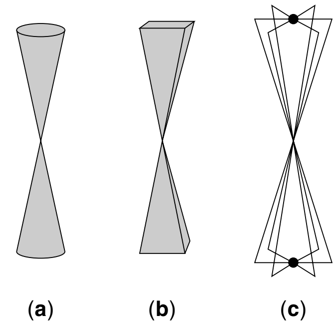


Figure 5. Biconical dipole antenna and variations: (a) biconical dipole, (b) flat bowtie, (c) wire version of biconical dipole.

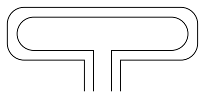


Figure 6. Folded dipole antenna.

FOLDED DIPOLE ANTENNAS

A folded dipole antenna is shown in Fig. 6. The dipole is created by joining two cylindrical dipoles at the ends and driving the entire structure by a transmission line (often a two-wire transmission line) at the center of one arm as shown. The feedpoint impedance of a folded dipole of two identical-diameter arms is four times as large as for an unfolded dipole of the same length. This can actually be advantageous, since the feedpoint resistance may now be comparable to the characteristic impedance Z_0 of the transmission or feeder line. The reactance of the antenna may easily be compensated by using a lumped element with a reactance that is the negative of the reactance at the terminals of the folded dipole antenna or else by using a foreshortened antenna length to resonant length arms so that $X_a = 0$ (see Table 1).

SHUNT-FED DIPOLES

Matching networks of reactive elements are generally required to match the feedpoint impedance ($R_a + jX_a$) of center-fed dipoles to transmission lines. Typically these lines have characteristic impedances on the order of 300 Ω to 600 Ω. To alleviate the need for matching networks, the antennas may be shunt-fed at symmetric locations off the center point as shown in Fig. 7. This procedure, using either the delta match [Fig. 7(a)] or the T match [Fig. 7(b)], is often used for half-wave dipoles ($2h = \lambda/2$) with A and B dimensions that are typically on the order of 0.10λ to 0.15λ (1).

APPLICATIONS

Dipole antennas and arrays of dipole antennas are used for short-wave (3 MHz to 30 MHz) and for VHF and UHF (30 MHz to 900 MHz) radio and TV broadcasting. If directional communication is desired such as for short-wave radio transmission via the ionosphere, a phased array of horizontal dipoles may be used mounted above a ground plane. The spacing is chosen so as to send the major lobe of radiation towards the sky at a suitable angle to reflect off the ionosphere and provide broadcast coverage over the desired service area.

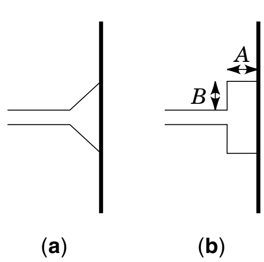


Figure 7. Shunt-fed dipoles: (a) delta match, (b) T match.

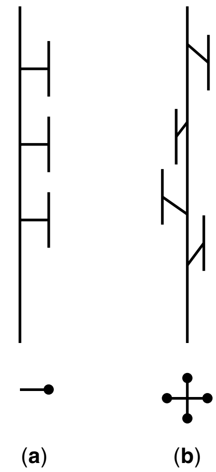


Figure 8. Collinearly mounted vertical dipoles for VHF and UHF radio and TV broadcasting: (a) pole-mounted array of collinear dipoles, (b) vertical dipoles spaced around a pole.

For VHF and UHF radio and TV broadcasting over a 360° azimuthal angle, collinearly mounted vertical dipoles that are excited in phase with each other are often used. Two examples of this are shown in Figs. 8(a) and (b). An example variation of this is a three- to eight-bay turnstile antenna used for TV broadcasting, shown in Fig. 9(a). Each of the turnstiles is made of two perpendicular slot antennas as shown in Fig. 9(b).

