Antenna Technology

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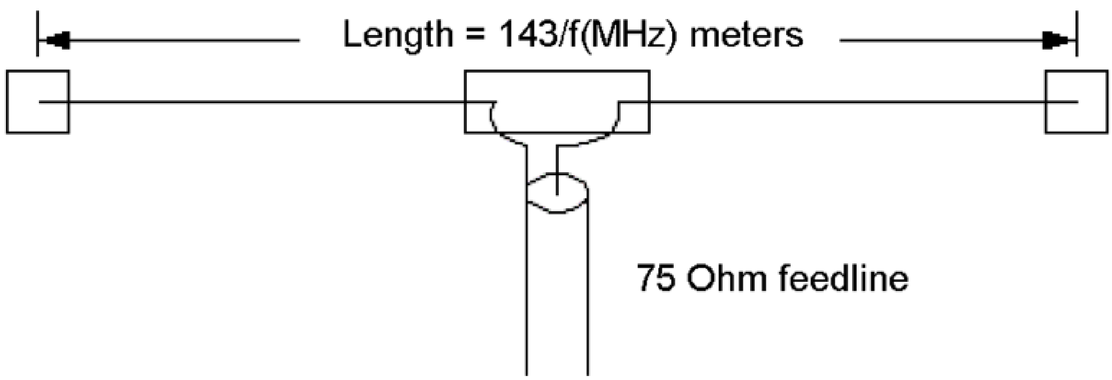
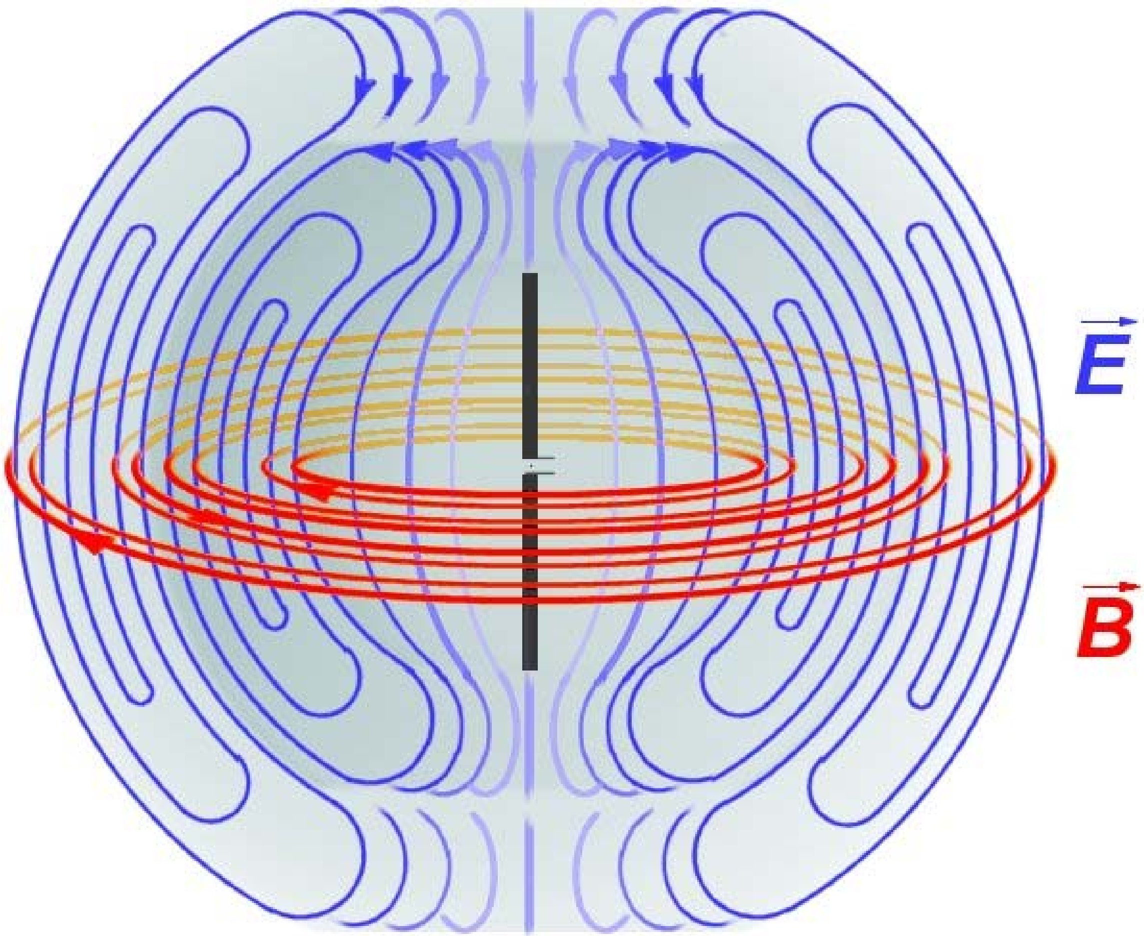
Dipole Antenna



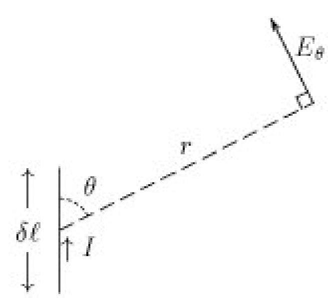
A schematic of a half-wave dipole antenna that a shortwave listener might build.

A **dipole antenna** is a radio antenna that can be made of a simple wire, with a center-fed driven element. It consists of two metal conductors of rod or wire, oriented parallel and collinear with each other (in line with each other), with a small space between them. The radio frequency voltage is applied to the antenna at the center, between the two conductors. These antennas are the simplest practical antennas from a theoretical point of view. They are used alone as antennas, notably in traditional "rabbit ears" television antennas, and as the driven element in many other types of antennas, such as the Yagi. Dipole antennas were invented by German physicist Heinrich Hertz around 1886 in his pioneering experiments with radio waves.



Electric fields *(blue)* and magnetic fields *(red)* radiated by a dipole antenna

Elementary doublet



An elementary doublet is a small length of conductor $\delta\ell$(small compared to the wavelength λ) carrying an alternating current:

$$I = I_0 e^{i\omega t}.$$

Here $\omega = 2\pi f$ is the angular frequency (and f the frequency), and i is $\sqrt{-1}$, so that I is a phasor.

Note that this dipole cannot be physically constructed because the current needs somewhere to come from and somewhere to go to. In reality, this small length of conductor will be just one of the multiple segments into which we must divide a real antenna, in order to calculate its properties. The interest of this imaginary elementary antenna is that we can easily calculate the electrical far field of the electromagnetic wave radiated by each elementary doublet. We give just the result:

$$E_\theta = \frac{-i I_\circ \sin\theta}{2\varepsilon_\circ c r} \frac{\delta\ell}{\lambda} e^{i(\omega t - kr)}$$

Where,

- E_θ is the far electric field of the electromagnetic wave radiated in the θ direction.
- $\varepsilon_\circ$ is the permittivity of vacuum.
- c is the speed of light in vacuum.
- r is the distance from the doublet to the point where the electrical field E_θ is evaluated.
- k is the wavenumber $k = \frac{2\pi}{\lambda}$

The exponent of e accounts for the phase dependence of the electrical field on time and the distance from the dipole.

The far electric field E_θ of the electromagnetic wave is coplanar with the conductor and perpendicular with the line joining the dipole to the point where the field is evaluated. If the dipole is placed in the center of a sphere in the axis south-north, the electric field would be parallel to geographic meridians and the magnetic field of the electromagnetic wave would be parallel to geographic parallels.

Near Field

The above formulas are valid for the far field of the antenna ($r \gg \lambda/(2\pi)$), and are the only contribution to the radiated field. The formulas in the near field have additional terms that reduce with r^2 and r^3. These are,

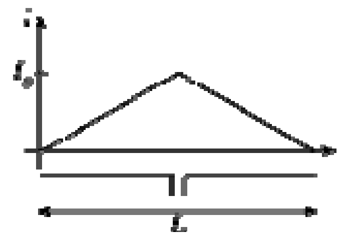
$$E_r = \frac{Z}{2\pi} I_0 \, \delta l \left(\frac{1}{r^2} - i \, \frac{\lambda}{2\pi \, r^3} \right) e^{i(\omega t - kr)} \; \cos(\theta)$$

$$E_\theta = i \frac{Z}{2\lambda} I_0 \, \delta l \left(\frac{1}{r} - i \, \frac{\lambda}{2\pi \, r^2} - \frac{\lambda^2}{4\pi^2 \, r^3} \right) e^{i(\omega t - kr)} \; \sin(\theta)$$

$$H_\phi = i \frac{1}{2\lambda} I_0 \, \delta l \left(\frac{1}{r} - i \, \frac{\lambda}{2\pi \, r^2} \right) e^{i(\omega t - kr)} \; \sin(\theta)$$

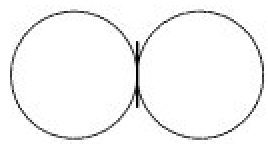
where $Z = \sqrt{\mu/\varepsilon} = 1/(\varepsilon c) = \mu c$. The energy associated with the term of the near field flows back and forward out and into the antenna.

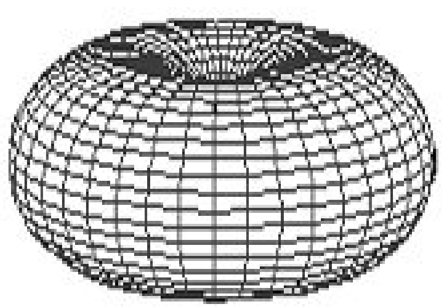
Short dipole



A short dipole is a physically feasible dipole formed by two conductors with a total length L very small compared with the wavelength λ. The two conducting wires are fed at the centre of the dipole. We assume the hypothesis that the current is maximal at the centre (where the dipole is fed) and that it decreases linearly to be zero at the ends of the wires. Note that the direction of the current is the same in both the dipole branches - to the right in both or to the left in both. The far field E_θ of the electromagnetic wave radiated by this dipole is:

$$E_\theta = \frac{-i I_\circ \sin\theta}{4\varepsilon_\circ c r} \frac{L}{\lambda} e^{i(\omega t - kr)}.$$





Emission is maximal in the plane perpendicular to the dipole and zero in the direction of wires which is the direction of the current. The emission diagram is circular section torus shaped (right image) with zero inner diameter. In the left image the doublet is vertical in the torus centre.

Knowing this electric field, we can compute the total emitted power and then compute the resistive part of the series impedance of this dipole due to the radiated field, known as the radiation resistance:

$$R_{series} = \frac{\pi}{6} Z_0 \left(\frac{L}{\lambda}\right)^2 \text{ (for } L \ll \lambda\text{).}$$

where Z_0 is the impedance of free space. Using a common approximation of $Z_0 = 120\pi$ ohms, we get:

$$R_{series} = 20\pi^2 \left(\frac{L}{\lambda}\right)^2 \text{ ohms}$$

Antenna gain

Antenna gain is the ratio of surface power radiated by the antenna to the surface power radiated by a hypothetical isotropic antenna:

$$G = \frac{\left(\frac{P}{S}\right)_{ant}}{\left(\frac{P}{S}\right)_{iso}}$$

The surface power carried by an electromagnetic wave is:

$$\left(\frac{P}{S}\right)_{ant} = \frac{1}{2} c\varepsilon_0 E_\theta^2 \simeq \frac{1}{120\pi} E_\theta^2$$

The surface power radiated by an isotropic antenna feed with the same power is:

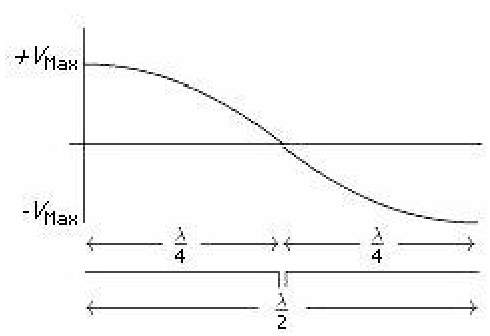
$$\left(\frac{P}{S}\right)_{iso} = \frac{\frac{1}{2} R_{series} I_0^2}{4\pi r^2}$$

Substituting values for the case of a short dipole, final result is:

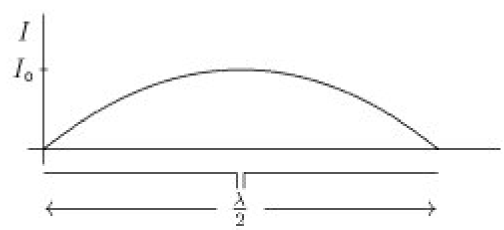
$$G = \frac{\pi \left(\frac{L}{\lambda}\right)^2}{\varepsilon_0 c \frac{2\pi}{6\varepsilon_0 c} \left(\frac{L}{\lambda}\right)^2} = 1.5 = 1.76 \text{ dBi}$$

dBi simply means decibels gain, relative to an **i**sotropic antenna.

Half-wave antenna



Typically a dipole antenna is formed by two quarter wavelength conductors or elements placed back to back for a total length of $\lambda/2$. A standing wave on an element of a length ~$\lambda/4$ yields the greatest voltage differential, as one end of the element is at a node while the other is at an antinode of the wave. The larger the differential voltage, the greater the current between the elements.



Assuming a sinusoidal distribution, the current impressed by this voltage differential is given by:

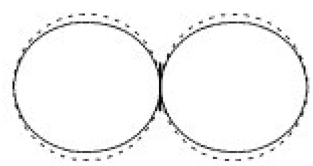
$$I = I_\circ e^{i\omega t} \cos k\ell$$

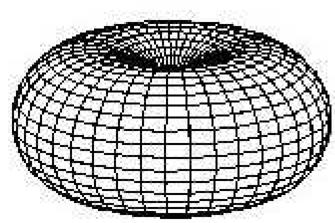
For the far-field case, the formula for the electric field of a radiating electromagnetic wave is somewhat more complex:

$$E_\theta = \frac{-iI_\circ}{2\pi\varepsilon_\circ cr} \frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta} e^{i(\omega t - kr)}$$

But the fraction $\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta}$ is not very different from $\sin\theta$.

The resulting emission diagram is a slightly flattened torus.





The image on the left shows the section of the emission pattern. We have drawn, in dotted lines, the emission pattern of a short dipole. We can see that the two patterns are very similar. The image at right shows the perspective view of the same emission pattern.

This time it is not possible to compute analytically the total power emitted by the antenna (the last formula does not allow), though a simple numerical integration or series expansion leads to the more precise, actual value of the half-wave resistance:

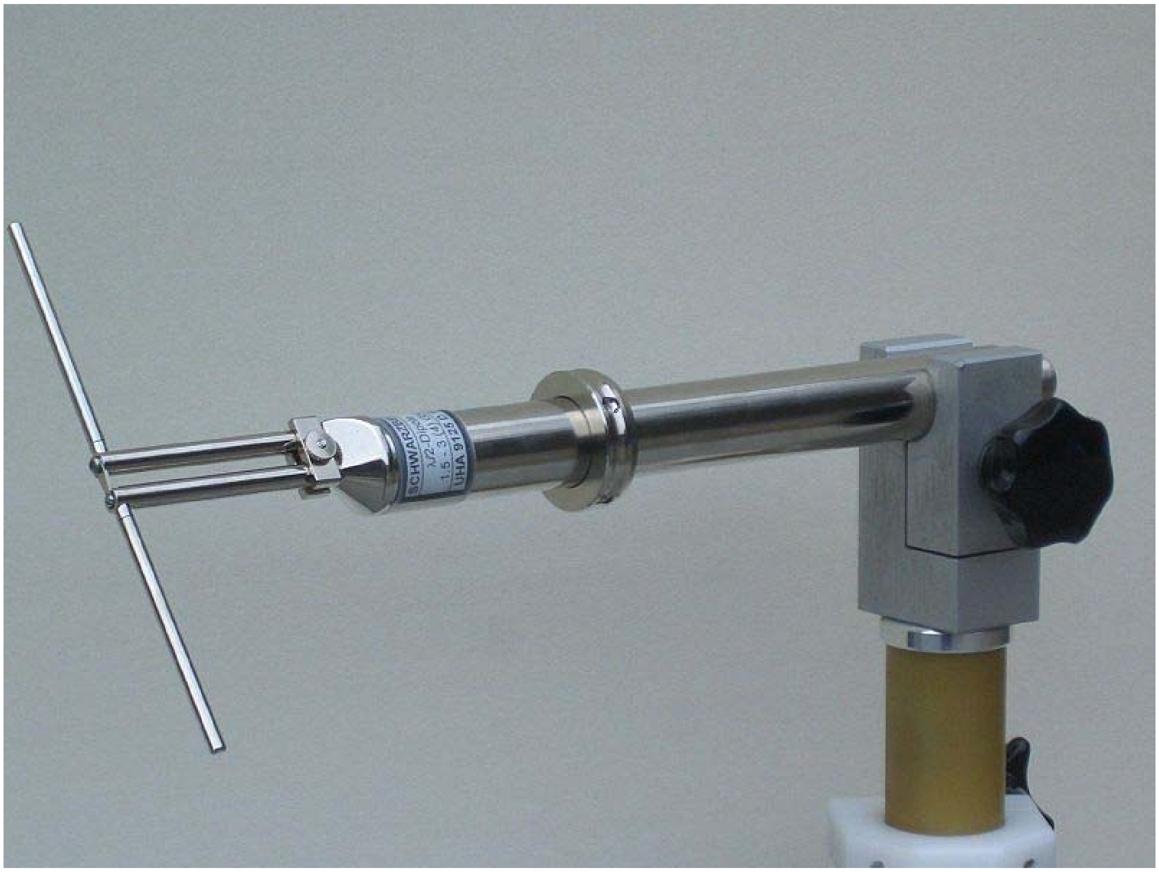
$$\begin{aligned} R_{\frac{\lambda}{2}} &= 60\mathrm{Cin}(2\pi) = 60\left[\ln(2\pi\gamma) - \mathrm{Ci}(2\pi)\right] = 120\int_0^{\frac{\pi}{2}} \frac{\cos\left(\frac{\pi}{2}\cos\theta\right)^2}{\sin\theta}d\theta, \\ &= 15\left[2\pi^2 - \frac{1}{3}\pi^4 + \frac{4}{135}\pi^6 - \frac{1}{630}\pi^8 + \frac{4}{70875}\pi^{10} \ldots - (-1)^n\frac{(2\pi)^{2n}}{n(2n)!}\right], \\ &\approx 73.13\Omega; \end{aligned}$$

This leads to the gain of a dipole antenna, $G_{\frac{\lambda}{2}}$:

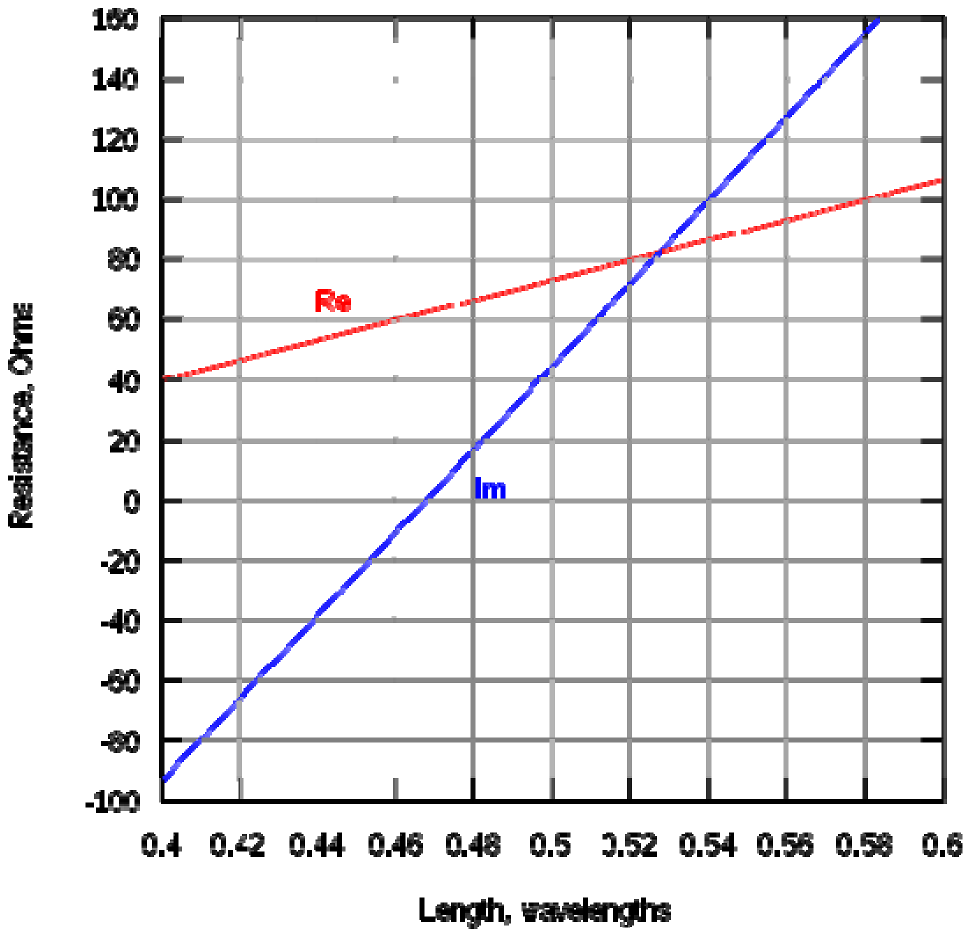
$$\begin{aligned} G_{\frac{\lambda}{2}} &= \frac{60^2}{30R_{\frac{\lambda}{2}}} = \frac{3600}{30R_{\frac{\lambda}{2}}} = \frac{120}{R_{\frac{\lambda}{2}}} = \frac{1}{\int_0^{\frac{\pi}{2}} \frac{\cos\left(\frac{\pi}{2}\cos\theta\right)^2}{\sin\theta}d\theta}, \\ &\approx \frac{120}{73.1296} \approx 1.64 \approx 2.15\,\mathrm{dBi}; \end{aligned}$$

The resistance, however, is not enough to characterize the dipole impedance, as there is also an imaginary part——it is better to measure the impedance.

In the image below, the real and imaginary parts of a dipole's impedance are drawn for lengths going from $0.4\ \lambda$to $0.6\ \lambda$, accompanied by a chart comparing the gains of dipole antennas of other lengths (note that gains are **not** in dBi but in natural number):



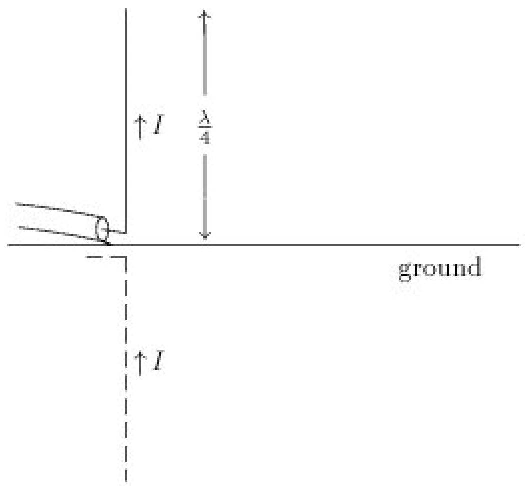
UHF–Half–Wave Dipole, 1.0–4 GHz



Gain of dipole antennas

length **L** in λ	Gain	Gain(dB)
$\ll 0.1$	1.50	1.76dB
0.5	**1.64**	**2.15dB**
1.0	1.80	2.55dB
1.5	2.00	3.01dB
2.0	2.30	3.62dB
3.0	2.80	4.47dB
4.0	3.50	5.44dB
8.0	7.10	8.51dB

Quarter-wave antenna



The antenna and its image form a $\frac{\lambda}{2}$dipole that radiates only upward.

The quarter wave monopole antenna is a single element antenna fed at one end, that behaves as a dipole antenna. It is formed by a conductor $\frac{\lambda}{4}$ in length. It is fed in the lower end, which is near a conductive surface which works as a reflector. The current in the reflected image has the same direction and phase as the current in the real antenna. The quarter-wave conductor and its image together form a half-wave dipole that radiates only in the upper half of space.

In this upper side of space the emitted field has the same amplitude of the field radiated by a half-wave dipole fed with the same current. Therefore, the total emitted power is one-half the emitted power of a half-wave dipole fed with the same current. As the current is the same, the radiation resistance (real part of series impedance) will be one-half of the series impedance of a half-wave dipole. As the reactive part is also divided by 2, the impedance of a quarter wave antenna is $\frac{73+i43}{2}=36+i21$ohms. Since the fields above ground are the same as for the dipole, but only half the power is applied, the gain is twice (3dB over) that for a half-wave dipole ($\frac{\lambda}{2}$), that is 5.14 dBi.

The earth can be used as ground plane, but it is a poor conductor: the reflected antenna image is only clear at glancing angles (far from the antenna). At these glancing angles, electromagnetic fields and radiation patterns are thus the same as for a half-wave dipole.

Naturally, the impedance of the earth is far inferior to that of a good conductor ground plane -- this can be improved (at cost) by laying a copper mesh.

When ground is not available (such as in a vehicle) other metallic surfaces can serve as a ground plane (typically the vehicle's roof). Alternatively, radial wires placed at the base of the antenna can simulate a ground plane. For VHF bands, the radiating and ground-plane elements can be constructed from rigid rods or tubes.

Dipole characteristics

Frequency versus length

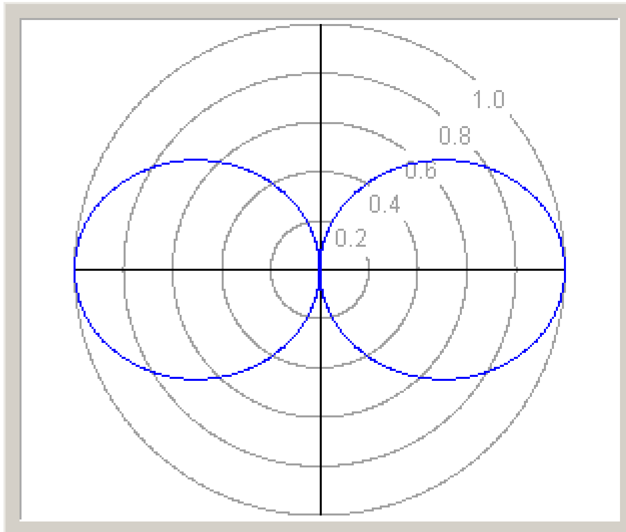
Dipoles that are much smaller than the wavelength of the signal are called *Hertzian, short, or infinitesimal dipoles*. These have a very low radiation resistance and a high reactance, making them inefficient, but they are often the only available antennas at very long wavelengths. Dipoles whose length is half the wavelength of the signal are called *half-wave dipoles*, and are more efficient. In general radio engineering, the term *dipole* usually means a half-wave dipole (center-fed).

A half-wave dipole is cut to length *l* for frequency *f* MHz according to the formula $l = \frac{143}{f}$ where *l* is in metres or $l = \frac{468}{f}$ where *l* is in feet. This is because the impedance of the dipole is resistive pure at about this length. The length of the dipole antenna is about 95% of half a wavelength at the speed of light in free space.

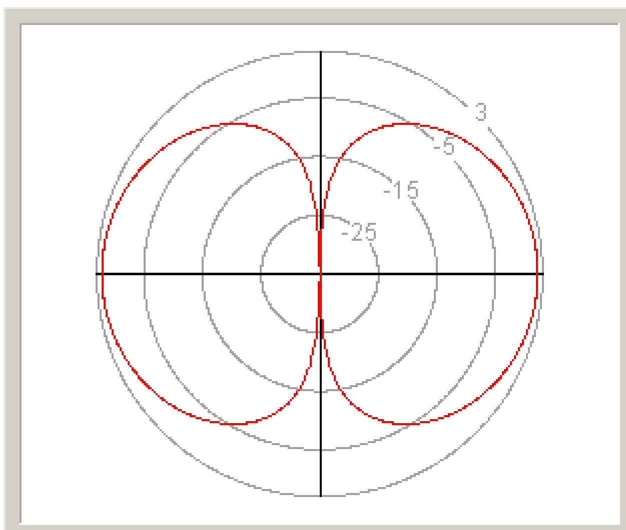
The magic numbers above are derived from a one Hz wavelength which is the distance that light radio travels in one second. Speed of light in vacuum is 299,792,458 m/s, which is divided by 1 million to account for MHz rather than Hz, which is then divided by 2 for a half-wave dipole antenna. A fudge factor of approximately 0.95 is multiplied to account for the damping due to radiation, which results in the magic number of 143 m·MHz or 468 ft·MHz.

Radiation pattern and gain

Dipoles have an omnidirectional radiation pattern, shaped like a toroid (doughnut) symmetrical about the axis of the dipole. The radiation is maximum at right angles to the dipole, dropping off to zero on the antenna's axis. The theoretical maximum gain of a Hertzian dipole is 10 log 1.5 or 1.76 dBi. The maximum theoretical gain of a λ/2-dipole is 10 log 1.64 or 2.15 dBi.



Radiation pattern of a half-wave dipole antenna. The scale is linear.



Gain of a half-wave dipole (same as left). The scale is in dBi (decibels over isotropic).

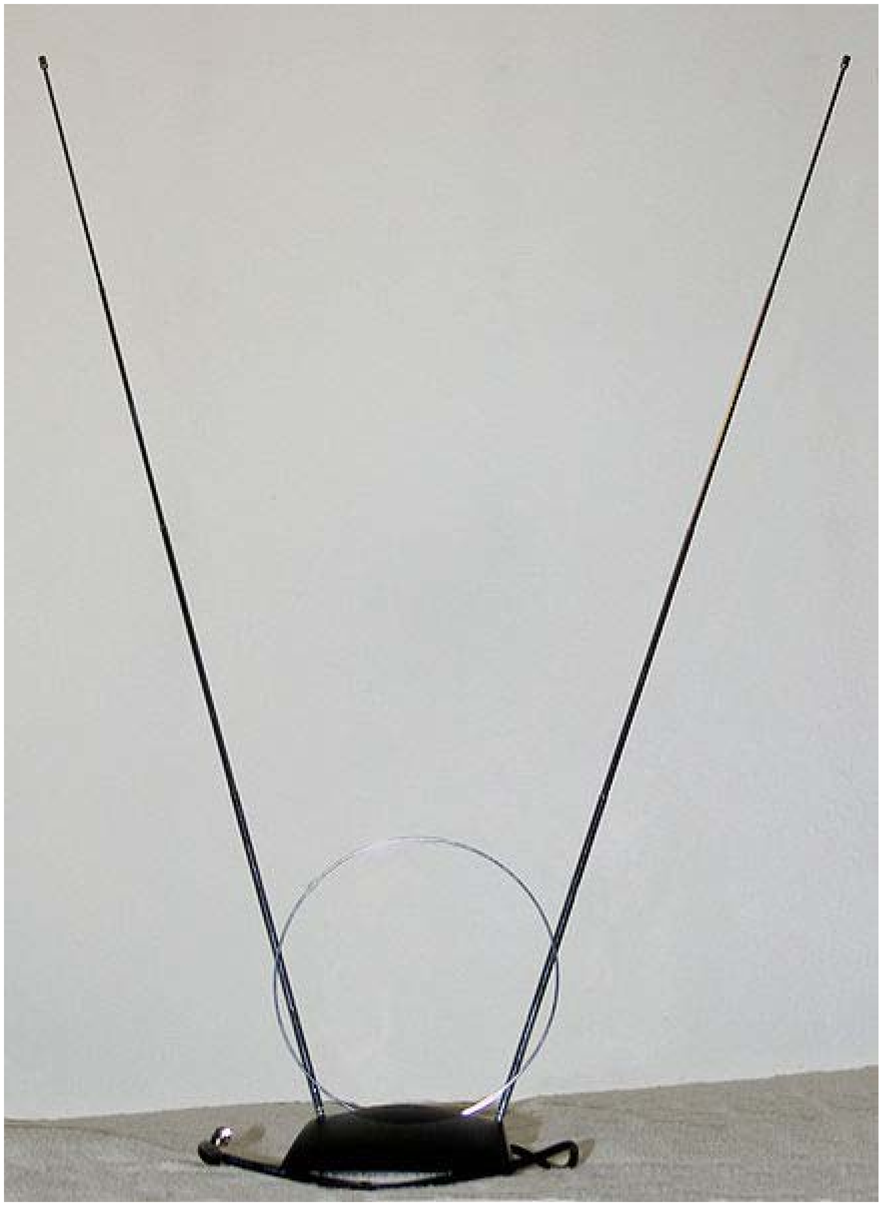
Feeder line

Ideally, a half-wave (λ/2) dipole should be fed with a balanced line matching the theoretical 73 ohm impedance of the antenna. A folded dipole uses a 300 ohm balanced feeder line.

Many people have had success in feeding a dipole directly with a coaxial cable feed rather than a ladder-line. However, coax is not symmetrical and thus not a balanced feeder. It is unbalanced, because the outer shield is connected to earth potential at the other end. When a balanced antenna such as a dipole is fed with an unbalanced feeder, common mode currents can cause the coax line to radiate in addition to the antenna itself, and the radiation pattern may be asymmetrically distorted. This can be remedied with the use of a balun.

Common applications

Set-top TV antenna



A "rabbit-ears" antenna with a UHF loop antenna.

The most common dipole antenna is the type used with televisions, often colloquially referred to as "**rabbit ears**" or "**bunny ears**." While in most applications the dipole elements are arranged along the same line, rabbit ears are adjustable in length and angle. Larger dipoles are sometimes hung in a V shape with the center near the radio equipment on the ground or the ends on the ground with the center supported. Shorter dipoles can be hung vertically. Some have extra elements to get better reception such as loops (especially for UHF transmissions), which can be turnable around a vertical axis, or a dial, which modifies the electrical properties of the antenna at each dial position.

Folded dipole

Folded dipole antenna

Another common place one can see dipoles is as antennas for the FM band - these are folded dipoles. The tips of the antenna are folded back until they almost meet at the feedpoint, such that the antenna comprises one entire wavelength. This arrangement has a greater bandwidth than a standard half-wave dipole. If the conductor has a constant radius and cross-section, at resonance the input impedance is four times that of a half-wave dipole.

Shortwave antenna

A DIY-made dipole antenna with mast

Dipoles for longer wavelengths are made from solid or stranded wire. Portable dipole antennas are made from wire that can be rolled up when not in use. Ropes with weights on the ends can be thrown over supports such as tree branches and then used to hoist up the antenna. The center and the connecting cable can be hoisted up with the ends on the ground or the ends hoisted up between two supports in a V shape. While permanent antennas can be trimmed to the proper length, it is helpful if portable antennas are adjustable to allow for local conditions when moved. One easy way is to fold the ends of the elements to form loops and use adjustable clamps. The loops can then be used as attachment points.

It is important to fit a good insulator at the ends of the dipole, as failure to do so can lead to a flashover if the dipole is used with a transmitter. Various purchased or improvised insulators can be used.

Whip antenna

The whip antenna is probably the most common and simplest-looking antenna. These are monopoles, and the most common and practical is the quarter-wave monopole which could be considered as half of a dipole using a ground plane as the image of the other half. The commonly referred-to end-fed dipole is actually just a half-wave monopole whip antenna.

Dipoles versus whip antennas

Dipoles are generally more efficient than whip antennas (quarter-wave monopoles). The total radiated power and the radiation resistance are twice that of a quarter-wave monopole. Thus, if a whip antenna were used with an infinite perfectly conducting ground plane, then it would be as efficient in half-space as a dipole in free space an infinite distance from any conductive surfaces such as the earth's surface.

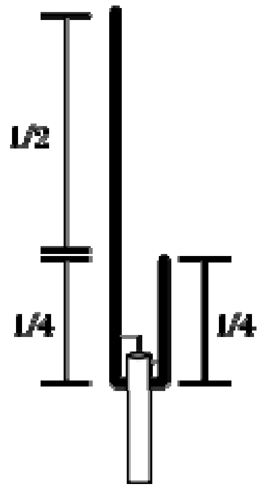
Dipole towers

Large constructed half-wavelength dipole towers include the Warsaw radio mast — the only half-wave dipole for longwave ever built — and Blaw-Knox Towers.

Military

US Military personnel occasionally use a 'doublet' antenna, especially during dismounted unconventional warfare. A radio operator may choose to bring several doublet antennas for different frequencies, such as an antenna cut to length for the set MEDEVAC (medical evacuation) frequency, NCS (net control station) frequency, and tactical frequency (the frequency used by troops in the field). This approach may not be acceptable depending on the mission. Note that a doublet antenna will not work with the standard SINCGARS radio when using frequency hopping(FH) but is effective for single channel (SC). A doublet antenna is more practical for radios not intended for FH.

Collinear antenna systems based on dipoles



J-Pole Antenna

Dipoles can be stacked end to end in phased arrays to make collinear antenna arrays, which exhibit more gain in certain directions—the toroidal radiation pattern is flattened out, giving maximum gain at right angles to the axis of the colinear array.

Slim Jim or J-pole

A Slim Jim or J-pole is a form of end-fed dipole connected to a quarter-wave stub matching section.

Dipole types

Ideal half-wavelength dipole

This type of antenna is a special case where each wire is exactly one-quarter of the wavelength, for a total of a half wavelength. The radiation resistance is about 73 ohms if wire diameter is ignored, making it easily matched to a coaxial transmission line. The directivity is a constant 1.64, or 2.15 dB. Actual gain will be a little less due to ohmic losses.

If the dipole is not driven at the centre then the feed point resistance will be higher. If the feed point is distance *x* from one end of a half wave (λ/2) dipole, the resistance will be described by the following equation.

$$R_r = \frac{75}{\sin^2\left(\frac{2\ \pi\ x}{\lambda}\right)}$$

If taken to the extreme then the feed point resistance of a $\lambda/2$ long rod is infinite, but it is possible to use a $\lambda/2$ pole as an aerial; the right way to drive it is to connect it to one terminal of a parallel LC resonant circuit. The other side of the circuit must be connected to the braid of a coaxial cable lead and the core of the coaxial cable can be connected part way up the coil from the RF ground side. An alternative means of feeding this system is to use a second coil which is magnetically coupled to the coil attached to the aerial.

Folded dipole

A folded dipole is a half-wave dipole with an additional wire connecting its two ends. If the additional wire has the same diameter and cross-section as the dipole, two nearly identical radiating currents are generated. The resulting far-field emission pattern is nearly identical to the one for the single-wire dipole described above; however, at resonance its input (feedpoint) impedance R_{df} is four times the radiation resistance of a single-wire dipole. This is because for a fixed amount of power, the total radiating current I_0 is equal to twice the current in each wire and thus equal to twice the current at the feed point. Equating the average radiated power to the average power delivered at the feedpoint, we may write

$$\frac{1}{2}R_{\frac{\lambda}{2}}I_0^2 = \frac{1}{2}R_{fd}\left(I_0/2\right)^2 .$$

It follows that

$$R_{fd} = 4R_{\frac{\lambda}{2}} = 292.52\Omega.$$

The folded dipole is therefore well matched to 300-Ohm balanced transmission lines.

Hertzian dipole (current element)

The Hertzian dipole is a theoretical short dipole (significantly smaller than the wavelength) with a uniform current along its length. A true Hertzian dipole cannot physically exist, since the assumed current distribution implies an infinite accumulation of charge at its ends.

The radiation resistance is given by:

$$R_r = \frac{2\pi}{3}Z_0\left(\frac{\ell}{\lambda}\right)^2 .$$

where Z_0 is the impedance of free space. This is precisely four times the radiation resistance of the real short dipole with the linearly tapered current distribution.

The radiation resistance is typically a fraction of an ohm, making the infinitesimal dipole an inefficient radiator. The directivity D, which is the theoretical gain of the antenna assuming no ohmic losses (not real-world), is a constant of 1.5, which corresponds to

1.76 dB. Actual gain will be much less due to the ohmic losses and the loss inherent in connecting a transmission line to the antenna, which is very hard to do efficiently considering the incredibly low radiation resistance. The maximum effective aperture is:

$$A_e = \frac{3\lambda^2}{8\pi}$$

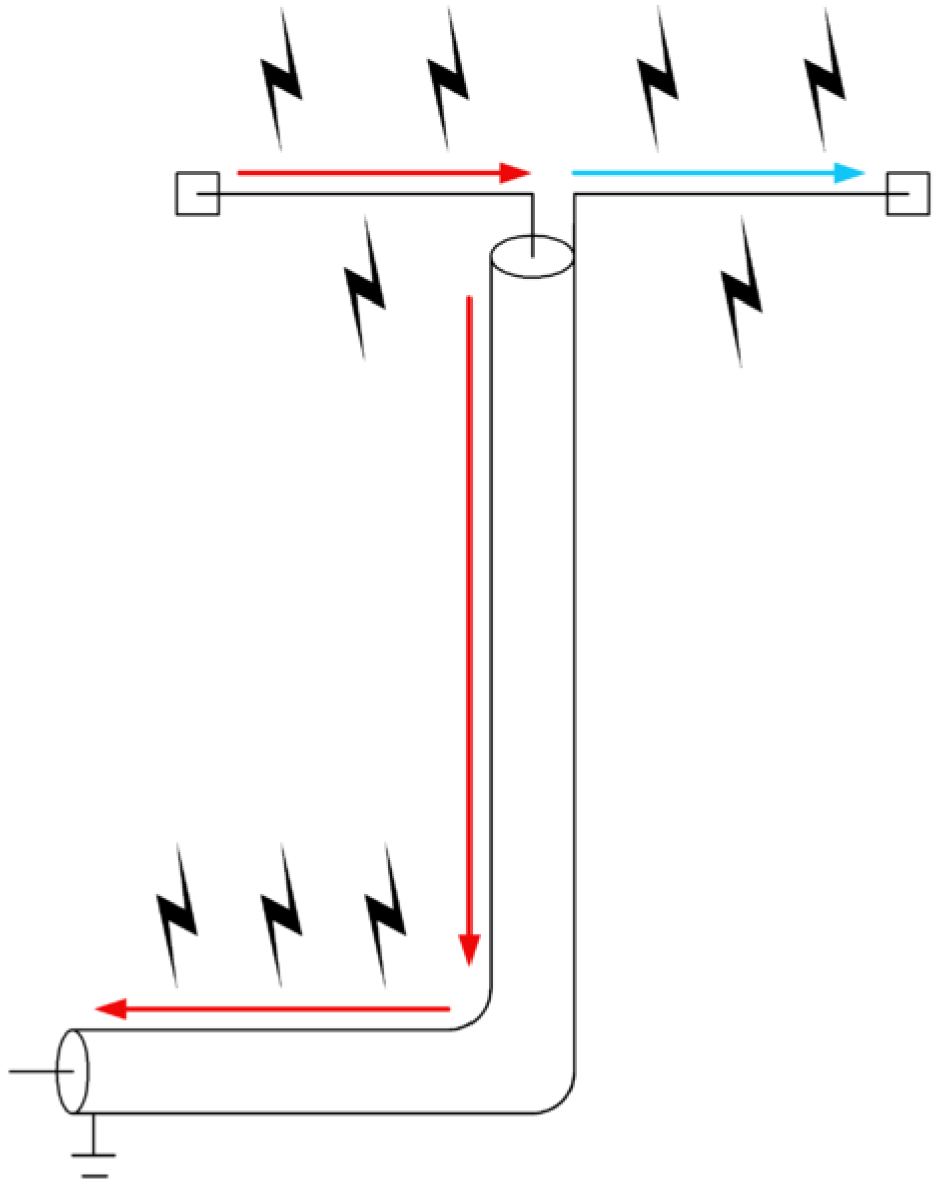
A surprising result is that even though the Hertzian dipole is minute, its effective aperture is comparable to antennas many times its size.

Dipole as a reference standard

Antenna gain is sometimes measured as "*x* dB above a dipole", which means that the antenna in question is being compared to a dipole, and has *x* dB more gain (has more directivity) than the dipole tuned to the same operating frequency. In this case one says the antenna has a gain of "*x* dBd". More often, gains are expressed relative to an isotropic radiator, which is an imaginary aerial that radiates equally in all directions. In this case one uses dBi instead of dBd. As it is impossible to build an isotropic radiator, gain measurements expressed relative to a dipole are more practical when a reference dipole aerial is used for experimental measurements. 0 dBd is often considered equal to 2.15 dBi.

From Babinet's principle, a dipole antenna is complementary to a slot antenna consisting of a slot the same size and shape as a dipole cut from an infinite sheet of metal; both give the same radiation pattern.

Dipole with baluns

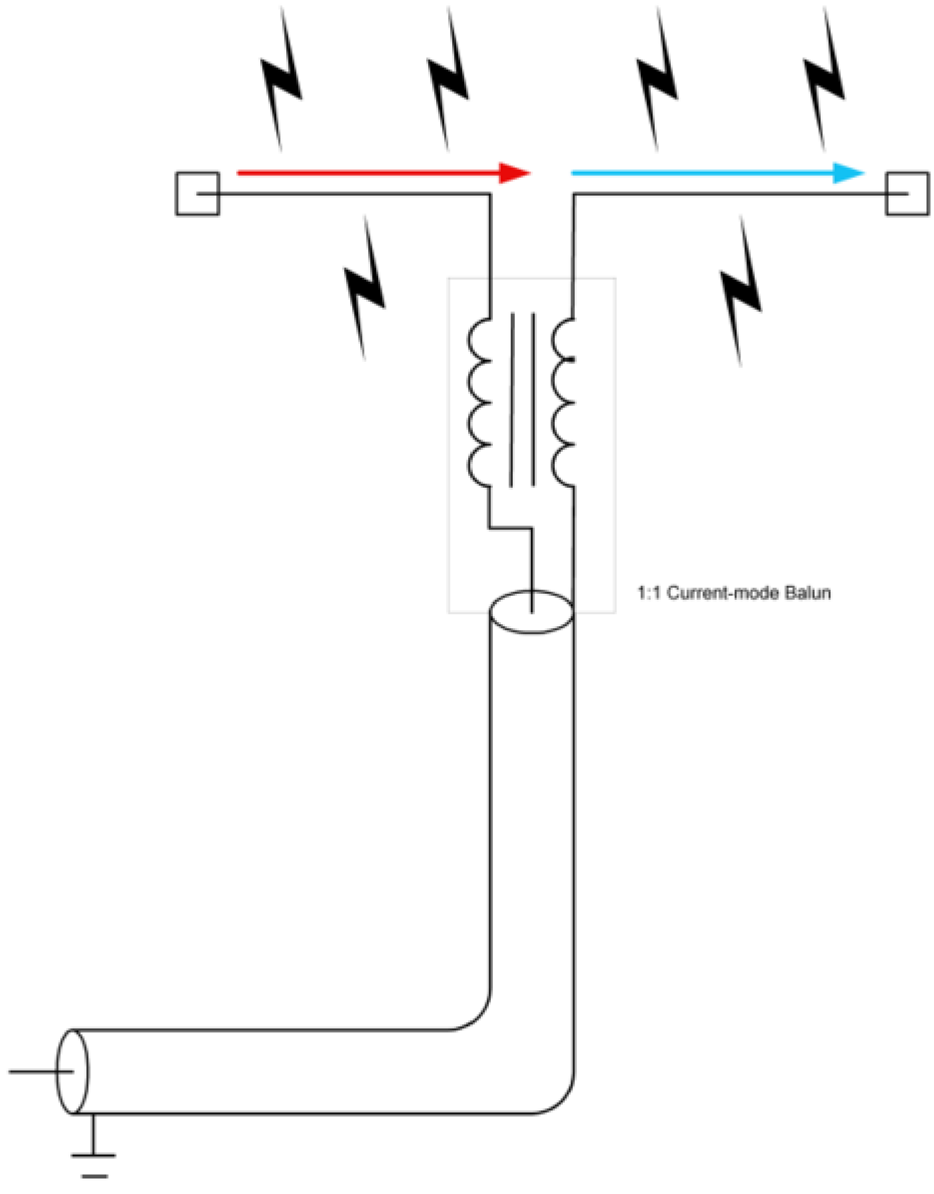


Coax and antenna both acting as radiators instead of only the antenna.

A dipole, being composed of two symmetrical ungrounded elements, works best when fed by a balanced transmission line, such as ladder line. When a dipole with an unbalanced feedline such as coaxial cable is used for transmitting, the shield side of the cable, in addition to the antenna, radiates. This can induce RF currents into other electronic equipment near the radiating feedline, causing RF interference. Furthermore, the antenna is not as efficient as it could be because it is radiating closer to the ground and its radiation (and reception) pattern may be distorted asymmetrically. At higher frequencies, where the length of the dipole becomes significantly shorter than the diameter of the feeder coax, this becomes a more significant problem. To prevent this, dipoles fed by coaxial cables have a balun between the cable and the antenna, to convert the unbalanced signal provided by the coax to a balanced symmetrical signal for the antenna.