LOG-PERIODIC ANTENNAS

For broad-band applications, log-periodic antennas are also commonly used as both transmitting and receiving antennas. The bandwidth is easily controlled by adjusting the relative lengths of the longest and shortest elements in the array. The

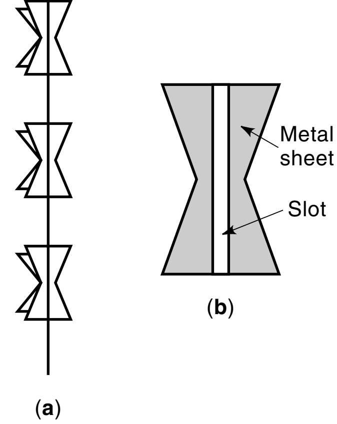
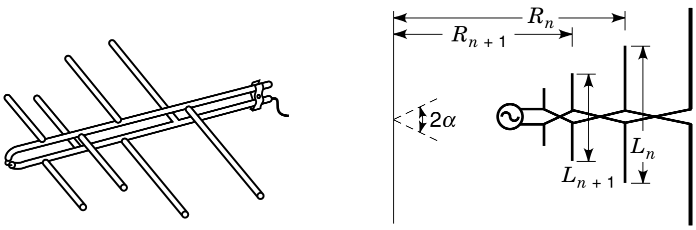


Figure 9. Variation on collinearly mounted vertical dipoles: (a) turnstile antenna used for TV broadcasting, (b) two perpendicular slot antennas that make up each turnstile.



(a) (b)

Figure 10. Log-periodic dipole array: (a) geometry of a log-periodic array, showing how the phase-reversal feed system for this antenna is constructed (from Ref. 1), (b) equivalent antenna model of the log-periodic array.

geometry of a log-periodic array is shown in Fig. 10(a), which shows how the phase-reversal feed system for this antenna is constructed. The equivalent antenna model of this array is shown in Fig. 10(b). The elements of the array are dipole antennas that increase in both length and spacing according to the formula

$$\tau = \frac{R_{n+1}}{R_n} = \frac{L_{n+1}}{L_n} = \frac{d_{n+1}}{d_n} < 1 \tag{13}$$

where $\tau = f_n/f_{n+1}$ is the ratio of the resonant frequencies f_n and f_{n+1} of adjacent dipole elements. Since lengths and spacings are interrelated, the choice of one initial value controls the design of the remaining elements. The spacing between one dipole and its adjacent shorter neighbor is given by

$$\sigma = \frac{d_n}{2L_n} = \frac{1-\tau}{4}\cot\alpha \tag{14}$$

Log-periodic arrays are generally constructed with small values of α [$10° \leq \alpha \leq 45°$ (2)] and large values of τ [$0.7 \leq \tau \leq 0.95$ (3)], which essentially gives a traveling wave propagating to the left in the backfire direction, away from the antenna array. The mechanism of this array is that only the elements that are approximately half-wavelength long radiate, and since they are radiating to the left, the smaller elements do not interfere with them. This is accomplished by the phase reversal of the feeds. An array that is built without the phase reversal radiates in the end-fire direction. The interference of the longer elements to the right of radiating elements results in unwanted reflections and erratic impedance behavior, known as *end effect.*

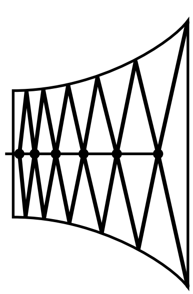


Figure 11. Log-periodic array with sawtooth wire elements for increased bandwidth. Dots indicate feed point locations. Heavy wires indicate dipole antennas. Light wires indicate wires for structural support only.

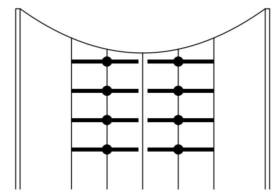


Figure 12. A broadband dipole curtain. Dots indicate feed point locations.

An effective way to further increase the bandwidth of a log-periodic array is to change from dipole elements to elements with individual broader bandwidths, similarly to changing from a dipole antenna to a biconical antenna. This is accomplished for log-periodic arrays by using a configuration of wires such as is shown in Fig. 11, where each element is a sawtooth element and therefore has broader bandwidth than the individual dipole elements.