Several type of baluns are commonly used to transmit on a dipole: current baluns and coax baluns.

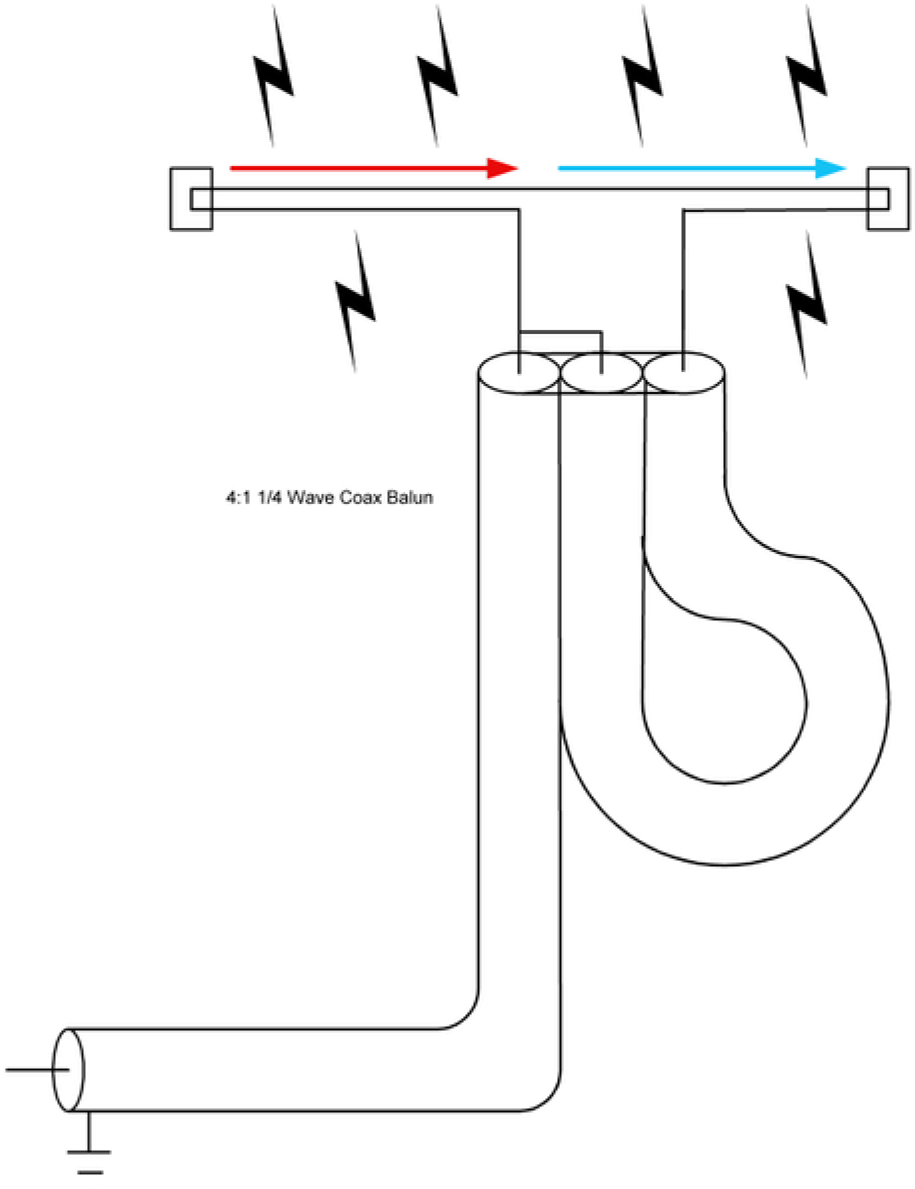
Current balun



Dipole with a current balun.

A current balun is a bit more expensive but has the characteristic of being more broadband. It can also be as simple as winding the coax cable over a ferrite core. Or nothing but coax cable:

Coax balun

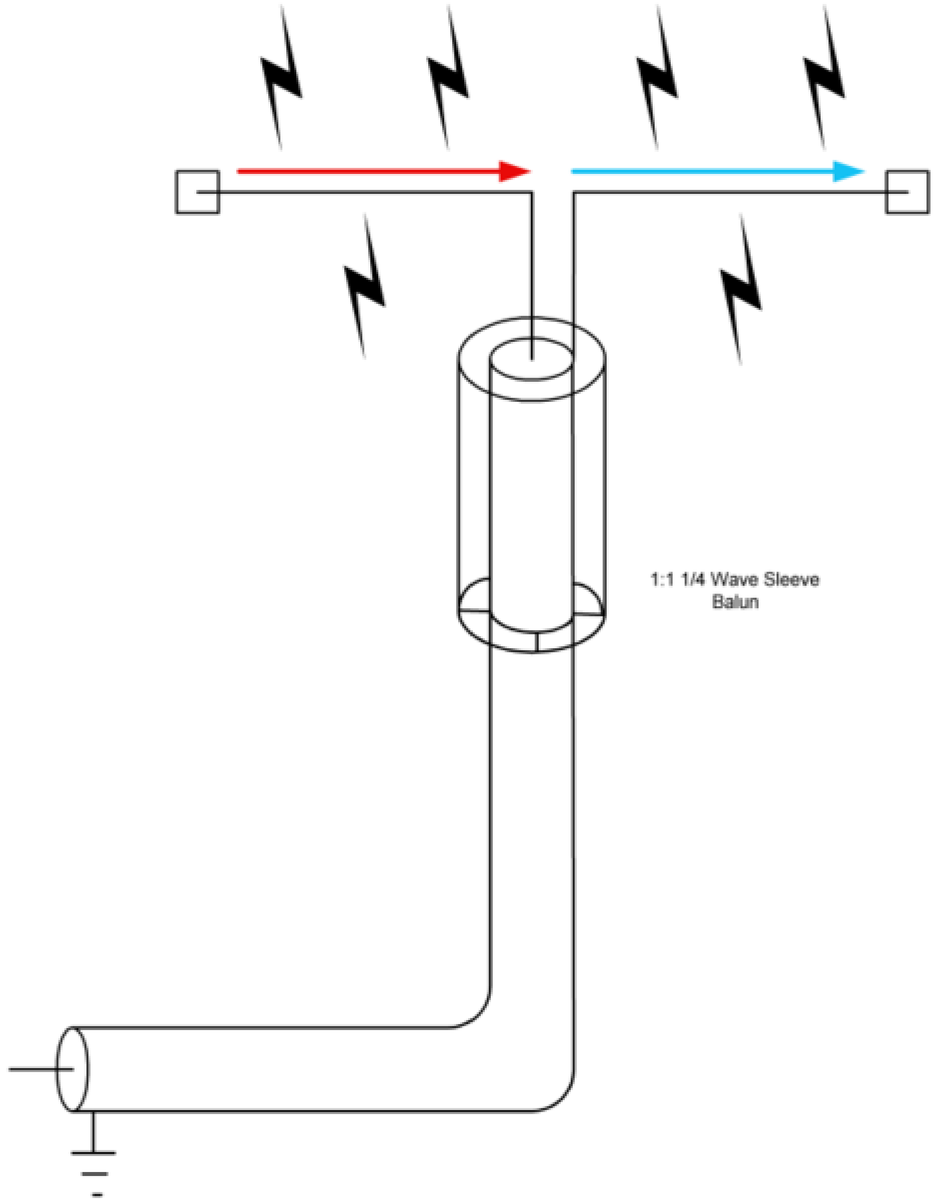


Here is a dipole using a coax balun.

A coax balun is a cost effective method to eliminate feeder radiation, but is limited to a narrow set of operating frequencies.

- One easy way to make a balun is a (λ/2) length of coaxial cable. The inner core of the cable is linked at each end to one of the balanced connections for a feeder or dipole. One of these terminals should be connected to the inner core of the coaxial feeder. All three braids should be connected together. This then forms a 4:1 balun which works correctly at only a narrow band of frequencies.

Sleeve balun



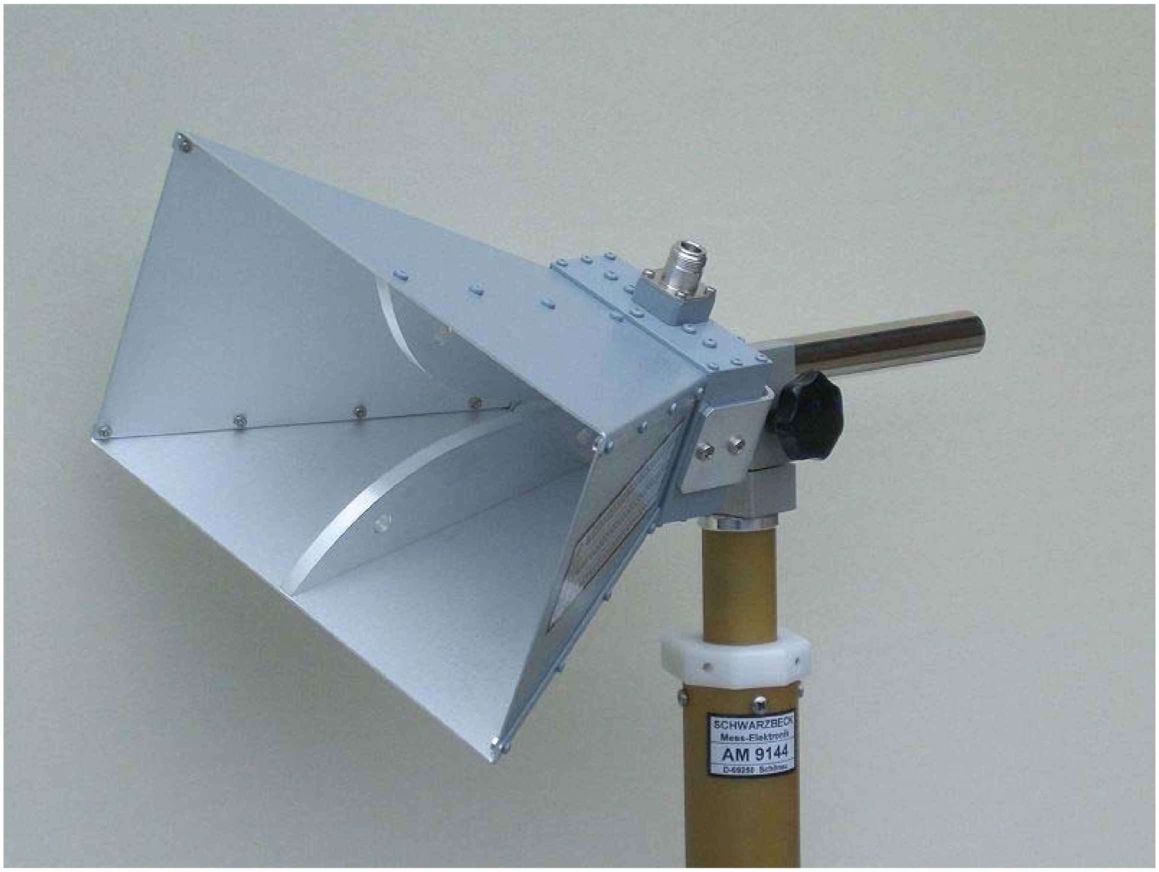
Here is a dipole using a sleeve balun.

At VHF frequencies, a sleeve balun can also be built to remove feeder radiation.

- Another narrow band design is to use a λ/4 length of metal pipe. The coaxial cable is placed inside the pipe; at one end the braid is wired to the pipe while at the other end no connection is made to the pipe. The balanced end of this balun is at the end where the pipe is wired to the braid. The λ/4 conductor acts as a transformer converting the infinite impedance at the unconnected end into a zero impedance at the end connected to the braid. Hence any current entering the balun through the connection, which goes to the braid at the end with the connection to the pipe, will flow into the pipe. This balun design is impractical for low frequencies because of the long length of pipe that will be needed.

Chapter 2

Horn Antenna



Pyramidal microwave horn antenna, with a bandwidth of 0.8 to 18 GHz. A coaxial cable feedline attaches to the connector visible at top. This type is called a ridged horn; the curving fins visible inside the mouth of the horn increase the antenna's bandwidth.

A **horn antenna** or **microwave horn** is an antenna that consists of a flaring metal waveguide shaped like a horn to direct the radio waves. Horns are widely used as antennas at UHF and microwave frequencies, above 300 MHz. They are used as feeders (called feed horns) for larger antenna structures such as parabolic antennas, as standard calibration antennas to measure the gain of other antennas, and as directive antennas for such devices as radar guns, automatic door openers, and microwave radiometers. Their advantages are moderate directivity (gain), low SWR, broad bandwidth, and simple construction and adjustment.

One of the first horn antennas was constructed in 1897 by Indian radio researcher Jagadish Chandra Bose in his pioneering experiments with microwaves. In the 1930s the first experimental research (Southworth and Barrow, 1936) and theoretical analysis (Barrow and Chu, 1939) of horns as antennas was done. The development of radar in World War 2 stimulated horn research. The corrugated horn proposed by Kay in 1962 has become widely used as a feed horn for microwave antennas such as satellite dishes and radio telescopes.

An advantage of horn antennas is that since they don't have any resonant elements, they can operate over a wide range of frequencies, a wide bandwidth. The useable bandwidth of horn antennas is typically of the order of 10:1, and can be up to 20:1 (for example allowing it to operate from 1 GHz to 20 GHz). The input impedance is slowly-varying over this wide frequency range, allowing low VSWR over the bandwidth. The gain of horn antennas ranges up to 25 dBi, with 10 - 20 dBi being typical.

Description

A horn antenna is used to transmit radio waves from a waveguide (a metal pipe used to carry radio waves) out into space, or collect radio waves into a waveguide for reception. It typically consists of a short length of rectangular or cylindrical metal tube (the waveguide), closed at one end, flaring into an open-ended conical or pyramidal shaped horn on the other end. The radio waves are usually introduced into the waveguide by a coaxial cable attached to the side, with the central conductor projecting into the waveguide. The waves then radiate out the horn end in a narrow beam. However in some equipment the radio waves are conducted from the transmitter or to the receiver by a waveguide, and in this case the horn is just attached to the end of the waveguide.

How it works

Corrugated conical horn antenna used as a feed horn on a Hughes Direcway home satellite dish.

A horn antenna serves the same function for electromagnetic waves that an acoustical horn does for sound waves in a musical instrument such as a trumpet; it provides a gradual transition structure to match the impedance of a tube to the impedance of free space, enabling the waves from the tube to radiate efficiently into space.

If a simple open-ended waveguide were to be used as an antenna, without the horn, the sudden end of the conductive walls causes an abrupt impedance change at the aperture, from the characteristic impedance of the waveguide to the impedance of free space, 377 ohms. When radio waves travelling through the waveguide hit the opening, it acts as a bottleneck, reflecting most of the wave energy back down the guide toward the source, so only part of the power is radiated. It acts similarly to an open-circuited transmission line, or to a boundary between optical mediums with a high and low index of refraction, like a glass surface. The reflected waves cause standing waves in the waveguide, increasing the VSWR, wasting energy and possibly overheating the transmitter. In addition, the small aperture of the waveguide (around one wavelength) causes severe diffraction of the waves issuing from it, resulting in a wide radiation pattern without much directivity.

To improve these poor characteristics, the ends of the waveguide are flared out to form a horn. The taper of the horn changes the impedance gradually along the horn's length. This acts like an impedance matching transformer, allowing most of the wave energy to radiate out the end of the horn into space, with minimal reflection. The taper functions similarly to a tapered transmission line, or an optical medium with a smoothly-varying refractive index. In addition, the wide aperture of the horn projects the waves in a narrow beam

The horn shape that gives minimum reflected power is an exponential taper. Exponential horns are used in special applications that require minimum signal loss, such as satellite antennas and radio telescopes. However conical and pyramidal horns are most widely used, because they have straight sides and are easier to fabricate.

Radiation pattern

The waves travel down a horn as spherical wavefronts, with their origin at the apex of the horn. The pattern of electric and magnetic fields at the aperture plane of the horn, which determines the radiation pattern, is a scaled-up reproduction of the fields in the waveguide. However, because the wavefronts are spherical, the phase increases smoothly from the center of the aperture plane to the edges, because of the difference in length of the center point and the edge points from the apex point. The difference in phase between the center point and the edges is called the *phase error*. This phase error, which increases with the flare angle, reduces the gain and increases the beamwidth, giving horns wider beamwidths than plane-wave antennas such as parabolic dishes.

At the flare angle, the radiation of the beam lobe is down about -20 dB from its maximum value.

The increasing phase error limits the aperture size of practical horns to about 15 wavelengths; larger apertures would require impractically long horns. This limits the gain of practical horns to about 1000 (30 dB) and the corresponding minimum beamwidth to about 5 - 10°.

Optimum horn

Large pyramidal horn used in 1951 to detect the 21 cm (1.43 GHz) radiation from hydrogen gas in the Milky Way galaxy.

For a given frequency and horn length, there is some flare angle that gives minimum reflection and maximum gain. The reflections in straight-sided horns come from the two locations along the wave path where the impedance changes abruptly; the mouth or aperture of the horn, and the throat where the sides begin to flare out. The amount of reflection at these two sites varies with the *flare angle* of the horn (the angle the sides make with the axis). In narrow horns with small flare angles most of the reflection occurs at the mouth of the horn. The gain of the antenna is low because the small mouth approximates an open-ended waveguide. As the angle is increased, the reflection at the mouth decreases rapidly and the antenna's gain increases. In contrast, in wide horns with flare angles approaching 90° most of the reflection is at the throat. The horn's gain is again low because the throat approximates an open-ended waveguide. As the angle is decreased, the amount of reflection at this site drops, and the horn's gain again increases.

This discussion shows that there is some flare angle which gives maximum gain and minimum reflection. This is called the *optimum horn*. Most practical horn antennas are designed as optimum horns. In a pyramidal horn, the dimensions that give an optimum horn are:

$$a_E = \sqrt{3\lambda L_E} \qquad a_H = \sqrt{2\lambda L_H}$$

For a conical horn, the dimensions that give an optimum horn are:

$$d = \sqrt{3\lambda L}$$

where

a_E is the width of the aperture in the E-field direction
a_H is the width of the aperture in the H-field direction
L_E is the slant length of the side in the E-field direction
L_H is the slant length of the side in the H-field direction.
d is the diameter of the cylindrical horn aperture
L is the slant length of the cone from the apex.
λ is the wavelength

An optimum horn does not give maximum gain for a given *aperture size*; this is achieved by a very long horn. It gives the maximum gain for a given horn *length*. Tables showing dimensions for optimum horns for various frequencies are given in microwave handbooks.

Gain

Horns have very little loss, so the directivity of a horn is roughly equal to its gain. The gain G of a pyramidal horn antenna (the ratio of the radiated power intensity along its beam axis to the intensity of an isotropic antenna with the same input power) is:

$$G = \frac{4\pi A}{\lambda^2} e_A$$

For conical horns, the gain is:

$$G = \left(\frac{\pi d}{\lambda}\right)^2 e_A$$

where

> A is the area of the aperture,
> d is the aperture diameter of a conical horn
> λ is the wavelength,
> e_A is a dimensionless parameter called the *aperture efficiency*,

The aperture efficiency ranges from 0.4 to 0.8 in practical horn antennas. For optimum pyramidal horns, $e_A = 0.511$., while for optimum conical horns $e_A = 0.522$. So an approximate figure of 0.5 is often used. The aperture efficiency increases with the length of the horn, and for aperture-limited horns is approximately unity.

Types of horn antennas

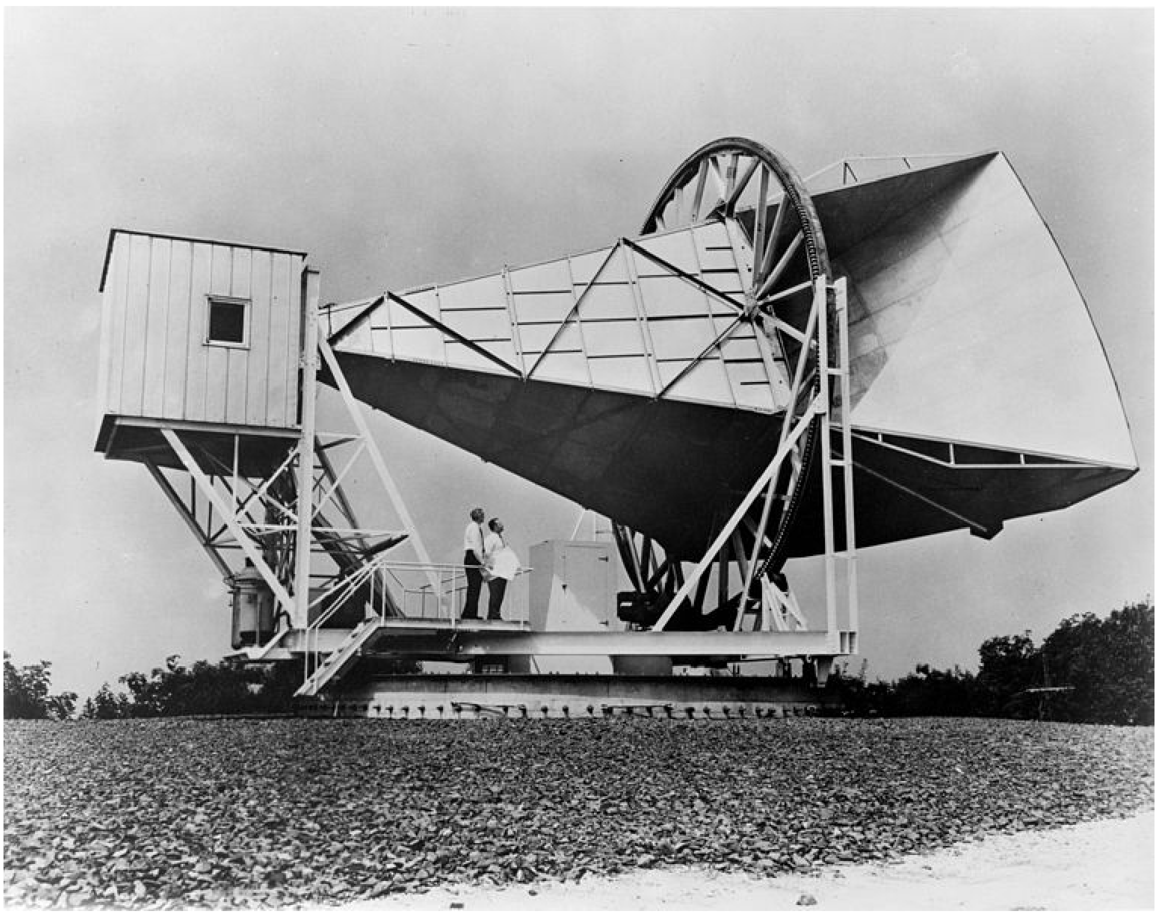
Aperture-limited corrugated horn, used as a feed horn in a radio telescope for millimeter waves.

These are the common types of horn antenna. Horns can have different flare angles as well as different expansion curves (elliptic, hyperbolic, etc.) in the E-field and H-field directions, making possible a wide variety of different beam profiles.

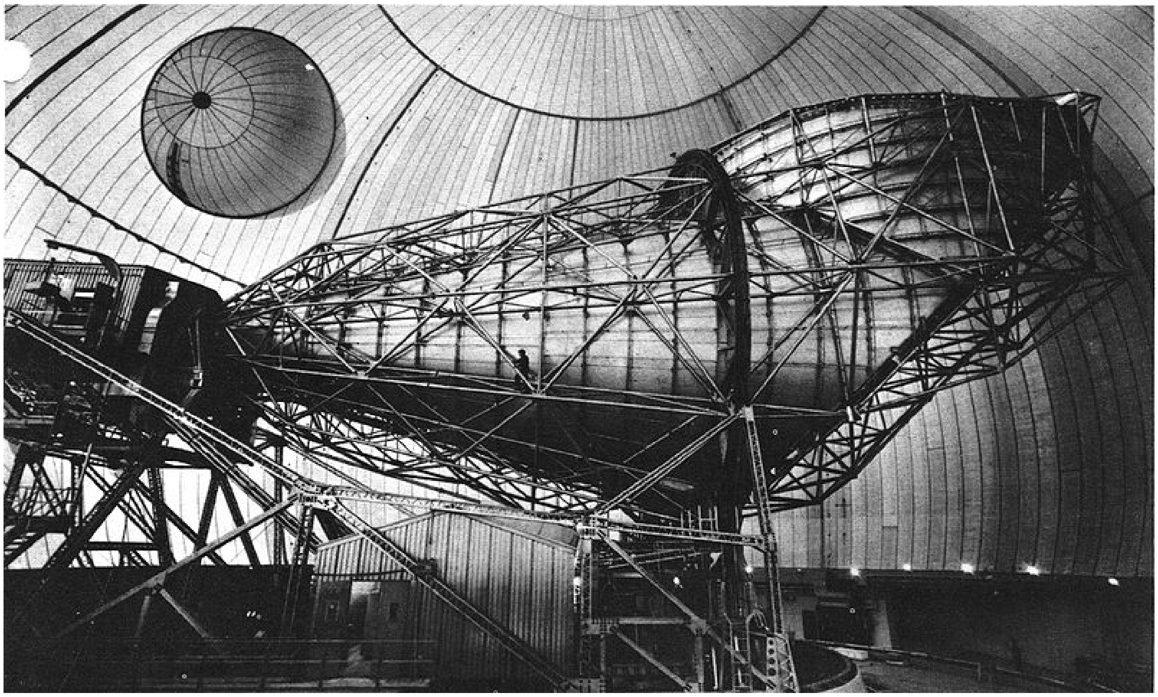
- Pyramidal horn - a horn antenna with the horn in the shape of a four-sided pyramid, with a rectangular cross section. They are the most widely used type, used with rectangular waveguides, and radiate linearly polarized radio waves.
- Sectoral horn - A pyramidal horn with only one pair of sides flared and the other pair parallel. It produces a fan-shaped beam, which is narrow in the plane of the flared sides, but wide in the plane of the narrow sides.
    - E-plane horn - A sectoral horn flared in the direction of the electric or E-field in the waveguide.
    - H-plane horn - A sectoral horn flared in the direction of the magnetic or H-field in the waveguide.
- Conical horn - A horn in the shape of a cone, with a circular cross section. They are used with cylindrical waveguides.
- Corrugated horn - A horn with parallel slots or grooves, small compared with a wavelength, covering the inside surface of the horn, transverse to the axis. Corrugated horns have wider bandwidth and smaller sidelobes and cross-

polarization, and are widely used as feed horns for satellite dishes and radio telescopes.

- Ridged horn - A pyramidal horn with ridges or fins attached to the inside of the horn, extending down the center of the sides. The fins lower the cutoff frequency, increasing the antenna's bandwidth.
- Septum horn - A horn which is divided into several subhorns by metal partitions (septums) inside, attached to opposite walls.
- Aperture-limited horn - a long narrow horn, long enough so the phase error is a fraction of a wavelength, so it essentially radiates a plane wave. It has an aperture efficiency of 1.0 so it gives the maximum gain and minimum beamwidth for a given aperture size. The gain is not affected by the length but only limited by diffraction at the aperture. Used as feed horns in radio telescopes and other high-resolution antennas.



50 ft. Holmdel horn antenna at Bell labs in Holmdel, New Jersey, USA, with which Arno Penzias and Robert Wilson discovered cosmic microwave background radiation in 1964.



Large 177 ft. Hogg horn antenna at AT&T satellite communications facility in Andover, Maine, USA, used in 1960s to communicate with the first direct relay communications satellite, Telstar.

Hogg microwave relay antennas on roof of AT&T telephone switching center, Seattle, Washington, USA
Hogg antennas

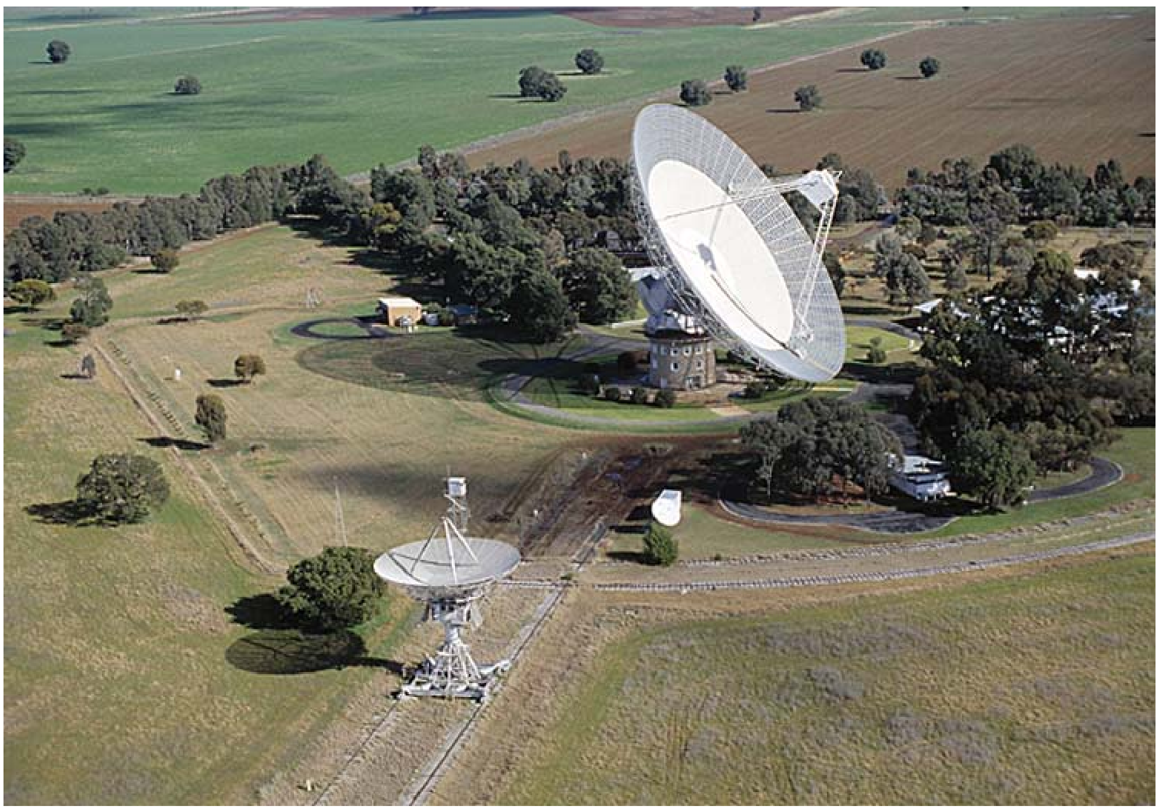
Hogg horn antenna

A type of antenna that combines a horn with a parabolic reflector is the Hogg antenna, invented by D. C. Hogg at Bell labs around 1960. It consisted of a horn antenna with a reflector mounted in the mouth of the horn at a 45 degree angle so the radiated beam is at right angles to the horn axis. The reflector is a segment of a parabolic reflector, so the device is equivalent to a parabolic antenna fed off-axis. The advantage of this design over a standard parabolic antenna is that the horn shields the antenna from radiation coming from angles outside the main beam axis, so its radiation pattern has very small sidelobes.

Also, the aperture isn't partially obstructed by the feed and its supports, as with ordinary front-fed parabolic dishes. The disadvantage is that it is far larger and heavier for a given aperture area than a parabolic dish, and must be mounted on a cumbersome turntable to be fully steerable. This design was used for a few radio telescopes and communication satellite ground antennas during the 1960s. Its largest use, however, was as fixed antennas for microwave relay links in the AT&T Long Lines microwave network. Probably the most photographed and well-known example is the 15 meter (50 foot) long Holmdel Horn Antenna at Bell Labs in Holmdel, New Jersey, with which Arno Penzias and Robert Wilson discovered cosmic microwave background radiation in 1965, for which they won the 1978 Nobel Prize in Physics.

Chapter 3

Radio Telescope



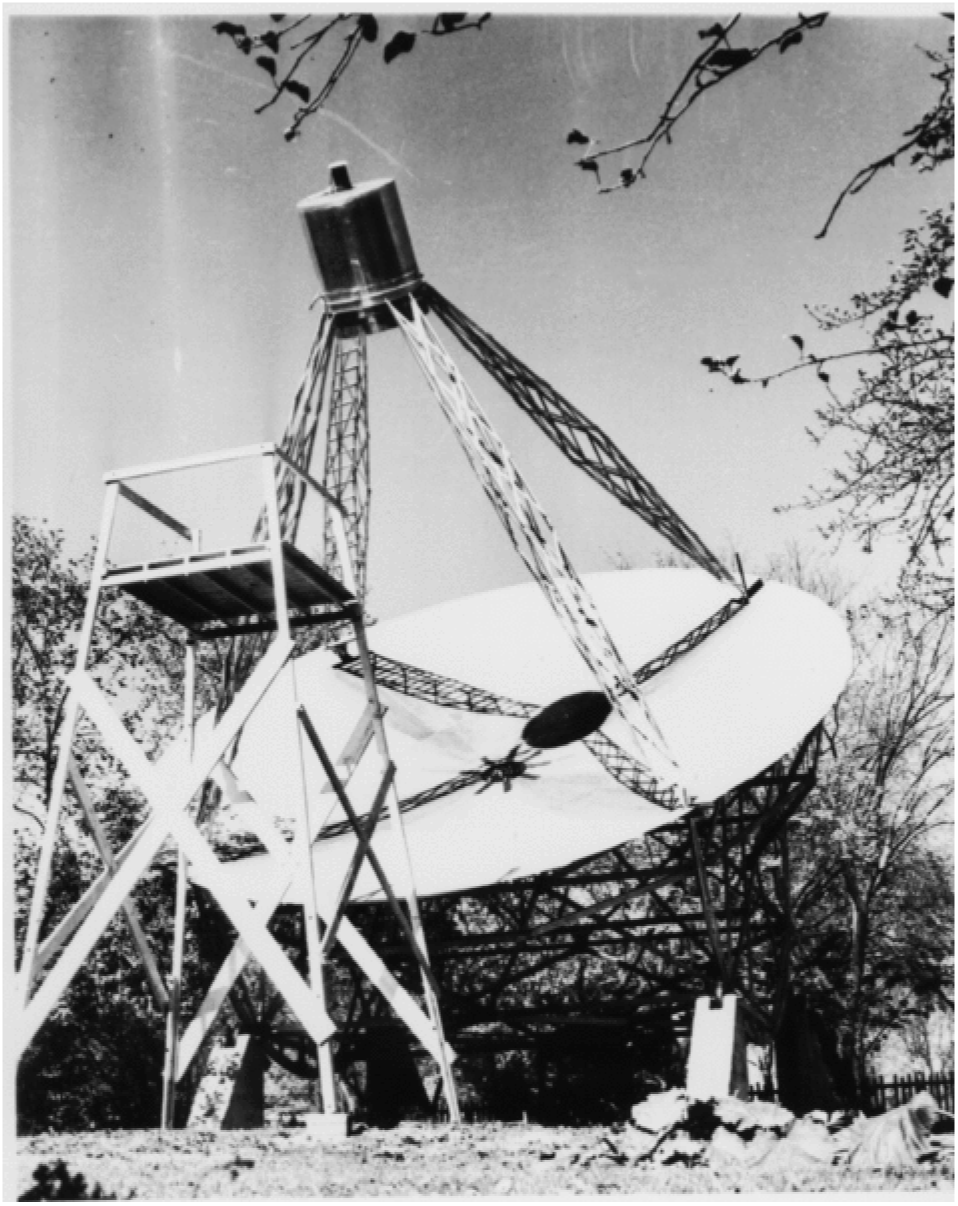
The 64 meter radio telescope at Parkes Observatory

A **radio telescope** is a form of directional radio antenna used in radio astronomy. The same types of antennas are also used in tracking and collecting data from satellites and space probes. In their astronomical role they differ from optical telescopes in that they operate in the radio frequency portion of the electromagnetic spectrum where they can detect and collect data on radio sources. Radio telescopes are typically large parabolic ("dish") antennas used singly or in an array. Radio observatories are preferentially located far from major centers of population to avoid electromagnetic interference (EMI) from radio, TV, radar, and other EMI emitting devices. This is similar to the locating of optical telescopes to avoid light pollution, with the difference being that radio observatories are often placed in valleys to further shield them from EMI as opposed to clear air mountain tops for optical observatories.

Early radio telescopes

Full-size replica of the first radio telescope, Jansky's dipole array now at the US National Radio Astronomy Observatory

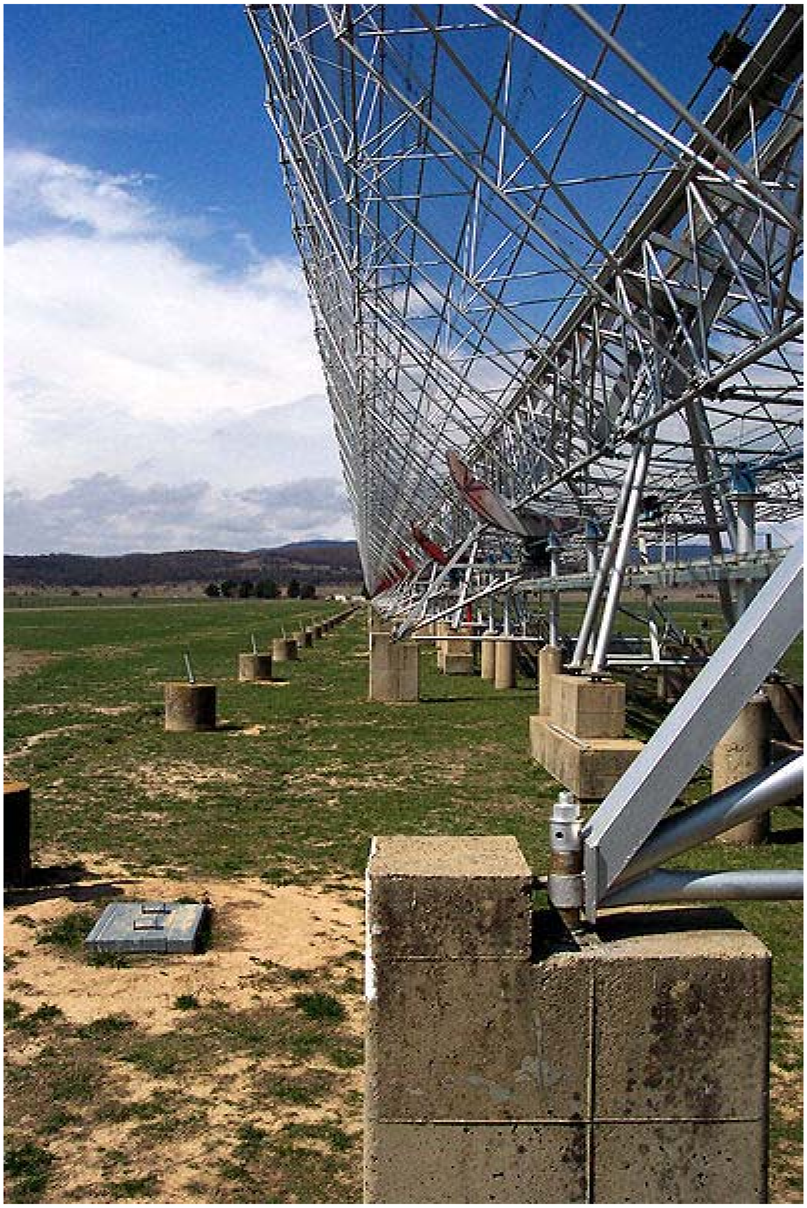
The first radio antenna used to identify an astronomical radio source was one built by Karl Guthe Jansky, an engineer with Bell Telephone Laboratories, in 1931. Jansky was assigned the job of identifying sources of static that might interfere with radio telephone service. Jansky's antenna was an array of dipoles and reflectors designed to receive short wave radio signals at a frequency of 20.5 MHz (wavelength about 14.6 metres). It was mounted on a turntable that allowed it to rotate in any direction, earning it the name "Jansky's merry-go-round". It had a diameter of approximately 100 ft (30 m). and stood 20 ft (6 m). tall. By rotating the antenna on a set of four Ford Model-T tires, the direction of the received interfering radio source (static) could be pinpointed. A small shed to the side of the antenna housed an analog pen-and-paper recording system. After recording signals from all directions for several months, Jansky eventually categorized them into three types of static: nearby thunderstorms, distant thunderstorms, and a faint steady hiss of unknown origin. Jansky finally determined that the "faint hiss" repeated on a cycle of 23 hours and 56 minutes. This period is the length of an astronomical sidereal day, the time it takes any "fixed" object located on the celestial sphere to come back to the same location in the sky. Thus Jansky suspected that the hiss originated well beyond the Earth's atmosphere, and by comparing his observations with optical astronomical maps, Jansky concluded that the radiation was coming from the Milky Way Galaxy and was strongest in the direction of the center of the galaxy, in the constellation of Sagittarius.



Reber's first "dish" radio telescope - Wheaton, IL 1937

An amateur radio operator, Grote Reber, was one of the pioneers of what became known as radio astronomy when he built the first parabolic "dish" radio telescope (9 metres (30 ft) in diameter) in his back yard in Illinois in 1937. He was instrumental in repeating Karl Guthe Jansky's pioneering but somewhat simple work at higher frequencies, and he went on to conduct the first sky survey at very high radio frequencies. The rapid development of radar technology during World War II was easily translated into radio astronomy technology after the war, and the field of radio astronomy began to blossom.

Types



A *cylindrical paraboloid* antenna.

The range of frequencies in the electromagnetic spectrum that makes up the radio spectrum is very large. This means that the types of antennas that are used as radio telescopes vary widely in design, size, and configuration. At wavelengths of 30 meters to 3 meters (10 MHz - 100 MHz), they are generally either directional antenna arrays similar to "TV antennas" or large stationary reflectors with moveable focal points. Since the wavelengths being observed with these types of antennas are so long, the "reflector" surfaces can be constructed from coarse wire mesh such as chicken wire. At shorter wavelengths “dish” style radio telescopes predominate. The angular resolution of a dish style antenna is determined by the diameter of the dish expressed as a number of wavelengths of the electromagnetic radiation being observed. This dictates the dish size a radio telescope needs for a useful resolution. Radio telescopes that operate at wavelengths of 3 meters to 30 cm (100 MHz to 1 GHz) are usually well over 100 meters in diameter. Telescopes working at wavelengths shorter than 30 cm (above 1 GHz) range in size from 3 to 90 meters in diameter.

Big dishes

RT-70 planetary radar

World's largest single-aperture radio telescope at Arecibo Observatory in Puerto Rico

ALMA construction site

The world's largest filled-aperture telescope (i.e., a full dish) is the Arecibo radio telescope located in Arecibo, Puerto Rico, whose 305 m (1,001 ft) dish is fixed in the ground. It was designed by engineer Bill Gordon (d. 2010). The suspension system was designed by George and Helias Doundoulakis, for which Helias Doundoulakis received a patent along with assignee William J. Casey, ex-Central Intelligence Agency Director under President Ronald Reagan. The antenna beam is steerable (by means of a moving receiver) within about 20° of the zenith. The largest individual radio telescope of any kind is the RATAN-600 located near Nizhny Arkhyz, Russia, which consists of a 576-meter circle of rectangular radio reflectors, each of which can be pointed towards a central conical receiver.

The largest radio telescope in Europe is the 100-meter diameter antenna in Effelsberg, Germany, which also was the world's largest fully-steerable telescope for 30 years until the slightly larger Green Bank Telescope was opened in West Virginia, United States, in 2000. The third-largest fully-steerable radio telescope is the 76-metre Lovell Telescope at Jodrell Bank Observatory in Cheshire, England. The fourth-largest fully-steerable radio telescopes is four the 70-metre radio telescopes: RT-70, Goldstone. Feature of these telescopes is that it is the world's largest planetary radars (except Suffa RT-70).

A typical size of the single antenna of a radio telescope is 25 meters. Dozens of radio telescopes with comparable sizes are operated in radio observatories all over the world.

China officially started construction of the world's largest single-aperture radio telescope in 2009, the FAST. The FAST, with a dish area as large as 30 football fields, will stand in a region of typical Karst depressions in Guizhou, and will be finished by 2013.

Radio interferometry

The Very Large Array, an interferometric array formed from many smaller telescopes, like many larger radio telescopes.

One of the most notable developments came in 1946 with the introduction of the technique called astronomical interferometry. Astronomical radio interferometers usually consist either of arrays of parabolic dishes (e.g., the One-Mile Telescope), arrays of one-dimensional antennas (e.g., the Molonglo Observatory Synthesis Telescope) or two-dimensional arrays of omni-directional dipoles (e.g., Tony Hewish's Pulsar Array). All of the telescopes in the array are widely separated and are usually connected together using coaxial cable, waveguide, optical fiber, or other type of transmission line. Recent advances in the stability of electronic oscillators also now permit interferometry to be carried out by independent recording of the signals at the various antennas, and then later correlating the recordings at some central processing facility. This process is known as VLBI (Very Long Baseline Interferometry). Interferometry does increase the total signal collected, but its primary purpose is to vastly increase the resolution through a process called Aperture synthesis. This technique works by superposing (interfering) the signal waves from the different telescopes on the principle that waves that coincide with the same phase will add to each other while two waves that have opposite phases will cancel each other out. This creates a combined telescope that is equivalent in resolution (though not in sensitivity) to a single antenna whose diameter is equal to the spacing of the antennas furthest apart in the array. A high quality image requires a large number of different separations between telescopes. Projected separation between any two telescopes, as seen from the radio source, is called a baseline. For example, the Very Large Array (VLA) near Socorro, New Mexico has 27 telescopes with 351 independent baselines at once, which achieves a resolution of 0.2 arc seconds at 3 cm wavelengths). Martin Ryle's group in Cambridge obtained a Nobel Prize for interferometry and aperture synthesis. The Lloyd's mirror interferometer was also developed independently in 1946 by Joseph Pawsey's group at the University of Sydney. In the early 1950s the Cambridge Interferometer mapped the radio sky to produce the famous 2C and 3C surveys of radio sources. The largest existing physically-connected radio telescope array is the Giant Metrewave Radio Telescope, located in Pune, India. A larger array, LOFAR (the 'LOw Frequency ARray') is currently being constructed in western Europe, consisting of 25 000 small antennas over an area several hundreds of kilometres in diameter. VLBI systems using post-observation processing have been constructed with antennas thousands of miles apart. Radio interferometers have also been used to obtain detailed images of the anisotropies and the polarization of the Cosmic Microwave Background, like the CBI interferometer in 2004.

Astronomical observations

Many astronomical objects are not only observable in visible light but also emit radiation at radio wavelengths. Besides observing energetic objects such as pulsars and quasars, radio telescopes are able to "image" most astronomical objects such as galaxies, nebulae, and even radio emissions from planets.

Chapter 4

Parabolic Antenna

A parabolic antenna at Erdfunkstelle Raisting, the biggest facility for satellite communication in the world, based in Raisting, Bavaria, Germany. It has a Cassegrain type feed.

A **parabolic antenna** is an antenna that uses a parabolic reflector, a surface with the cross-sectional shape of a parabola, to direct the radio waves. The most common form is shaped like a dish and is popularly called a **dish antenna** or **parabolic dish**. The main advantage of a parabolic antenna is that it is highly directive; it functions analogously to a searchlight or flashlight reflector to direct the radio waves in a narrow beam, or receive radio waves from one particular direction only. Parabolic antennas have some of the highest gains, that is they can produce the narrowest beam width angles, of any antenna type. They are used as high-gain antennas for point-to-point radio, television and data communications, and also for radiolocation (radar), on the UHF and microwave (SHF) parts of the radio spectrum. The relatively short wavelength of electromagnetic radiation at these frequencies allows reasonably sized reflectors to exhibit the desired highly directional response.

With the advent of TVRO and DBS satellite television dishes, parabolic antennas have become a ubiquitous feature of the modern landscape. They are also widely used for terrestrial microwave relay links, ground based and airborne radar antennas, wireless WAN/LAN links, satellite and spacecraft communication antennas, and radio telescopes.