BROADBAND DIPOLE CURTAIN ARRAYS

A broadband dipole curtain as shown in Fig. 12 is commonly used for high-power (100 kW to 500 kW) HF ionospheric broadcasting and short-wave broadcasting stations. The curtain is composed of several dipoles, usually half a wavelength long, mounted horizontally or vertically in a rectangular or square array, often backed by a reflecting plane or wire mesh. This array has several desirable features, including high gain, broad bandwidth, independent control of horizontal and vertical radiation patterns, ease of matching (low VSWR), and the ability to broadcast high power efficiently. Using a phased-feeds system, this array allows beam steering of the radiation pattern in both the azimuthal and the elevation plane, providing a very high degree of flexibility.

VHF–UHF COMMUNICATION APPLICATIONS

Yagi–Uda Dipole Array

Yagi–Uda arrays are commonly used as general-purpose antennas from 3 MHz to 3000 MHz, and in particular as home TV antennas. They are inexpensive, have reasonable bandwidth, and have gains up to 17 dBi or more if multiple arrays are used. They have unidirectional beams with moderate side lobes (1).

A typical Yagi–Uda array is shown in Fig. 13. This array is a simple end-fire array of dipole antennas where only one

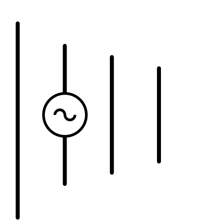


Figure 13. Yagi–Uda array.

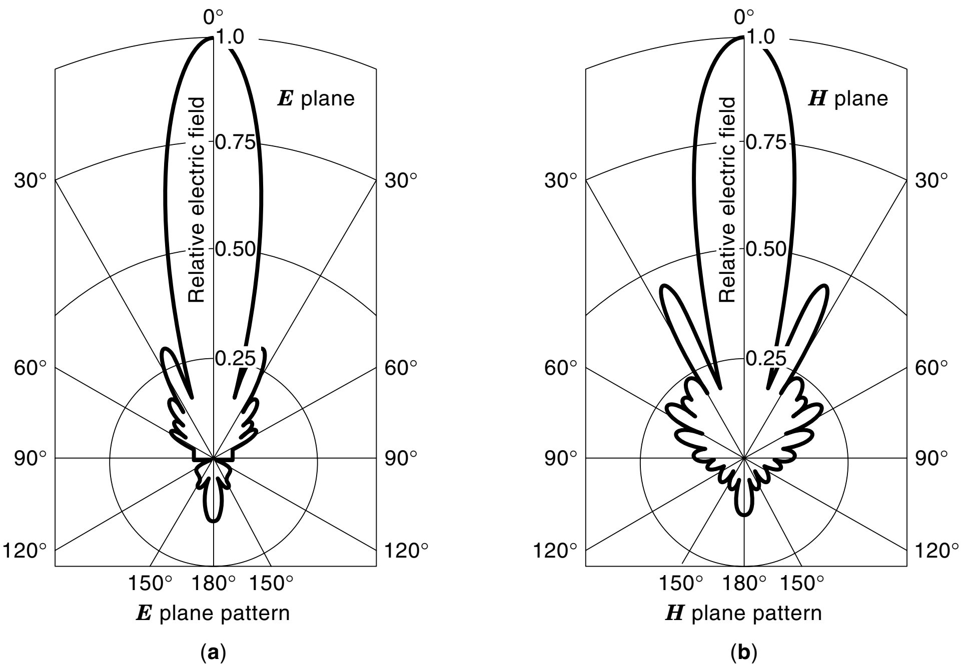


Figure 14. Typical *E*- and *H*-plane patterns of a Yagi–Uda array. Total number of elements = 27, number of directors = 25, number of reflectors = 1, number of driven elements = 1, total length of reflector = 0.5λ, total length of feeder = 0.47λ, total length of each director = 0.406λ, spacing between reflector and feeder = 0.125λ, spacing between adjacent directors = 0.34λ, radius of wires = 0.003λ. From G. A. Thiele, "Analysis of Yagi–Uda Antennas," *IEEE Trans. Antennas & Propag.,* **17**: 1969, © IEEE.