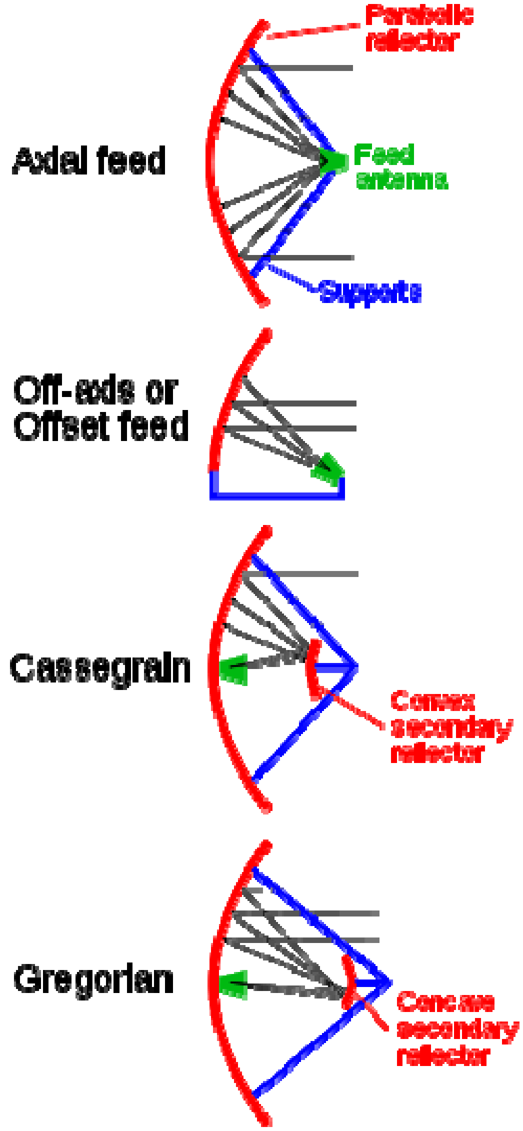
History

The idea of using parabolic reflectors for radio antennas was taken from optics, where the power of a parabolic mirror to focus light into a beam has been known since classical antiquity. The designs of some specific types of parabolic antenna, such as the Cassegrain and Gregorian, come from similarly named analogous types of reflecting telescope, which were invented by astronomers during the 15th century.

German physicist Heinrich Hertz constructed the world's first parabolic reflector antenna in 1888. The antenna was a cylindrical parabolic reflector made of zinc sheet metal supported by a wooden frame, and had a spark-gap excited dipole along the focal line. Its aperture was 1.2 meters wide, with a focal length of 0.12 meters, and was used at an operating frequency of about 450 MHz. With two such antennas, one used for transmitting and the other for receiving, Hertz demonstrated the existence radio waves which had been predicted by James Clerk Maxwell some 22 years earlier.

The first parabolic antenna used for satellite communications was established in 1962 at Goonhilly in Cornwall, England, UK and was intended to communicate with Telstar.

Types



Main types of parabolic antenna feeds.

Parabolic antennas are distinguished by their shapes:

- *Paraboloidal* or *dish* - The reflector is shaped like a paraboloid. This is the most common type. It radiates a narrow pencil-shaped beam along the axis of the dish.
    - *Shrouded dish* - Sometimes a cylindrical metal shield is attached to the rim of the dish. The shroud shields the antenna from radiation from angles outside the main beam axis, reducing the sidelobes. It is sometimes used to prevent interference in terrestrial microwave links, where several antennas using the same frequency are located close together. The shroud is coated

inside with microwave absorbent material. Shrouds can reduce back lobe radiation by 10 dB.

- *Cylindrical* - The reflector is curved in only one direction and flat in the other. The radio waves come to a focus not at a point but along a line. The feed is often a dipole antenna located along the focal line. It radiates a fan-shaped beam, narrow in the curved dimension, and wide in the uncurved dimension. The curved ends of the reflector are sometimes capped by flat plates, to prevent radiation out the ends, and this is called a *pillbox* antenna.
    - *"Orange peel"* - Another type is very long and narrow, shaped like the letter "C". This is called an *orange peel* design, and radiates an even wider fan beam. It is often used for radar antennas.

They are also classified by the type of *feed*; how the radio waves are supplied to the antenna:

- *Axial* or *front feed* - This is the most common type of feed, with the feed antenna located in front of the dish at the focus, on the beam axis. A disadvantage of this type is that the feed and its supports block some of the beam, which limits the aperture efficiency to only 55 - 60%.
- *Offset* or *off-axis feed* - The reflector is an asymmetrical segment of a paraboloid, so the focus, and the feed antenna, are located to one side of the dish. The purpose of this design is to move the feed structure out of the beam path, so it doesn't block the beam. It is widely used in home satellite television dishes, which are small enough that the feed structure would otherwise block a significant percentage of the signal.
- *Cassegrain* - In a Cassegrain antenna the feed is located on or behind the dish, and radiates forward, illuminating a convex hyperboloidal secondary reflector at the focus of the dish. The radio waves from the feed reflect back off the secondary reflector to the dish, which forms the main beam. An advantage of this configuration is that the feed, with its waveguides and "front end" electronics does not have to be suspended in front of the dish, so it is used for antennas with complicated or bulky feeds, such as large satellite communication antennas and radio telescopes. Aperture efficiency is on the order of 65 - 70%
- *Gregorian* - Similar to the Cassegrain design except that the secondary reflector is concave, (ellipsoidal) in shape. Aperture efficiency over 70% can be achieved.

Design

The operating principle of a parabolic antenna is that a point source of radio waves at the focal point in front of a parabolic reflector will be reflected into a collimated plane wave beam along the axis of the reflector. Conversely, an incoming plane wave parallel to the axis will be focused to a point at the focal point.

A typical parabolic antenna consists of a parabolic reflector with a small feed antenna at its focus, pointed back toward the reflector. The reflector is a metallic surface formed into a paraboloid of revolution and usually truncated in a circular rim that forms the diameter of the antenna.

The reflector dish can be of sheet metal, metal screen, or wire grill construction, and it can be either circular or various other shapes to create different beam shapes. A mesh screen reflects radio waves as well as a solid metal surface as long as the holes are smaller than 1/10 of a wavelength, so screen reflectors are often used to reduce weight and wind loads on the dish. To achieve the maximum gain, it is necessary that the shape of the dish be accurate within a small fraction of a wavelength, to ensure the waves from different parts of the antenna arrive in phase. Large dishes often require a truss structure behind them to provide the required stiffness.

The feed antenna at the reflector's focus is typically a low-gain type such as a half-wave dipole or more ofteh a small horn antenna called a feed horn. In more complex designs, such as the Cassegrain and Gregorian, a secondary reflector is used to direct the energy into the parabolic reflector from a feed antenna located away from the primary focal point. The feed antenna is connected to the associated radio-frequency (RF) transmitting or receiving equipment by means of a coaxial cable transmission line or waveguide.

Feed pattern

The radiation pattern of the feed antenna has a strong influence on the *aperture efficiency*, which determines the antenna gain. Radiation from the feed that falls outside the edge of the dish is called "*spillover*" and is wasted, reducing the gain and increasing the backlobes, possibly causing interference or (in receiving antennas) increasing susceptibility to ground noise. However, maximum gain is only achieved when the dish is uniformly "illuminated" with a constant field strength to its edges. So the ideal radiation pattern of a feed antenna would be a constant field strength throughout the solid angle of the dish, dropping abruptly to zero at the edges. However, practical feed antennas have radiation patterns that drop off gradually at the edges, so the feed antenna is a compromise between acceptably low spillover and adequate illumination.

Gain

The directive qualities of an antenna are measured by a dimensionless parameter called its gain, which is the ratio of the power received by the antenna from a source along its beam axis to the power received by a hypothetical isotropic antenna. The gain of a parabolic antenna is:

$$G = \frac{4\pi A}{\lambda^2} e_A = \frac{\pi^2 d^2}{\lambda^2} e_A$$

where:

- A is the area of the antenna aperture, that is, the mouth of the parabolic reflector
- d is the diameter of the parabolic reflector

- λ is the wavelength of the radio waves.
- e_A is a dimensionless parameter called the *aperture efficiency*. The aperture efficiency of typical parabolic antennas is 0.55 to 0.70.

The largest dish antenna in the world, the radio telescope at Arecibo Observatory, Puerto Rico, 305 meters (1000 feet) in diameter. It has a gain of 10 million, or 70 dBi, at 2.38 GHz.

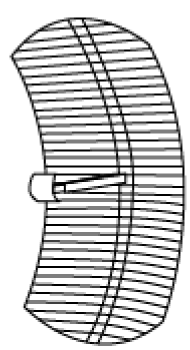
It can be seen that, as with any *aperture antenna*, the larger the aperture is, compared to the wavelength, the higher the gain. The gain increases with the square of the ratio of aperture width to wavelength, so large parabolic antennas, such as those used for spacecraft communication and radio telescopes, can have extremely high gain. Applying the above formula to the 25-meter-diameter antennas used by the VLA and VLBA radio telescopes at a wavelength of 21 cm (1.42 GHz, a common radio astronomy frequency) yields an approximate maximum gain of 140,000 times or about 50 dBi (decibels above the isotropic level).

As of 2009, the largest "dish" antenna in the world is the Arecibo Observatory's radio telescope, at Arecibo, Puerto Rico, which has a diameter of 1,000 ft. (305 m). It has a gain of about 10 million, or 70 dBi, at 2.38 GHz. The dish is built into a valley in the landscape, so it is not steerable. To steer the beam to different points in the sky, the feed antenna is moved. For this reason, the dish actually has a spherical rather than a parabolic shape. A spherical reflector does not have a single focal "point", however, the Arecibo antenna is a three-reflector variety of Gregorian telescope, and uses its secondary and tertiary reflectors to focus the radio waves to a single point.

Aperture efficiency e_A is a catchall variable which accounts for various losses that reduce the gain of the antenna from the maximum that could be achieved with the given aperture. The major factors reducing the aperture efficiency in parabolic antennas are:.

- *Feed spillover* - Some of the radiation from the feed antenna falls outside the edge of the dish and so doesn't contribute to the main beam.
- *Feed illumination taper* - The maximum gain for any aperture antenna is only achieved when the intensity of the radiated beam is constant across the aperture area. However the radiation pattern from the feed antenna usually tapers off toward the outer part of the dish, so the outer parts of the dish are "illuminated" with a lower intensity of radiation. Even if the feed provided constant illumination across the angle subtended by the dish, the outer parts of the dish are farther away from the feed antenna than the inner parts, so the intensity would drop off with distance from the center. So the intensity of the beam radiated by a parabolic antenna is maximum at the center of the dish and falls off with distance from the axis, reducing the efficiency.
- *Aperture blockage* - In axis-fed parabolic dishes where the feed antenna is located in front of the dish in the beam path, the feed structure and its supports block some of the beam. In small dishes such as home satellite dishes, where the size of the feed structure is comparable with the size of the dish, this can seriously reduce the antenna gain. To prevent this problem these types of antennas often use an *off-axis* feed, where the feed antenna is located to one side, outside the beam area. The aperture efficiency for these types of antennas can reach 0.7 to 0.8.
- *Shape errors* - random surface errors in the shape of the reflector reduce efficiency. The loss is approximated by Ruze's Equation.

For theoretical considerations of mutual interference (at frequencies between 2 and c. 30 GHz - typically in the Fixed Satellite Service) where specific antenna performance has not been defined, a *reference antenna* based on Recommendation ITU-R S.465 is used to calculate the interference, which will include the likely sidelobes for off-axis effects.



Wire grid-type parabolic antenna (Wi-Fi / WLAN antenna) at 2.4 GHz).

Beamwidth

C-band Satellite dish, Bucharest, Romania

The angular width of the beam radiated by high-gain antennas is measured by the *half-power beam width* (HPBW), which is the angular separation between the points on the antenna radiation pattern at which the power drops to one-half (-3 dB) its maximum value. For parabolic antennas, the HPBW θ is given by:

$$\theta = k\lambda/d$$

where k is a factor which depends on the shape of the reflector and the feed illumination pattern. For a "typical" parabolic antenna $k = 70$ when θ is in degrees.

For a typical 2 meter satellite dish operating on C band (4 GHz), like the one shown at right, this formula gives a beamwidth of about 2.6°. For the Arecibo antenna at 2.4 GHz the beamwidth is 0.028°. It can be seen that parabolic antennas can produce very narrow beams, and aiming them can be a problem. Some parabolic dishes are equipped with a boresight so they can be aimed accurately at the other antenna.

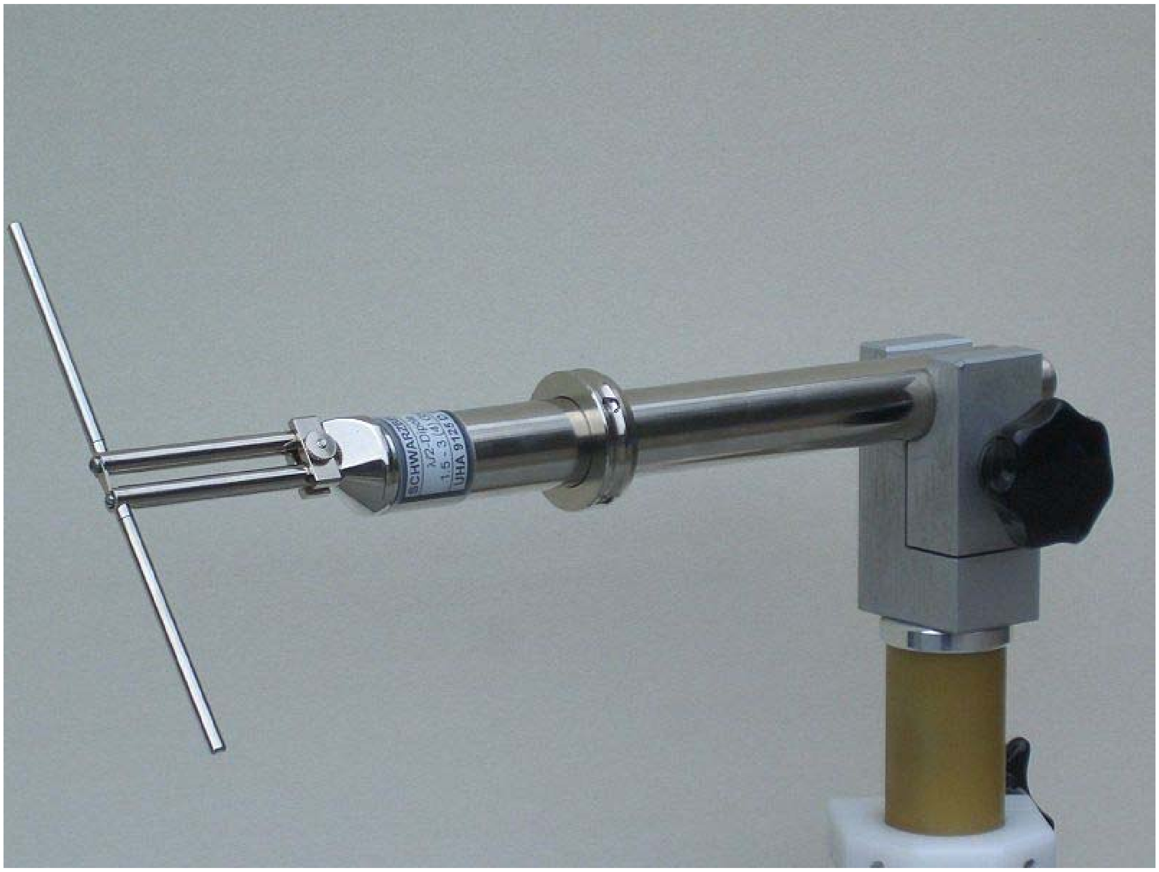
It can be seen there is an inverse relation between gain and beam width. By combining the beamwidth equation with the gain equation, the relation is:

$$G - \left(\frac{\pi k}{\theta}\right)^2 \epsilon_A$$

Chapter 5

Antenna (Radio)

Whip antenna on car



Half-wave dipole antenna

Large parabolic antenna for communicating with spacecraft

Rooftop directional antennas, typical for use at VHF and UHF frequencies

An **antenna** (or **aerial**) is an electrical device which couples radio waves in free space to an electrical current used by a radio receiver or transmitter. In reception, the antenna intercepts some of the power of an electromagnetic wave in order to produce a tiny voltage that the radio receiver can amplify. Alternatively, a radio transmitter will produce a large radio frequency current that may be applied to the terminals of the same antenna in order to convert it into an electromagnetic wave (radio wave) radiated into free space. Antennas are thus essential to the operation of all radio equipment, both transmitters and receivers. They are used in systems such as radio and television broadcasting, two-way radio, wireless LAN, mobile telephony, radar, and satellite communications.

Typically an antenna consists of an arrangement of metallic conductors (or "elements") with an electrical connection (often through a transmission line) to the receiver or transmitter. A current forced through such a conductor by a radio transmitter will create an alternating magnetic field according to Ampère's law. Or the alternating magnetic field due to a distant radio transmitter will induce a voltage at the antenna terminals, according to Faraday's law, which is connected to the input of a receiver. In the so-called far field, at a considerable distance away from the antenna, the oscillating magnetic field is coupled with a similarly oscillating electric field; together these define an electromagnetic wave which is capable of propagating great distances.

Light is one example of electromagnetic radiation, along with infrared and x-rays, while radio waves differ only in their much lower frequency (and much longer wavelength). Electronic circuits can operate at these lower frequencies, processing radio signals conducted through wires. But it is only through antennas that those radio frequency electrical signals are converted to (and from) propagating radio waves. Depending on the design of the antenna, radio waves can be sent toward and received from all directions ("omnidirectional"), whereas a directional or beam antenna is designed to operate in a particular direction.

The first antennas were built in 1888 by Heinrich Hertz (1857–1894) in his pioneering experiments to prove the existence of electromagnetic waves predicted by the theory of James Clerk Maxwell. Hertz placed dipole antennas at the focal point of parabolic reflectors for both transmitting and receiving. He published his work and installation drawings in *Annalen der Physik und Chemie* (vol. 36, 1889).

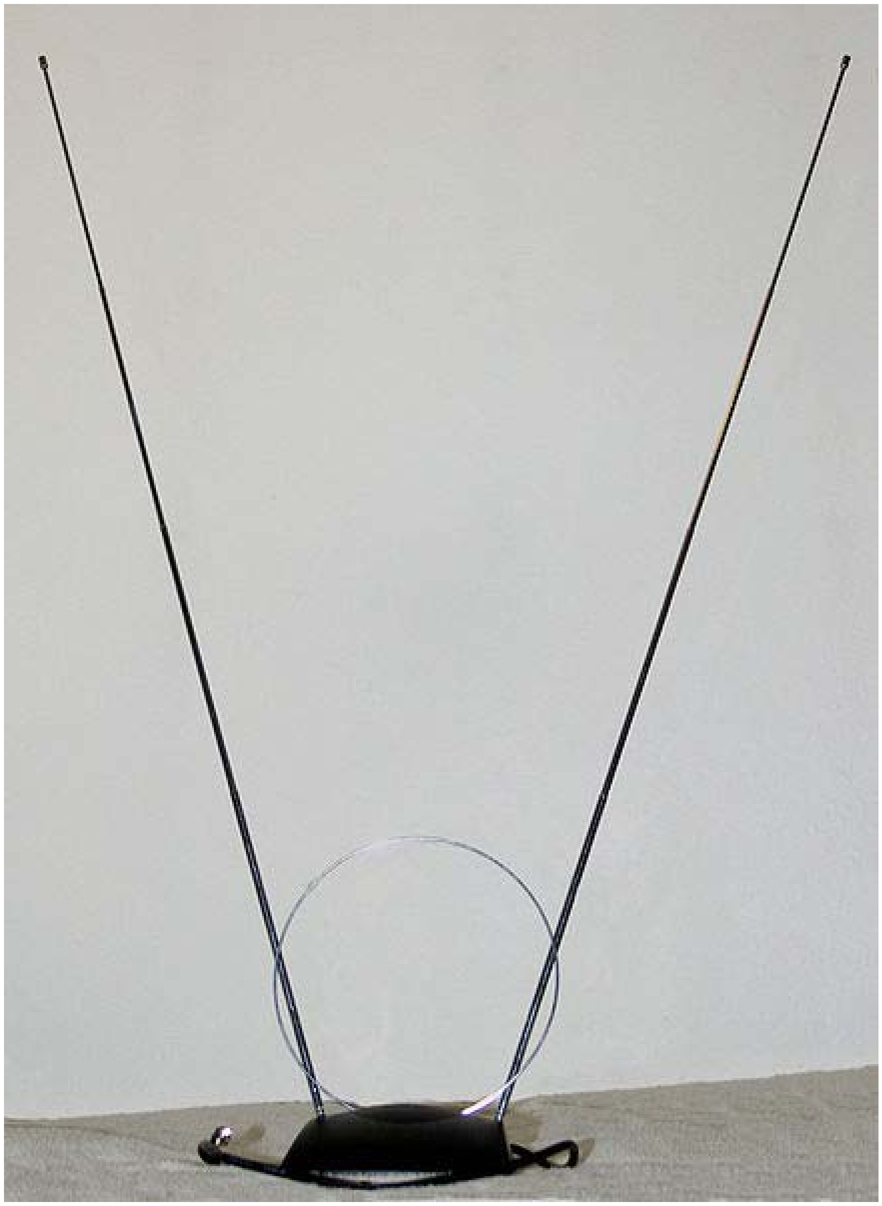
Terminology

The words *antenna* (plural: *antennas*) and *aerial* are used interchangeably; but usually a rigid metallic structure is termed an antenna and a wire format is called an aerial. In the United Kingdom and other British English speaking areas the term aerial is more common, even for rigid types. The noun *aerial* is occasionally written with a diaeresis mark—*aërial*—in recognition of the original spelling of the adjective *aërial* from which the noun is derived.

The origin of the word *antenna* relative to wireless apparatus is attributed to Guglielmo Marconi. In 1895, while testing early radio apparatuses in the Swiss Alps at Salvan, Switzerland in the Mont Blanc region, Marconi experimented with early wireless equipment. A 2.5 meter long pole, along which was carried a wire, was used as a radiating and receiving aerial element. In Italian a tent pole is known as *l'antenna centrale,* and the pole with a wire alongside it used as an aerial was simply called *l'antenna.* Until then wireless radiating transmitting and receiving elements were known simply as aerials or terminals. Marconi's use of the word *antenna* (Italian for *pole*) would become a popular term for what today is uniformly known as the *antenna*.

In common usage, the word *antenna* may refer broadly to an entire assembly including support structure, enclosure (if any), etc. in addition to the actual functional components.

Especially at microwave frequencies, a receiving antenna may include not only the actual electrical antenna but an integrated preamplifier and/or mixer.

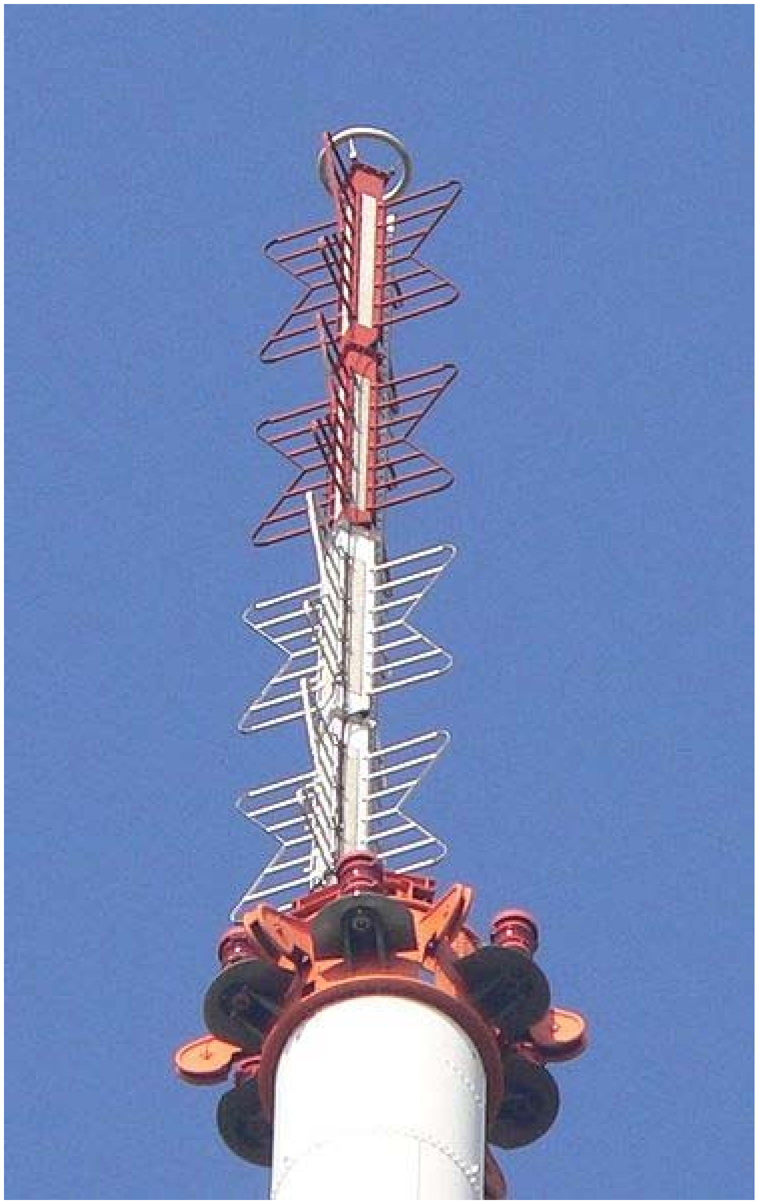


"Rabbit ears" dipole antenna for television reception

Cell phone base station antennas

Satellite link antenna used by Himalaya Television Nepal

Yagi antenna used for mobile military communications station, Dresden, Germany, 1955



"Super Turnstile" type transmitting antenna for VHF low band television broadcasting station, Germany.

Folded dipole antenna

Large Yagi antenna used by amateur radio hobbyist

A vertical mast radiator, Chapel Hill, North Carolina

Overview

Antennas are required by any radio receiver or transmitter in order to couple its electrical connection to the electromagnetic field. Radio waves are electromagnetic waves which carry signals through the air (or through space) at almost the speed of light with almost no transmission loss. Radio transmitters and receivers are used to convey signals (information) in systems including broadcast (audio) radio, television, mobile telephones, wi-fi (WLAN) data networks, trunk lines and point-to-point communications links (telephone, data networks), satellite links, many remote controlled devices such as garage door openers, and wireless remote sensors, among many others. Radio waves are also used directly for measurements in technologies including RADAR, GPS, and radio astronomy. In each and every case, the transmitters and receivers involved require antennas, although these are sometimes hidden (such as the antenna inside an AM radio or inside a laptop computer equipped with wi-fi).

According to their applications and technology available, antennas generally fall in one of two catagories:

1. Omnidirectional or only weakly directional antennas which receive or radiate more or less in all directions. These are employed when the relative position of the other station is unknown or arbitrary. They are also used at lower frequencies where a directional antenna would be too large, or simply to cut costs in applications where a directional antenna isn't required.
2. Directional or *beam* antennas which are intended to preferentially radiate or receive in a particular direction or directional pattern.

In common usage "omnidirectional" usually refers to all horizontal directions, typically with reduced performance in the direction of the sky or the ground (a truly isotropic radiator is not even possible). A "directional" antenna usually is intended to maximize its coupling to the electromagnetic field in the direction of the other station, or sometimes to cover a particular sector such as a 120° horizontal fan pattern in the case of a panel antenna at a cell site.

One example of omnidirectional antennas is the very common *vertical antenna* or whip antenna consisting of a metal rod (often, but not always, a quarter of a wavelength long). A dipole antenna is similar but consists of two such conductors extending in opposite directions, with a total length that is often, but not always, a half of a wavelength long. Dipoles are typically oriented horizontally in which case they are weakly directional: signals are reasonably well radiated toward or received from all directions with the exception of the direction along the conductor itself; this region is called the antenna blind cone or null.

Both the vertical and dipole antennas are simple in construction and relatively inexpensive. The dipole antenna, which is the basis for most antenna designs, is a balanced component, with equal but opposite voltages and currents applied at its two terminals through a balanced transmission line (or to a coaxial transmission line through a so-called balun). The vertical antenna, on the other hand, is a *monopole* antenna. It is typically connected to the inner conductor of a coaxial transmission line (or a matching network); the shield of the transmission line is connected to ground. In this way, the ground (or any large conductive surface) plays the role of the second conductor of a dipole, thereby forming a complete circuit. Since monopole antennas rely on a conductive ground, a so-called grounding structure may be employed in order to provide a better ground contact to the earth or which itself acts as a ground plane to perform that function regardless of (or in absence of) an actual contact with the earth.

Antennas fancier than the dipole or vertical designs are usually intended to increase the directivity and consequently the gain of the antenna. This can be accomplished in many different ways leading to a plethora of antenna designs. The vast majority of designs are fed with a balanced line (unlike a monopole antenna) and are based on the dipole antenna with additional components (or *elements*) which increase its directionality.

For instance, a phased array consists of two or more simple antennas which are connected together through an electrical network. This often involves a number of parallel dipole antennas with a certain spacing. Depending on the relative phase introduced by the network, the same combination of dipole antennas can operate as a "broadside array" (directional normal to a line connecting the elements) or as an "end-fire array" (directional along the line connecting the elements). Antenna arrays may employ any basic (omnidirectional or weakly directional) antenna type, such as dipole, loop or slot antennas. These elements are often identical.

However a log-periodic dipole array consists of a number of dipole elements of *different* lengths in order to obtain a somewhat directional antenna having an extremely wide bandwidth: these are frequently used for television reception in fringe areas. The dipole antennas composing it are all considered "active elements" since they are all electrically connected together (and to the transmission line). On the other hand, a superficially similar dipole array, the Yagi-Uda Antenna (or simply "Yagi"), has only one dipole element with an electrical connection; the other so-called parasitic elements interact with the electromagnetic field in order to realize a fairly directional antenna but one which is limited to a rather narrow bandwidth. The Yagi antenna has similar looking parasitic dipole elements but which act differently due to their somewhat different lengths. There may be a number of so-called "directors" in front of the active element in the direction of propagation, and usually a single (but possibly more) "reflector" on the opposite side of the active element.

Greater directionality can be obtained using beam-forming techniques such as a parabolic reflector or a horn. Since the size of a directional antenna depends on it being large compared to the wavelength, very directional antennas of this sort are mainly feasible at UHF and microwave frequencies. On the other hand, at low frequencies (such as AM broadcast) where a practical antenna must be much smaller than a wavelength, significant directionality isn't even possible. A vertical antenna or loop antenna small compared to the wavelength is typically used, with the main design challenge being that of impedance matching. With a vertical antenna a *loading coil* at the base of the antenna may be employed to cancel the reactive component of impedance; small loop antennas are tuned with parallel capacitors for this purpose.

An antenna lead-in is the transmission line (or *feed line*) which connects the antenna to a transmitter or receiver. The *antenna feed* may refer to all components connecting the antenna to the transmitter or receiver, such as an impedance matching network in addition to the transmission line. In a so-called aperture antenna, such as a horn or parabolic dish, the "feed" may also refer to a basic antenna inside the entire system (normally at the focus of the parabolic dish or at the throat of a horn) which could be considered the one active element in that antenna system. A microwave antenna may also be fed directly from a waveguide in lieu of a (conductive) transmission line.

An antenna counterpoise or ground plane is a structure of conductive material which improves or substitutes for the ground. It may be connected to or insulated from the natural ground. In a monopole antenna, this aids in the function of the natural ground, particularly where variations (or limitations) of the characteristics of the natural ground interfere with its proper function. Such a structure is normally connected to the return connection of an unbalanced transmission line such as the shield of a coaxial cable.

An electromagnetic wave *refractor* in some aperture antennas is a component which due to its shape and position functions to selectively delay or advance portions of the electromagnetic wavefront passing through it. The refractor alters the spatial characteristics of the wave on one side relative to the other side. It can, for instance, bring the wave to a focus or alter the wave front in other ways, generally in order to maximize the directivity of the antenna system. This is the radio equivalent of an optical lens.

An antenna coupling network is a passive network (generally a combination of inductive and capacitive circuit elements) used for impedance matching in between the antenna and the transmitter or receiver. This may be used to improve the standing wave ratio in order to minimize losses in the transmission line (especially at higher frequencies and/or over longer distances) and to present the transmitter or receiver with a standard resistive impedance (such as 75 ohms) that it expects to see for optimum operation.

Reciprocity

It is a fundamental property of antennas that the characteristics of an antenna described in the next section, such as gain, radiation pattern, impedance, bandwidth, resonant frequency and polarization, are the same whether the antenna is transmitting or receiving. For example, the "*receiving pattern*" (sensitivity as a function of direction) of an antenna when used for reception is identical to the radiation pattern of the antenna when it is *driven* and functions as a radiator. This is a consequence of the reciprocity theorem of electromagnetics. Therefore in discussions of antenna properties no distinction is usually made between receiving and transmitting terminology, and the antenna can be viewed as either transmitting or receiving, whichever is more convenient.

A necessary condition for the above reciprocity property is that the materials in the antenna and transmission medium are linear and reciprocal. *Reciprocal* (or *bilateral*) means that the material has the same response to an electric or magnetic field, or a current, in one direction, as it has to the field or current in the opposite direction. Most materials used in antennas meet these conditions, but some microwave antennas use high-tech components such as isolators and circulators, made of nonreciprocal materials such as ferrite or garnet. These can be used to give the antenna a different behavior on receiving than it has on transmitting, which can be useful in applications like radar.

Parameters

There are several critical parameters affecting an antenna's performance that can be adjusted during the design process. These are resonant frequency, impedance, gain, aperture or radiation pattern, polarization, efficiency and bandwidth. Transmit antennas may also have a maximum power rating, and receive antennas differ in their noise rejection properties. All of these parameters can be measured through various means.

Resonant frequency

Many types of antenna are tuned to work at one particular frequency, and are effective only over a range of frequencies centered on this frequency, called the resonant frequency. These are called *resonant antennas*. The antenna acts as an electrical resonator. When driven at its resonant frequency, large standing waves of voltage and current are excited in the antenna elements. These large currents and voltages radiate intense electromagnetic waves, so the power radiated by the antenna is maximum at the resonant frequency.

In antennas made of thin linear conductive elements, the length of the driven element(s) determines the resonant frequency. To be resonant, the length of a driven element should typically be either half or a quarter of the wavelength at that frequency; these are called half-wave and quarter-wave antennas. The length referred to is not the physical length, but the electrical length of the element, which is the physical length divided by the velocity factor (the ratio of the speed of wave propagation in the wire to c_0, the speed of light in a vacuum). Antennas are usually also resonant at multiples (harmonics) of the lowest resonant frequency.

Some antenna designs have multiple resonant frequencies, and some are relatively effective over a very broad range of frequencies. or bandwidth. One commonly known type of wide band antenna is the logarithmic or log-periodic antenna.

The resonant frequency also affects the impedance of the antenna. At resonance, the equivalent circuit of an antenna is a pure resistance, with no reactive component. At frequencies other than the resonant frequencies, the antenna has capacitance or inductance as well as resistance. An antenna can be made resonant at other frequencies besides its natural resonant frequency by compensating for these reactances by adding a loading coil or capacitor in series with it. Other properties of an antenna change with frequency, in particular the radiation pattern, so the antenna's operating frequency may be considerably different from the resonant frequency to optimize other important parameters.

Gain

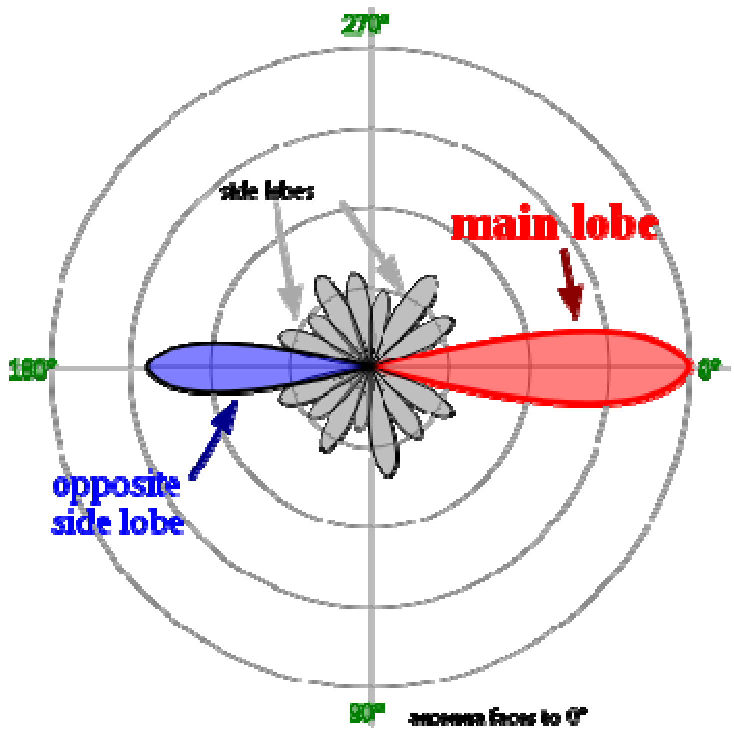
Gain is a parameter which measures the degree of directivity of the antenna's radiation pattern. An antenna with a low gain emits radiation with about the same power in all directions, whereas a high-gain antenna will preferentially radiate in particular directions. Specifically, the *antenna gain*, *directive gain*, or *power gain* of an antenna is defined as the ratio of the intensity (power per unit surface) radiated by the antenna in the direction of its maximum output, at an arbitrary distance, divided by the intensity radiated at the same distance by a hypothetical isotropic antenna.

The gain of an antenna is a passive phenomenon - power is not added by the antenna, but simply redistributed to provide more radiated power in a certain direction than would be transmitted by an isotropic antenna. An antenna designer must take into account the application for the antenna when determining the gain. High-gain antennas have the advantage of longer range and better signal quality, but must be aimed carefully in a particular direction. Low-gain antennas have shorter range, but the orientation of the antenna is relatively inconsequential. For example, a dish antenna on a spacecraft is a high-gain device that must be pointed at the planet to be effective, whereas a typical Wi-Fi antenna in a laptop computer is low-gain, and as long as the base station is within range, the antenna can be in any orientation in space. It makes sense to improve horizontal range at the expense of reception above or below the antenna. Thus most antennas labelled "omnidirectional" really have some gain.

In practice, the half-wave dipole is taken as a reference instead of the isotropic radiator. The gain is then given in **dBd** (decibels over **d**ipole):

NOTE: **0 dBd = 2.15 dBi**. It is vital in expressing gain values that the reference point be included. Failure to do so can lead to confusion and error.

Radiation pattern



polar plots of the horizontal cross sections of a (virtual) Yagi-Uda-antenna. Outline connects points with 3db field power compared to an ISO emitter.

The radiation pattern of an antenna is a plot of the relative field strength of the radio waves emitted by the antenna at different angles. It is typically represented by a three dimensional graph, or polar plots of the horizontal and vertical cross sections. The pattern of an ideal isotropic antenna, which radiates equally in all directions, would look like a sphere. Many nondirectional antennas, such as monopoles and dipoles, emit equal power in all horizontal directions, with the power dropping off at higher and lower angles; this is called an omnidirectional pattern and when plotted looks like a torus or donut.

The radiation of many antennas shows a pattern of maxima or "*lobes*" at various angles, separated by "*nulls*", angles where the radiation falls to zero. This is because the radio waves emitted by different parts of the antenna typically interfere, causing maxima at angles where the radio waves arrive at distant points in phase, and zero radiation at other angles where the radio waves arrive out of phase. In a directional antenna designed to project radio waves in a particular direction, the lobe in that direction is designed larger than the others and is called the "*main lobe*". The other lobes usually represent unwanted radiation and are called "*sidelobes*". The axis through the main lobe is called the "*principle axis*" or "*boresight axis*".

Impedance

As an electro-magnetic wave travels through the different parts of the antenna system (radio, feed line, antenna, free space) it may encounter differences in impedance (E/H, V/I, etc.). At each interface, depending on the impedance match, some fraction of the wave's energy will reflect back to the source, forming a standing wave in the feed line. The ratio of maximum power to minimum power in the wave can be measured and is called the standing wave ratio (**SWR**). A SWR of 1:1 is ideal. A SWR of 1.5:1 is considered to be marginally acceptable in low power applications where power loss is more critical, although an SWR as high as 6:1 may still be usable with the right equipment. Minimizing impedance differences at each interface (impedance matching) will reduce SWR and maximize power transfer through each part of the antenna system.

Complex impedance of an antenna is related to the electrical length of the antenna at the wavelength in use. The impedance of an antenna can be matched to the feed line and radio by adjusting the impedance of the feed line, using the feed line as an impedance transformer. More commonly, the impedance is adjusted at the load (see below) with an antenna tuner, a balun, a matching transformer, matching networks composed of inductors and capacitors, or matching sections such as the gamma match.

Efficiency

Efficiency is the ratio of power actually radiated to the power put into the antenna terminals. A dummy load may have an SWR of 1:1 but an efficiency of 0, as it absorbs all power and radiates heat but very little RF energy, showing that SWR alone is not an effective measure of an antenna's efficiency. Radiation in an antenna is caused by radiation resistance which can only be measured as part of total resistance including loss resistance. Loss resistance usually results in heat generation rather than radiation, and reduces efficiency. Mathematically, efficiency is calculated as radiation resistance divided by total resistance.

Bandwidth

The *bandwidth* of an antenna is the range of frequencies over which it is effective, usually centered on the resonant frequency. The bandwidth of an antenna may be increased by several techniques, including using thicker wires, replacing wires with *cages* to simulate a thicker wire, tapering antenna components (like in a feed horn), and combining multiple antennas into a single assembly (array) and allowing the natural impedance of suitable inductive RF filter traps to select the correct antenna. All these attempts to increase bandwidth by adding capacitance to the surface area have a detrimental effect on efficiency by reducing the Q factor. They also have an adverse effect on the rejection of unwanted harmonics, on both received and transmitted signal frequencies. Small antennas are usually preferred for convenience, but there is a fundamental limit relating bandwidth, size and efficiency.

Polarization

The *polarization* of an antenna is the orientation of the electric field (E-plane) of the radio wave with respect to the Earth's surface and is determined by the physical structure of the antenna and by its orientation. It has nothing in common with antenna directionality terms: "horizontal", "vertical" and "circular". Thus, a simple straight wire antenna will have one polarization when mounted vertically, and a different polarization when mounted horizontally. "Electromagnetic wave polarization filters" are structures which can be employed to act directly on the electromagnetic wave to filter out wave energy of an undesired polarization and to pass wave energy of a desired polarization.

Reflections generally affect polarization. For radio waves the most important reflector is the ionosphere - signals which reflect from it will have their polarization changed unpredictably. For signals which are reflected by the ionosphere, polarization cannot be relied upon. For line-of-sight communications for which polarization can be relied upon, it can make a large difference in signal quality to have the transmitter and receiver using the same polarization; many tens of dB difference are commonly seen and this is more than enough to make the difference between reasonable communication and a broken link.

Polarization is largely predictable from antenna construction but, especially in directional antennas, the polarization of side lobes can be quite different from that of the main propagation lobe. For radio antennas, polarization corresponds to the orientation of the radiating element in an antenna. A vertical omnidirectional WiFi antenna will have vertical polarization (the most common type). An exception is a class of elongated waveguide antennas in which vertically placed antennas are horizontally polarized. Many commercial antennas are marked as to the polarization of their emitted signals.

Polarization is the sum of the E-plane orientations over time projected onto an imaginary plane perpendicular to the direction of motion of the radio wave. In the most general case, polarization is elliptical, meaning that the polarization of the radio waves varies over time. Two special cases are linear polarization (the ellipse collapses into a line) and circular polarization (in which the two axes of the ellipse are equal). In linear polarization the antenna compels the electric field of the emitted radio wave to a particular orientation. Depending on the orientation of the antenna mounting, the usual linear cases are horizontal and vertical polarization. In circular polarization, the antenna continuously varies the electric field of the radio wave through all possible values of its orientation with regard to the Earth's surface. Circular polarizations, like elliptical ones, are classified as right-hand polarized or left-hand polarized using a "thumb in the direction of the propagation" rule. Optical researchers use the same rule of thumb, but pointing it in the direction of the emitter, not in the direction of propagation, and so are opposite to radio engineers' use.

In practice, regardless of confusing terminology, it is important that linearly polarized antennas be matched, lest the received signal strength be greatly reduced. So horizontal should be used with horizontal and vertical with vertical. Intermediate matchings will lose some signal strength, but not as much as a complete mismatch. Transmitters mounted on vehicles with large motional freedom commonly use circularly polarized antennas so that there will never be a complete mismatch with signals from other sources.

Transmission and reception

All of the antenna parameters are expressed in terms of a transmission antenna, but are identically applicable to a receiving antenna, due to reciprocity. Impedance, however, is not applied in an obvious way; for impedance, the impedance at the load (where the power is consumed) is most critical. For a transmitting antenna, this is the antenna itself. For a receiving antenna, this is at the (radio) receiver rather than at the antenna. Tuning is done by adjusting the length of an electrically long linear antenna to alter the electrical resonance of the antenna.

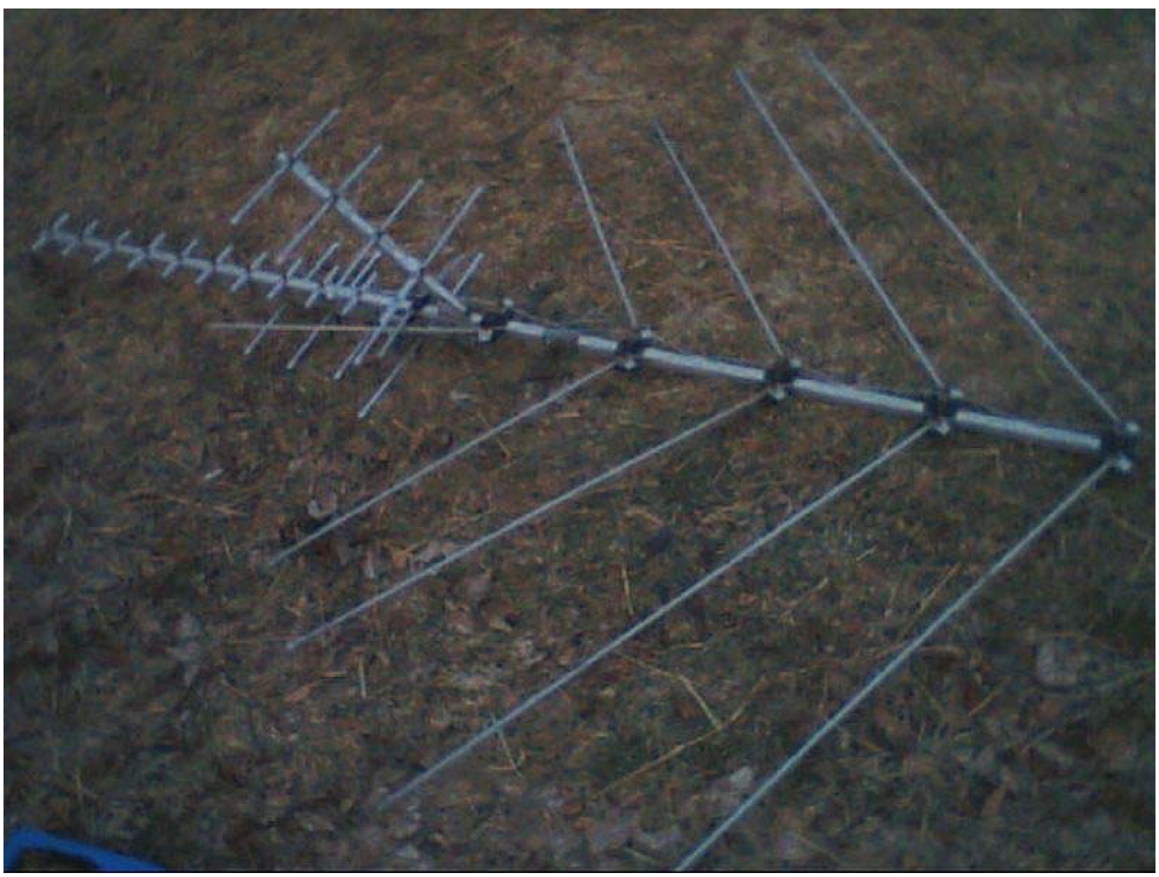
Antenna tuning is done by adjusting an inductance or capacitance combined with the active antenna (but distinct and separate from the active antenna). The inductance or capacitance provides the reactance which combines with the inherent reactance of the active antenna to establish a resonance in a circuit including the active antenna. The established resonance being at a frequency other than the natural electrical resonant frequency of the active antenna. Adjustment of the inductance or capacitance changes this resonance.