of the elements is driven and the rest are parasitic. The parasitic elements operate as either reflectors or directors. In general (1), the longest antenna, which is about $\lambda/2$ in length, is the main reflector, and is generally spaced $\lambda/4$ behind the driven dipole. The feed element is commonly a folded dipole antenna 0.45λ to 0.49λ long. Adding directors, which are generally 0.4λ to 0.45λ, to the front of the driven element increases the gain of the array. The directors are not always of the same length, diameter, or spacing. Common arrays have 6 to 12 directors and at most two reflectors. Additional improvements in gain by adding more elements are limited, but arrays have been designed with 30 to 40 elements (3). A gain (relative to isotropic) of 5 to 9 per wavelength of array length is typical for Yagi–Uda arrays, for an overall gain of 50 to 54 (14.8 dB to 17.3 dB).

The Yagi–Uda array is characterized by a main lobe of radiation in the direction of the director elements and small side lobes. The beamwidth is small, generally 30° to 60° (3). Typical *E*- and *H*-plane patterns of a Yagi–Uda array are shown in Fig. 14. Typically, the performance of a Yagi–Uda array is computed using numerical techniques (4). For the simple case where all of the elements are approximately the same size, the electric field pattern can be computed from the array factors of the various elements.

The input impedance of a Yagi–Uda array is often small. For example, for a 15-element array with reflector length 0.5λ, director spacing 0.34λ, and director length 0.406λ, the input impedance is 12 Ω, 22 Ω, 32 Ω, 50 Ω, or 62 Ω for reflector spacings of 0.10λ, 0.13λ, 0.15λ, 0.18λ, and 0.25λ, respectively. This can make matching to typical transmission lines (50, 75, or 300 Ω) difficult. Folded dipoles used for the driven element are therefore used to boost the input impedance by a factor of 4 or more.

Extensive studies of the design of Yagi–Uda arrays have been made (5), and tables are provided to optimize the Yagi–Uda array for a desired gain (2).

Dipoles for Circular Polarization

For applications that require a circularly polarized antenna such as TV and FM broadcasts and space communications, at least two dipoles, each of which has a linear polarization, must be combined in an array, often referred to as *crossed dipoles.* In a crossed-dipole configuration, dipoles are mounted perpendicular to each other for circular polarization or at other angles for elliptical polarization. Currents are fed 90° out of phase between the two dipoles. These can also be used as probes for sensing vector fields to isolate individual components of the electric field. Adaptations of the crossed dipole are shown in Figs. 15(a) and (b). Dipole arrays such as the

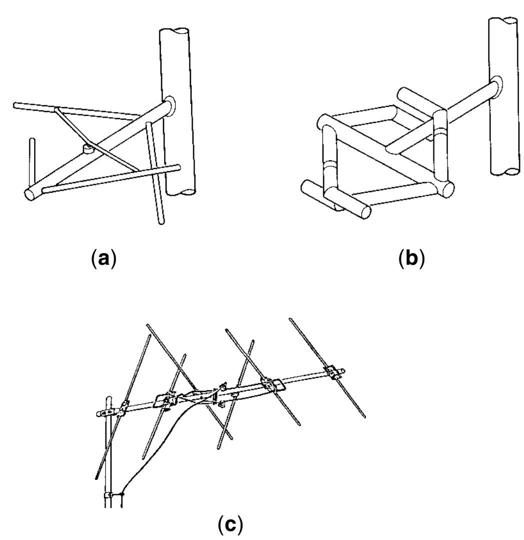


Figure 15. Cross-dipole applications for circular or elliptical polarization: (a) two shunt-feed slanted V dipoles, (b) series-fed slanted dipoles, (c) circularly polarized Yagi–Uda array. From Ref. 1.

Yagi–Uda can also be combined to provide circular polarization, as shown in Fig. 15(c).

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