Antennas used for transmission have a maximum power rating, beyond which heating, arcing or sparking may occur in the components, which may cause them to be damaged or destroyed. Raising this maximum power rating usually requires larger and heavier components, which may require larger and heavier supporting structures. This is a concern only for transmitting antennas, as the power received by an antenna rarely exceeds the microwatt range.

Antennas designed specifically for reception might be optimized for noise rejection capabilities. An *antenna shield* is a conductive or low reluctance structure (such as a wire, plate or grid) which is adapted to be placed in the vicinity of an antenna to reduce, as by dissipation through a resistance or by conduction to ground, undesired electromagnetic radiation, or electric or magnetic fields, which are directed toward the active antenna from an external source or which emanate from the active antenna. Other methods to optimize for noise rejection can be done by selecting a narrow bandwidth so that noise from other frequencies is rejected, or selecting a specific radiation pattern to reject noise from a specific direction, or by selecting a polarization different from the noise polarization, or by selecting an antenna that favors either the electric or magnetic field.

For instance, an antenna to be used for reception of low frequencies (below about ten megahertz) will be subject to both man-made noise from motors and other machinery, and from natural sources such as lightning. Successfully rejecting these forms of noise is an important antenna feature. A small coil of wire with many turns is more able to reject such noise than a vertical antenna. However, the vertical will radiate much more effectively on transmit, where extraneous signals are not a concern.

Basic antenna models



Typical US multiband TV antenna (aerial)

There are many variations of antennas. Below are a few basic models. More can be found in Category:Radio frequency antenna types.

- The isotropic radiator is a purely theoretical antenna that radiates equally in all directions. It is considered to be a point in space with no dimensions and no mass. This antenna cannot physically exist, but is useful as a theoretical model for comparison with all other antennas. Most antennas' gains are measured with reference to an isotropic radiator, and are rated in dBi (decibels with respect to an isotropic radiator).
- The dipole antenna is simply two wires pointed in opposite directions arranged either horizontally or vertically, with one end of each wire connected to the radio and the other end hanging free in space. Since this is the simplest practical antenna, it is also used as a reference model for other antennas; gain with respect to a dipole is labeled as dBd. Generally, the dipole is considered to be omnidirectional in the plane perpendicular to the axis of the antenna, but it has deep nulls in the directions of the axis. Variations of the dipole include the folded dipole, the half wave antenna, the ground plane antenna, the whip, and the J-pole.
- The Yagi-Uda antenna is a directional variation of the dipole with parasitic elements added which are functionality similar to adding a reflector and lenses (directors) to focus a filament light bulb.
- The random wire antenna is simply a very long (at least one quarter wavelength) wire with one end connected to the radio and the other in free space, arranged in any way most convenient for the space available. Folding will reduce effectiveness and make theoretical analysis extremely difficult. (The added length helps more than the folding typically hurts.) Typically, a random wire antenna will also require an antenna tuner, as it might have a random impedance that varies non-linearly with frequency.
- The horn is used where high gain is needed, the wavelength is short (microwave) and space is not an issue. Horns can be narrow band or wide band, depending on their shape. A horn can be built for any frequency, but horns for lower frequencies are typically impractical. Horns are also frequently used as reference antennas.
- The parabolic antenna consists of an active element at the focus of a parabolic reflector to reflect the waves into a plane wave. Like the horn it is used for high gain, microwave applications, such as satellite dishes.
- The patch antenna consists mainly of a square conductor mounted over a groundplane. Another example of a planar antenna is the tapered slot antenna (TSA), as the Vivaldi-antenna.

Practical antennas

"Rabbit ears" set-top antenna

Although any circuit can radiate if driven with a signal of high enough frequency, most practical antennas are specially designed to radiate efficiently at a particular frequency. An example of an inefficient antenna is the simple Hertzian dipole antenna, which radiates over wide range of frequencies and is useful for its small size. A more efficient variation of this is the half-wave dipole, which radiates with high efficiency when the signal wavelength is twice the electrical length of the antenna.

One of the goals of antenna design is to minimize the reactance of the device so that it appears as a resistive load. An "antenna inherent reactance" includes not only the distributed reactance of the active antenna but also the natural reactance due to its location and surroundings (as for example, the capacity relation inherent in the position of the active antenna relative to ground). Reactance diverts energy into the reactive field, which causes unwanted currents that heat the antenna and associated wiring, thereby wasting energy without contributing to the radiated output. Reactance can be eliminated by operating the antenna at its resonant frequency, when its capacitive and inductive reactances are equal and opposite, resulting in a net zero reactive current. If this is not possible, compensating inductors or capacitors can instead be added to the antenna to cancel its reactance as far as the source is concerned.

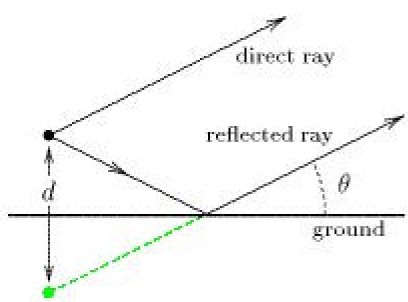
Once the reactance has been eliminated, what remains is a pure resistance, which is the sum of two parts: the ohmic resistance of the conductors, and the radiation resistance. Power absorbed by the ohmic resistance becomes waste heat, and that absorbed by the radiation resistance becomes radiated electromagnetic energy. The greater the ratio of radiation resistance to ohmic resistance, the more efficient the antenna.

Effect of ground

Antennas are typically used in an environment where other objects are present that may have an effect on their performance. Height above ground has a very significant effect on the radiation pattern of some antenna types.

At frequencies used in antennas, the ground behaves mainly as a dielectric. The conductivity of ground at these frequencies is negligible. When an electromagnetic wave arrives at the surface of an object, two waves are created: one enters the dielectric and the other is reflected. If the object is a conductor, the transmitted wave is negligible and the reflected wave has almost the same amplitude as the incident one. When the object is a dielectric, the fraction reflected depends (among others things) on the angle of incidence. When the angle of incidence is small (that is, the wave arrives almost perpendicularly) most of the energy traverses the surface and very little is reflected. When the angle of incidence is near 90° (grazing incidence) almost all the wave is reflected.

Most of the electromagnetic waves emitted by an antenna to the ground below the antenna at moderate (say < 60°) angles of incidence enter the earth and are absorbed (lost). But waves emitted to the ground at grazing angles, far from the antenna, are almost totally reflected. At grazing angles, the ground behaves as a mirror. Quality of reflection depends on the nature of the surface. When the irregularities of the surface are smaller than the wavelength reflection is good.



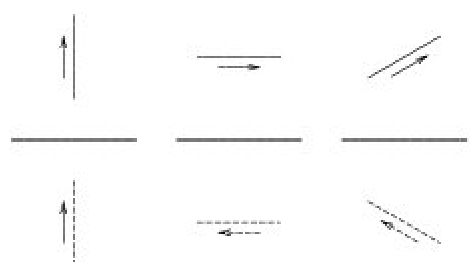
The wave reflected by earth can be considered as emitted by the image antenna

This means that the receptor "sees" the real antenna and, under the ground, the image of the antenna reflected by the ground. If the ground has irregularities, the image will appear fuzzy.

If the receiver is placed at some height above the ground, waves reflected by ground will travel a little longer distance to arrive to the receiver than direct waves. The distance will be the same only if the receiver is close to ground.

In the drawing at right, we have drawn the angle θfar bigger than in reality. Distance between the antenna and its image is d.

The situation is a bit more complex because the reflection of electromagnetic waves depends on the polarization of the incident wave. As the refractive index of the ground (average value $\simeq 2$) is bigger than the refractive index of the air ($\simeq 1$), the direction of the component of the electric field parallel to the ground inverses at the reflection. This is equivalent to a phase shift of πradians or 180°. The vertical component of the electric field reflects without changing direction. This sign inversion of the parallel component and the non-inversion of the perpendicular component would also happen if the ground were a good electrical conductor.



The vertical component of the current reflects without changing sign. The horizontal component reverses sign at reflection.

This means that a receiving antenna "sees" the image antenna with the current in the same direction if the antenna is vertical or with the current inverted if the antenna is horizontal.

For a vertical polarized emission antenna the far electric field of the electromagnetic wave produced by the direct ray plus the reflected ray is:

$$|E_\perp| = 2\,|E_{\theta_1}|\left|\cos\left(\tfrac{kd}{2}\sin\theta\right)\right|$$

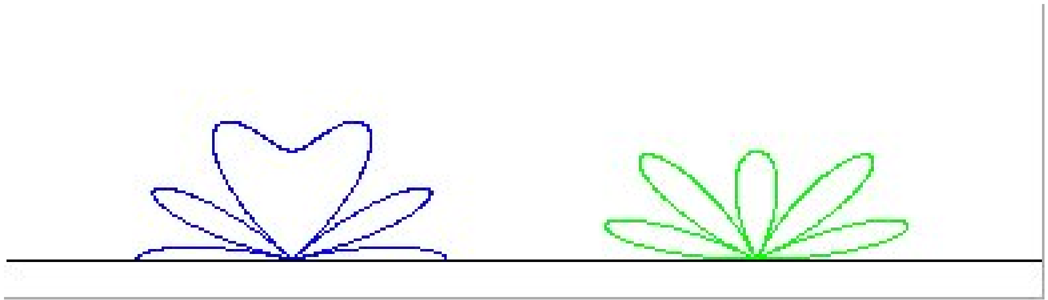
The sign inversion for the parallel field case just changes a cosine to a sine:

$$|E_=| = 2\,|E_{\theta_1}|\left|\sin\left(\tfrac{kd}{2}\sin\theta\right)\right|$$

In these two equations:

- $E_{\theta 1}$is the electrical field radiated by the antenna if there were no ground.
- $k=\frac{2\pi}{\lambda}$is the wave number.
- $\lambda$is the wave length.

- d is the distance between antenna and its image (twice the height of the center of the antenna).



Radiation patterns of antennas and their images reflected by the ground. At left the polarization is vertical and there is always a maximum for $\theta=0$. If the polarization is horizontal as at right, there is always a zero for $\theta=0$.

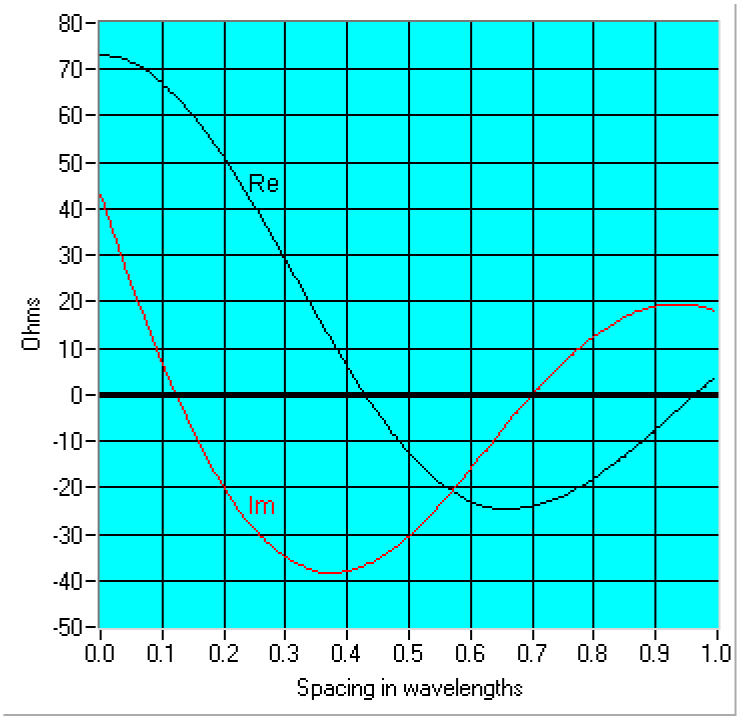
For emitting and receiving antenna situated near the ground (in a building or on a mast) far from each other, distances traveled by direct and reflected rays are nearly the same. There is no induced phase shift. If the emission is polarized vertically the two fields (direct and reflected) add and there is maximum of received signal. If the emission is polarized horizontally the two signals subtracts and the received signal is minimum. This is depicted in the image at right. In the case of vertical polarization, there is always a maximum at earth level (left pattern). For horizontal polarization, there is always a minimum at earth level. Note that in these drawings the ground is considered as a perfect mirror, even for low angles of incidence. In these drawings the distance between the antenna and its image is just a few wavelengths. For greater distances, the number of lobes increases.

Note that the situation is different–and more complex–if reflections in the ionosphere occur. This happens over very long distances (thousands of kilometers). There is not a direct ray but several reflected rays that add with different phase shifts.

This is the reason why almost all public address radio emissions have vertical polarization. As public users are near ground, horizontal polarized emissions would be poorly received. Observe household and automobile radio receivers. They all have vertical antennas or horizontal ferrite antennas for vertical polarized emissions. In cases where the receiving antenna must work in any position, as in mobile phones, the emitter and receivers in base stations use circular polarized electromagnetic waves.

Classical (analog) television emissions are an exception. They are almost always horizontally polarized, because the presence of buildings makes it unlikely that a good emitter antenna image will appear. However, these same buildings reflect the electromagnetic waves and can create ghost images. Using horizontal polarization, reflections are attenuated because of the low reflection of electromagnetic waves whose magnetic field is parallel to the dielectric surface near the Brewster's angle. Vertically polarized analog television has been used in some rural areas. In digital terrestrial television reflections are less obtrusive, due to the inherent robustness of digital signalling and built-in error correction.

Mutual impedance and interaction between antennas



Mutual impedance between parallel $\frac{\lambda}{2}$dipoles not staggered. Curves **Re** and **Im** are the resistive and reactive parts of the impedance.

Current circulating in any antenna induces currents in all others. One can postulate a **mutual impedance** Z_{12}between two antennas that has the same significance as the $j\omega M$in ordinary coupled inductors. The mutual impedance Z_{12}between two antennas is defined as:

$$Z_{12} = \frac{v_2}{i_1}$$

where $i_1$is the current flowing in antenna 1 and $v_2$is the voltage that would have to be applied to antenna 2–with antenna 1 removed–to produce the current in the antenna 2 that was produced by antenna 1.

From this definition, the currents and voltages applied in a set of coupled antennas are:

$$
\begin{array}{rcccccccc}
v_1 & = & i_1 Z_{11} & + & i_2 Z_{12} & + & \cdots & + & i_n Z_{1n} \\
v_2 & = & i_1 Z_{21} & + & i_2 Z_{22} & + & \cdots & + & i_n Z_{2n} \\
\vdots & & \vdots & & \vdots & & & & \vdots \\
v_n & = & i_1 Z_{n1} & + & i_2 Z_{n2} & + & \cdots & + & i_n Z_{nn}
\end{array}
$$

where:

- v_i is the voltage applied to the antenna *i*
- Z_{ii} is the impedance of antenna *i*
- Z_{ij} is the mutual impedance between antennas *i* and *j*

Note that, as is the case for mutual inductances,

$$Z_{ij} = Z_{ji}$$

This is a consequence of Lorentz reciprocity. If some of the elements are not fed (there is a short circuit instead a feeder cable), as is the case in television antennas (Yagi-Uda antennas), the corresponding v_i are zero. Those elements are called parasitic elements. Parasitic elements are unpowered elements that either reflect or absorb and reradiate RF energy.

In some geometrical settings, the mutual impedance between antennas can be zero. This is the case for crossed dipoles used in circular polarization antennas.

Antenna

Antennas and antenna arrays

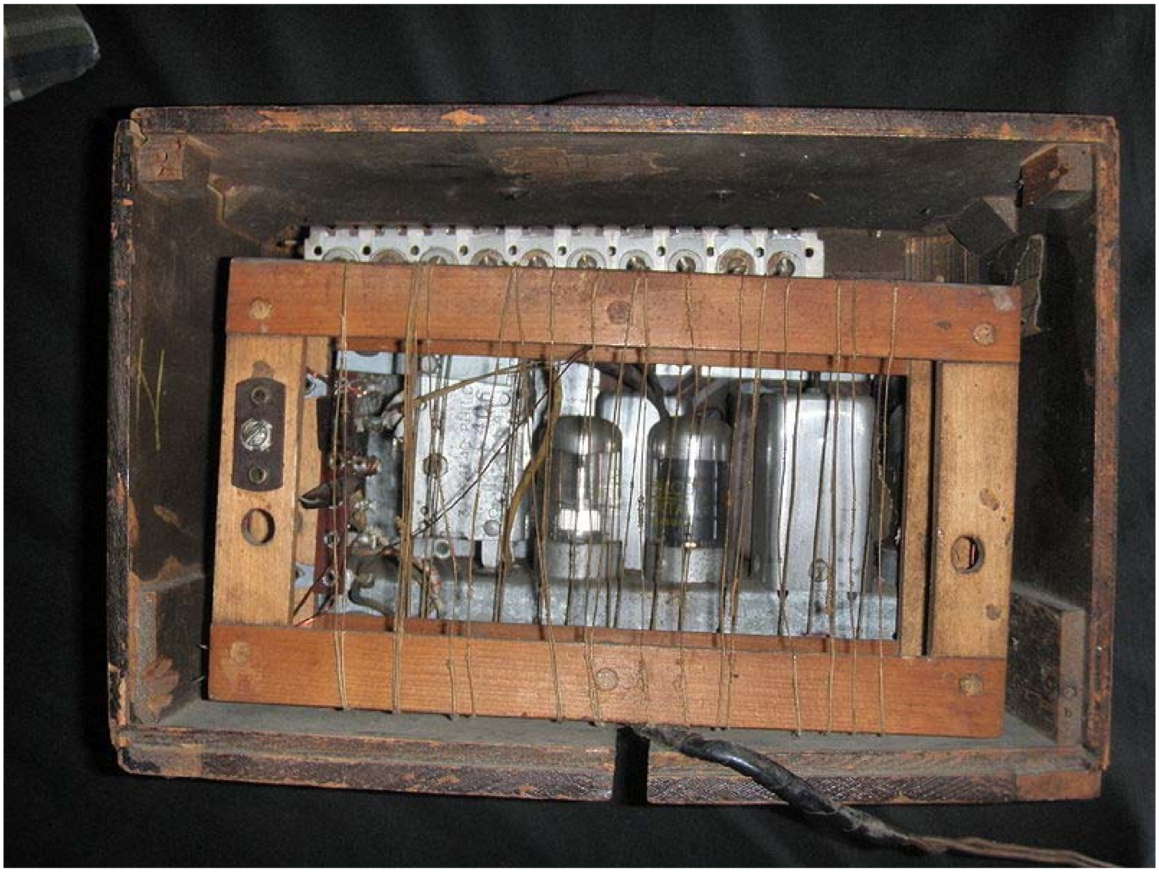
A Yagi-Uda beam antenna.

Rooftop TV antenna. It is actually three Yagi antennas. The longest elements are for the low band, while the medium and short elements are for the high and UHF band.

Examples of US 136-174 MHz base station antennas.

Low cost LF time signal receiver, antenna (left) and receiver (right).

"Rabbit ears" antenna



AM loop antenna

Antennas and supporting structures

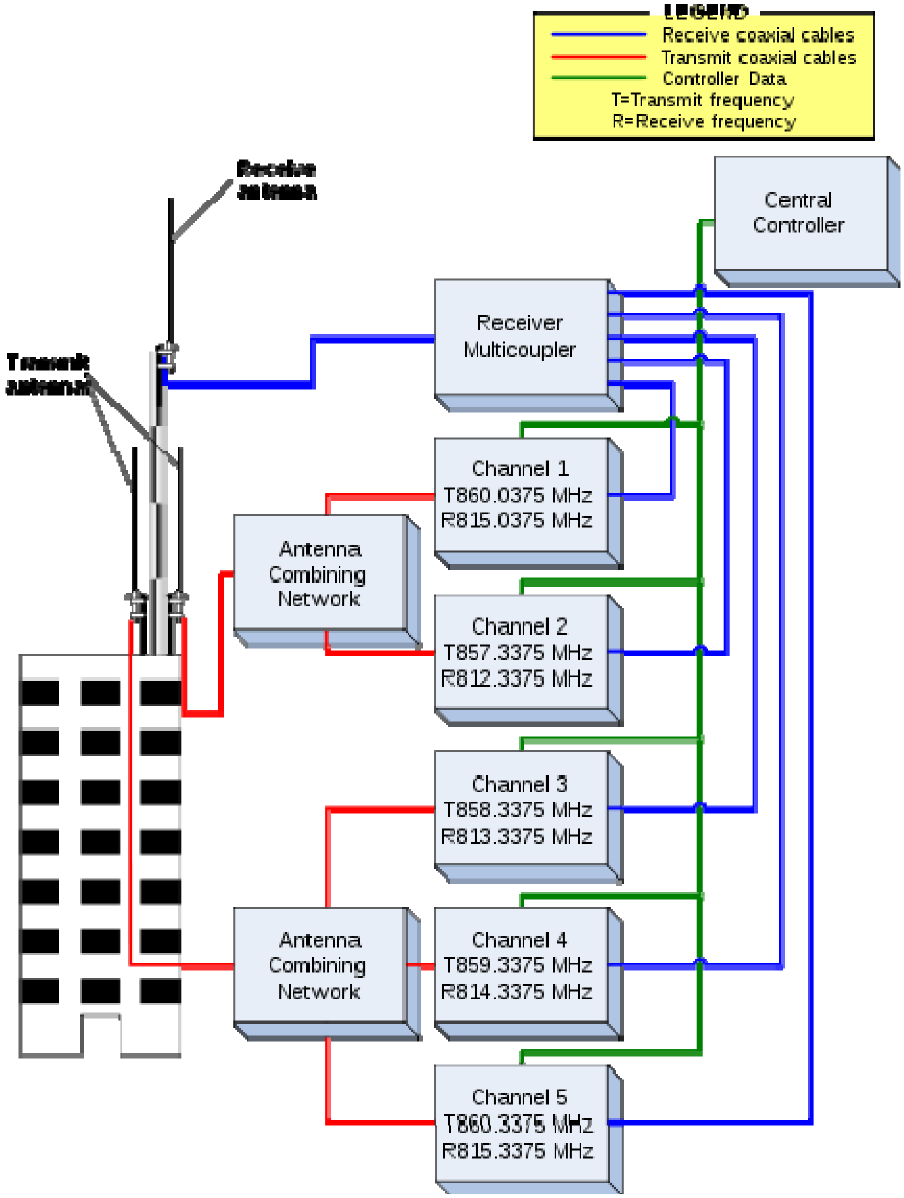
A building rooftop supporting numerous dish and sectored mobile telecommunications antennas (Doncaster, Victoria, Australia).

A water tower in Palmerston, Northern Territory with radio broadcasting and communications antennas.

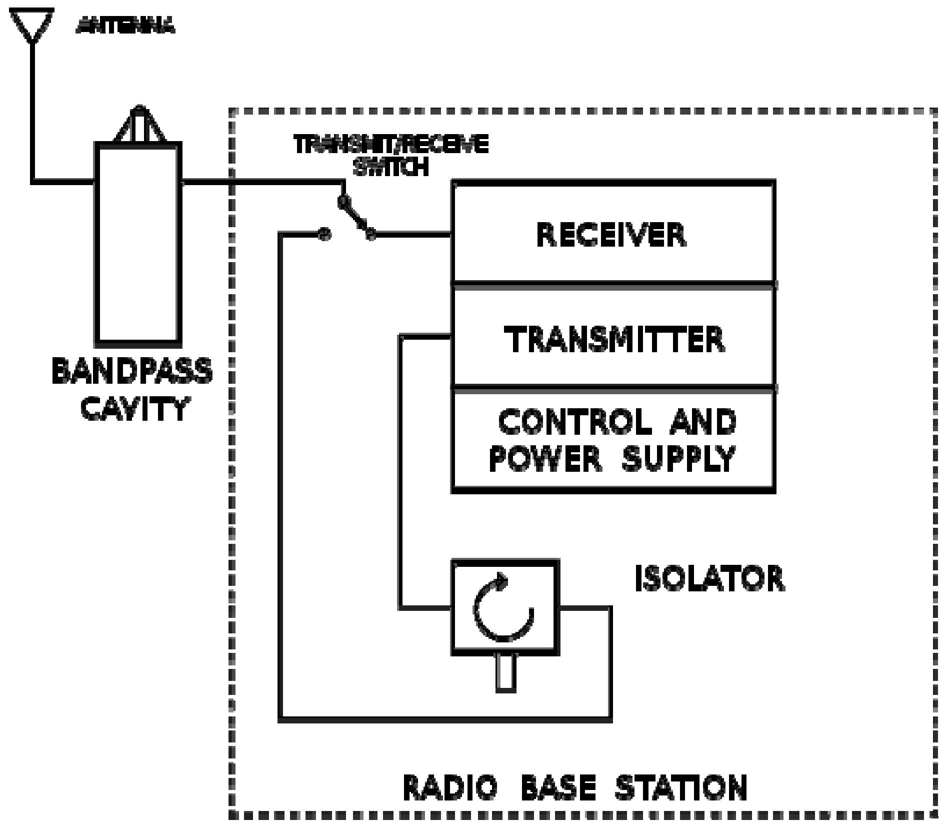
A three-sector telephone site in Mexico City.

Telephone site concealed as a palm tree.

Diagrams as part of a system



Antennas may be connected through a multiplexing arrangement in some applications like this trunked two-way radio example.



Antenna network for an emergency medical services base station.

Chapter 6

Television Antenna

A Winegard HD-7084P 68 element VHF/UHF aerial antenna

A **television antenna**, or **TV aerial**, is an antenna specifically designed for the reception of over the air broadcast television signals, which are transmitted at frequencies from about 41 to 250 MHz in the VHF band, and 470 to 960 MHz in the UHF band in different countries. To cover this range antennas generally consist of multiple conductors of different lengths which correspond to the wavelength range the antenna is intended to receive. The length of the elements of a TV antenna are usually half the wavelength of the signal they are intended to receive. The wavelength of a signal equals the speed of light (c) divided by the frequency. The design of a television broadcast receiving antenna is the same for the older analog transmissions and the digital television transmissions which are replacing them Sellers often claim to supply a special "digital" or "high definition" antenna advised as a replacement for an existing analog antenna, even if satisfactory: this is misinformation to generate sales of unneeded equipment.

Simple/indoor

Very common "rabbit ears" set-top antenna of older model

Simple half-wave dipole VHF antennas or UHF loop antennas that are made to be placed indoors are often used for television (and VHF radio); these are often called "rabbit ears" or "bunny aerials". because of their appearance. The length of the telescopic "ears" can be adjusted by the user, and should be about one half of the wavelength of the signal for the desired channel. These are not as efficient as an aerial rooftop antenna since they are less directional and not always adjusted to the proper length for the desired channel. Dipole antennas are bi-directional, that is, they receive evenly forward and backwards, and also cover a broader band than antennas with more elements. This makes them less efficient than antennas designed to maximise the signal from a narrower angle in one direction.

Coupled with the poor placing, indoors and closer to the ground, they are much worse than multi-element rooftop antennas at receiving signals which are not very strong, although often adequate for nearby transmitters, in which case they may be adequate and cheap. These simple antennas are called set-top antennas because they are often placed on top of the television set or receiver.

The actual length of the ears is optimally about 91% of half the wavelength of the desired channel in free space. Quarter-wave television antennas are also used. These use a single element, and use the earth as a ground plane; therefore, no ground is required in the feed line.*a*

Outdoor

An aerial or rooftop antenna generally consists of multiple conductive elements that are arranged such that it is a directional antenna. The length of the elements is about one half of the signal wavelength. Therefore, the length of each element corresponds to a certain frequency.

In a combined VHF/UHF antenna the longer elements (for picking up VHF frequencies) are at the "back" of the antenna, relative to the device's directionality, and the much shorter UHF elements are in the "front", and the antenna works best when "pointing" to the source of the signal to be received. The smallest elements in this design, located in the "front", are UHF director elements, which are usually identical and give the antenna its directionality, as well as improving gain. The longest elements, located in the "back" of the antenna form a VHF phased array. Other long elements may be UHF reflectors Another common aerial antenna element is the corner reflector, a type of UHF reflector which increases gain and directionality for UHF frequencies.

An antenna can have a smaller or larger number of directors; the more directors it has (requiring a longer boom), and the more accurate their tuning, the higher its gain will be. For the commonly used Yagi antenna this is not a linear relationship. Antenna gain is the ratio of the signal received from the preferred direction to the signal from an ideal omnidirectional antenna. Gain is inversely proportional to the antenna's acceptance angle. The thickness of the rods on a Yagi antenna and its bandwidth are inversely proportional; thicker rods provide a wider band. Thinner rods are preferable to provide a narrower band, hence higher gain in the preferred direction; however, they must be thick enough to withstand wind.

Two or more directional rooftop antennas can be set up and connected to one receiver. Antennas designed for rooftop use are sometimes located in attics.

Sometimes television transmitters are organised such that all receivers in a given location need receive transmissions in only a relatively narrow band of the full UHF television spectrum and from the same direction, so that a single antenna provides reception from all stations.

Types of outdoor antenna

A UHF television antenna

An antenna pole setup in a chimney, reaching 35 feet (10.7 meters) off the ground

Small multi-directional: The smallest of all outdoor television antennas. They are designed to receive equal amounts of signal from all directions. These generally receive signals up to a maximum of thirty miles away from the transmitting station, greatly depending on the type. But, things such as large buildings or thick woods may greatly affect signal. They come in many different styles, ranging from small dishes to small metal bars, some can even mount on existing satellite dishes.

Medium multi-directional: A step up from the small multi-directional, these also receive signals from all directions. These usually require an amplifier in situations when long cable lengths are between the television receiver and the antenna. Styles are generally similar to small multi-directionals, but slightly larger.

Large multi-directional: These are the largest of all multi-directional outdoor television antennas. Styles include large "nets" or dishes, but can also greatly vary. Depending on the type, signal reception usually ranges from 30 to up to 70 miles.

Small directional: The smallest of all directional antennas, these antennas are multi-element antennas, typically placed on rooftops. This style of antenna receives signals generally equal to that of large multi-directionals. One advantage that small directionals hold, however, is that they can significantly reduce "ghosting" effects of television picture.

Medium directional: These antennas are the ones most often seen on suburban rooftops. Usually consisting of many elements, and slightly larger than the small directionals, these antennas are ideal for receiving television signals in suburban areas. Signal usually ranges from 30 to 60 miles away from the broadcasting station.

Large directional: The largest of all common outdoor television antennas, these antennas are designed to receive the weakest available stations in an area. Larger than the medium directional, this type of antenna consists of many elements and is usually used in rural areas, where reception is difficult. When used in conjunction with an amplifier, these antennas can usually pick up stations from 60 up to and over 100 miles, depending on the type.

The use of outdoor antennas with an amplifier can improve signal on low signal strength channels. If the signal quality is low repositioning the antenna onto a high mast will improve signal

Installation

A short antenna pole next to a house; this setup would only work well for receiving signals on that side of the house as they would not go through stone, especially.

Multiple Yagi TV aerials in Israel

Antennas are commonly placed on rooftops, and sometimes in attics. Placing an antenna indoors significantly attenuates the signal available to it. Directional antennas must be pointed at the transmitter they are receiving; in most cases great accuracy is not needed. In a given region it is sometimes arranged that all television transmitters are located in roughly the same direction and use frequencies space closely enough that a single antenna suffices for all. A single transmitter location may transmit signals for several channels.

Analog television signals are susceptible to ghosting in the image, multiple closely-spaced images giving the impression of blurred and repeated images of edges in the picture. This was due to the signal being reflected from nearby objects (buildings, tree, mountains); several copies of the signal, of different strengths and subject to different delays, are picked up. This was different for different transmissions. Careful positioning of the antenna could produce a compromise position which minimized the ghosts on different channels. Ghosting is also possible if multiple antennas connected to the same receiver pick up the same station, especially if the lengths of the cables connecting them to the splitter/merger were different lengths or the antennas were too close together. Analog television is being replaced by digital, which is not subject to ghosting.

Rooftop and other outdoor antennas

Aerials are attached to roofs in various ways, usually on a pole to elevate it above the roof. This is generally sufficient in most areas. In some places; however, such as a deep valley or near taller structures, the antenna may need to be placed significantly higher, using a lattice tower or mast.

The higher the antenna is placed, the better it will perform. An antenna of higher gain will be able to receive weaker signals from its preferred direction. Intervening buildings, topographical features (mountains), and dense forest will weaken the signal; in many cases the signal will be reflected such that a usable signal is still available. There are physical dangers inherent to high or complex antennas, such as the structure falling or being destroyed by the weather. There are also varying local ordinances which restrict and limit such things as the height of a structure without obtaining permits. For example, in the USA, the Telecommunications Act of 1996 allows any homeowner to install "An antenna that is designed to receive local television broadcast signals", but that "masts higher than 12 feet above the roof-line may be subject to local permitting requirements."

Indoor antennas

As discussed previously, antennas may be placed indoors where signals are strong enough to overcome antenna shortcomings. The antenna is simply plugged into the television receiver and placed conveniently, often on the top of the receiver ("set-top"). Sometimes the position needs to be experimented with to get the best picture. Indoor antennas can also benefit from RF amplification, commonly called a TV booster. Indoor antennas will never be an option in weak signal areas.

Attic installation

Sometimes it is desired not to put an antenna on the roof; in these cases, antennas designed for outdoor use are often mounted in the attic or loft, although antennas designed for attic use are also available. Putting an antenna indoors significantly decreases its performance due to lower elevation above ground level and intervening walls; however, in strong signal areas reception may be satisfactory. One layer of asphalt shingles, roof felt, and a plywood roof deck are considered to attenuate the signal to about half.

Multiple antennas, rotators

Two aerials setup on a roof. Spaced horizontally and vertically

It is sometimes desired to receive signals from transmitters which are not in the same direction. This can be achieved, for one station at a time, by using a rotator operated by an electric motor to turn the antenna as desired. Alternatively, two or more antennas, each pointing at a desired transmitter and coupled by appropriate circuitry, can be used. To prevent the antennas interfering with each other, the vertical spacing between the booms must be at least half the wavelength of the lowest frequency to be received (Distance=$\lambda/2$). The wavelength of 54 MHz (Channel 2) is 5.5 meters ($\lambda \times f = c$) so the antennas must be a minimum of 2.25 meters, or ~89 inches apart. It is also important that the cables connecting the antennas to the signal splitter/merger be exactly the same length, to prevent phasing issues,which cause ghosting with analog reception. That is, the antennas might both pick up the same station; the signal from the one with the shorter cable will reach the receiver slightly sooner, supplying the receiver with two pictures slightly offset. There may be phasing issues even with the same length of down-lead cable. Bandpass filters or "signal traps" may help to reduce this problem.

For side-by-side placement of multiple antennas, as is common in a space of limited height such as an attic, they should be separated by at least one full wavelength of the lowest frequency to be received at their closest point.

Often when multiple antennas are used, one is for a range of co-located stations and the other is for a single transmitter in a different direction.

Safety

- TV antennas are large conductors of electricity and attract lightning, acting as a lightning rod. The use of a lightning arrestor is usual to protect against this. A large grounding rod connected to both the antenna and the mast or pole is required.

- Properly installed masts, especially tall ones, are guyed with galvanized cable; no insulators are needed. They are designed to withstand worst-case weather conditions in the area, and positioned so that they do not interfere with power lines if they fall.

- There is inherent danger in being on the rooftop of a house, required for installing or adjusting a television antenna.

Chapter 7

Radio Masts and Towers

Masts of the Rugby VLF transmitter in England

A dismantled radio mast in sections

Radio masts and towers are, typically, tall structures designed to support antennas (also known as aerials) for telecommunications and broadcasting, including television. They are among the tallest man-made structures. Similar structures include electricity pylons and towers for wind turbines.

Masts are sometimes named after the broadcasting organisations that use them, or after a nearby city or town.

The Warsaw Radio Mast was the world's tallest supported structure on land, but it collapsed in 1991, leaving the KVLY/KTHI-TV mast as the tallest.

In the case of a mast radiator or radiating tower, the whole mast or tower is itself the transmitting antenna.

Mast or tower?

A radio mast base showing how virtually all support is provided by the guy-wires

The terms "mast" and "tower" are often used interchangeably. However, in structural engineering terms, a tower is a self-supporting or cantilevered structure, while a mast is held up by stays or guys. By contrast, in broadcast engineering, a tower is an antenna structure attached to the ground, whereas a mast is a vertical antenna support mounted on some other structure (which itself may be a tower, a building, or a vehicle). Masts (to use the civil engineering terminology) tend to be cheaper to build but require an extended area surrounding them to accommodate the guy wires. Towers are more commonly used in cities where land is in short supply.

There are a few borderline designs which are partly free-standing and partly guyed. For example:

- The Gerbrandy tower consists of a self-supporting tower with a guyed mast on top.
- The few remaining Blaw-Knox towers do the opposite: they have a guyed lower section surmounted by a freestanding part.
- Zendstation Smilde a tall tower with a guyed mast on top (guys go to ground)

- Torre de Collserola a guyed tower, with a guyed mast on top. (Tower portion is not free-standing.)

Materials

Steel lattice

Steel lattice tower

The steel lattice is the most widespread form of construction. It provides great strength, low weight and wind resistance, and economy in the use of materials. Lattices of triangular cross-section are most common, and square lattices are also widely used.

When built as a stayed mast, usually the whole mast is parallel-sided. One exception is the Blaw-Knox type.

When built as a tower, the structure may be parallel-sided or taper over part or all of its height. When constructed of several sections which taper exponentially with height, in the manner of the Eiffel Tower, the tower is said to be an Eiffelized one. The Crystal Palace tower in London is an example.

Tubular steel

Guyed masts are sometimes also constructed out of steel tubes. This construction type has the advantage that cables and other equipment is protected from weather influence and that the structure may look nicer. They are mainly used for FM-/TV-broadcasting, but sometimes also as mast radiator, wherefore the big mast of Mühlacker transmitting station is a good example. A disadvantage of this mast type is that it is much more affected by winds than masts with open bodies. In fact several tubular guyed masts collapsed: in the UK, these were masts the Emley Moor and Waltham TV stations, which collapsed in the 1960s, in Germany that of Bielstein transmitter, which collapsed in 1985. Not in all countries such masts were built: while in Germany, France, UK, Czech, Slovakia and the former Soviet Union multiple tubular guyed masts were built, there are nearly none in Poland and North America.

At several cities in Russia and Ukraine, between 1960 and 1965 several tubular guyed masts with crossbars running from the mast structure to the guys were built. All these masts are exclusively used for FM and TV transmission and are except of the mast in Vinnytsia between 150 and 200 metres tall. The crossbars of these masts are equipped with a gangway and are equipped with smaller antennas. Their main purpose is oscillation damping.

First modern TV Tower in Stuttgart

Reinforced concrete

Reinforced concrete towers are relatively expensive to build but provide a high degree of mechanical rigidity in strong winds. This can be important when antennas with narrow beamwidths are used, such as those used for microwave point-to-point links, and when the structure is to be occupied by people.

In the 1950s, AT&T built numerous concrete towers, more resembling silos than towers, for its first transcontinental microwave route. Many are still in use today.

In Germany and the Netherlands most towers constructed for point-to-point microwave links are built of reinforced concrete, while in the UK most are lattice towers.

Concrete towers can form prestigious landmarks, such as the CN Tower in Toronto. As well as accommodating technical staff, these buildings may have public areas such as observation decks or restaurants.

The Stuttgart TV tower was the first tower in the world to be built in reinforced concrete. It was designed in 1956 by the local civil engineer Fritz Leonhardt.

Tokyo Tower

Fibreglass

Fibreglass poles are occasionally used for low-power non-directional beacons or medium-wave broadcast transmitters.

Wood

There are fewer wooden towers now than in the past. Many were built in the UK during World War II because of a shortage of steel. In Germany before World War II wooden towers were used at nearly all medium-wave transmission sites, but all of these towers have since been demolished, except for the Gliwice Radio Tower.

Ferryside Relay is an example of a TV relay transmitter using a wooden pole.

Other types of antenna supports and structures

Poles

Shorter masts may consist of a self-supporting or guyed wooden pole, similar to a telegraph pole. Sometimes self-supporting tubular galvanized steel poles are used: these may be termed monopoles.

Buildings

In some cases, it is possible to install transmitting antennas on the roofs of tall buildings. In North America, for instance, there are transmitting antennas on the Empire State Building, the Willis Tower ,and formerly on the World Trade Center towers. When the buildings collapsed, several local TV and radio stations were knocked off the air until backup transmitters could be put into service. Such facilities also exist in Europe, particularly for portable radio services and low-power FM radio stations.

Disguised cell-sites

Completed in December 2009 at Epiphany Lutheran Church in Lake Worth, Florida, this 100' tall cross conceals equipment for T-Mobile.

Many people view bare cellphone towers as ugly and an intrusion into their neighbourhoods. Even though people increasingly depend upon cellular communications, they are opposed to the bare towers spoiling otherwise scenic views. Many companies offer to 'hide' cellphone towers in, or as, trees, church towers, flag poles, water tanks and other features. There are many providers that offer these services as part of the normal tower installation and maintenance service. These are generally called "stealth towers" or "stealth installations".

The level of detail and realism achieved by disguised cellphone towers is remarkably high; for example, such towers disguised as trees are nearly indistinguishable from the real thing, even for local wildlife (who additionally benefit from the artificial flora). Such towers can be placed unobtrusively in national parks and other such protected places, such as towers disguised as cacti in Coronado National Forest.

Even when disguised, however, such towers can create controversy; a tower doubling as a flagpole attracted controversy in 2004 in relation to the U.S. Presidential campaign of that year, and highlighted the sentiment that such disguises serve more to allow the installation of such towers in subterfuge away from public scrutiny rather than to serve towards the beautification of the landscape.

Mast radiators

A mast radiator is a radio tower or mast in which the whole structure works as an antenna. It is used frequently as a transmitting antenna for long or medium wave broadcasting.

Structurally, the only difference is that a mast radiator may be supported on an insulator at its base. In the case of a tower, there will be one insulator supporting each leg.

Telescopic, pump-up and tiltover towers

A special form of the radio tower is the *telescopic mast*. These can be erected very quickly. Telescopic masts are used predominantly in setting up temporary radio links for reporting on major news events, and for temporary communications in emergencies. They are also used in tactical military networks. They can save money by needing to withstand high winds only when raised, and as such are widely used in amateur radio.

Telescopic masts consist of two or more concentric sections and come in two principal types:

- Pump-up masts are often used on vehicles, and are raised to their full height pneumatically or hydraulically. They are usually only strong enough to support fairly small antennas.
- Telescopic lattice masts are raised by means of a winch, which may be powered by hand or an electric motor. These tend to cater for greater heights and loads than the pump-up type. When retracted, the whole assembly can sometimes be lowered to a horizontal position by means of a second tiltover winch. This enables antennas to be fitted and adjusted at ground level before winching the mast up.

Balloons and kites

A tethered balloon or a kite can serve as a temporary support. It can carry an antenna or a wire (for VLF, LW or MW) up to an appropriate height. Such an arrangement is used occasionally by military agencies or radio amateurs. The American broadcasters TV Martí broadcast a television program to Cuba by means of such a balloon.

Other special structures

For two VLF transmitters wire antennas spun across deep valleys are used. The wires are supported by small masts or towers or rock anchors. The same technique was also used for the Criggion VLF transmitter.

For ELF transmitters ground dipole antennas are used. Such structures require no tall masts. They consist of two electrodes buried deep in the ground at least a few dozen kilometres apart. From the transmitter building to the electrodes, overhead feeder lines run. These lines look like power lines of the 10 kV level, and are installed on similar pylons.

Design features

Economic and aesthetic considerations

A radio amateur's do it yourself steel-lattice tower

Felsenegg-Girstel TV-tower

Uetliberg TV-tower

Communications tower, camouflaged as a slim tree

- The cost of a mast or tower is roughly proportional to the square of its height.
- A guyed mast is cheaper to build than a self-supporting tower of equal height.
- A guyed mast needs additional land to accommodate the guys, and is thus best suited to rural locations where land is relatively cheap. An unguyed tower will fit into a much smaller plot.
- A steel lattice tower is cheaper to build than a concrete tower of equal height.
- Two small towers may be less intrusive, visually, than one big one, especially if they look identical.
- Towers look less ugly if they and the antennas mounted on them appear symmetrical.
- Concrete towers can be built with aesthetic design - and they are, especially in Continental Europe. They are sometimes built in prominent places and include observation decks or restaurants.

Masts for HF/shortwave antennas

For transmissions in the shortwave range, there is little to be gained by raising the antenna more than a few wavelengths above ground level. Shortwave transmitters rarely use masts taller than about 100 metres.

Access for riggers

Because masts, towers and the antennas mounted on them require maintenance, access to the whole of the structure is necessary. Small structures are typically accessed with a ladder. Larger structures, which tend to require more frequent maintenance, may have stairs and sometimes a lift, also called a service elevator.

Aircraft warning features

Tall structures in excess of certain legislated heights are often equipped with aircraft warning lamps, usually red, to warn pilots of the structure's existence. In the past, ruggedized and under-run filament lamps were used to maximize the bulb life. Alternatively, neon lamps were used. Nowadays such lamps tend to use LED arrays.

Height requirements vary across states and countries, and may include additional rules such as requiring a white flashing strobe in the daytime and pulsating red fixtures at night. Structures over a certain height may also be required to be painted with contrasting color schemes such as white and orange or white and red to make them more visible against the sky.

Light pollution and nuisance lighting

In some countries where light pollution is a concern, tower heights may be restricted so as to reduce or eliminate the need for aircraft warning lights. For example in the United States the 1996 Telecommunications Act allows local jurisdictions to set maximum heights for towers, such as limiting tower height to below 200 feet and therefore not requiring aircraft illumination under U.S. Federal Communications Commission (FCC) rules. The limit is more commonly set to 190 or 180 feet to allow for masts extending above the tower.

Wind-induced oscillations

One problem with radio masts is the danger of wind-induced oscillations. This is particularly a concern with steel tube construction. One can reduce this by building cylindrical shock-mounts into the construction. One finds such shock-mounts, which look like cylinders thicker than the mast, for example, at the radio masts of DHO38 in Saterland. There are also constructions, which consist of a free-standing tower (usually from reinforced concrete), onto which a guyed radio mast is installed. The best known such construction is the Gerbrandy Tower in Lopik (the Netherlands). Further towers of this building method can be found near Smilde (the Netherlands) and Fernsehturm, Waldenburg, Baden-Württemberg, Germany).

Hazard to birds

Radio, television and cell towers have been documented to pose a hazard to birds. Reports have been issued documenting known bird fatalities and calling for research to find ways to minimize the hazard that communications towers can pose to birds.

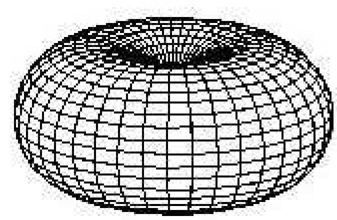
Law

Since June 2010, Telecom operators in the USA can erect new telecom masts or towers as the government has lifted the moratorium, which was earlier placed on the issuance of permits for the construction of telecommunication towers.

Chapter 8

Omnidirectional Antenna & Directional Antenna

Omnidirectional Antenna



Omnidirectional radiation pattern of a vertical dipole antenna. In this graph the antenna is at the center of the "donut". Radial distance from the center represents the power radiated in that direction. The power radiated is maximum in horizontal directions, dropping to zero directly above and below the antenna.

An **omnidirectional antenna** is an antenna which radiates power uniformly in all directions in one plane, with the radiated power decreasing with elevation angle above or below the plane, dropping to zero on the antenna's axis. This radiation pattern is often described as "donut shaped". Note that this is different from an isotropic antenna, in which the gain is uniform in *all* directions ("spherical"). Omnidirectional antennas oriented vertically are widely used for nondirectional antennas on the surface of the Earth because they radiate equally in all horizontal directions, while the power radiated drops off with elevation angle so little radio energy is aimed into the sky or down toward the earth and wasted. Omnidirectional antennas are widely used for radio broadcasting antennas, and in mobile devices that use radio such as cell phones, FM radios, walkie-talkies, Wifi, cordless phones, GPS as well as for base stations that communicate with mobile radios, such as police and taxi dispatchers and aircraft communications.

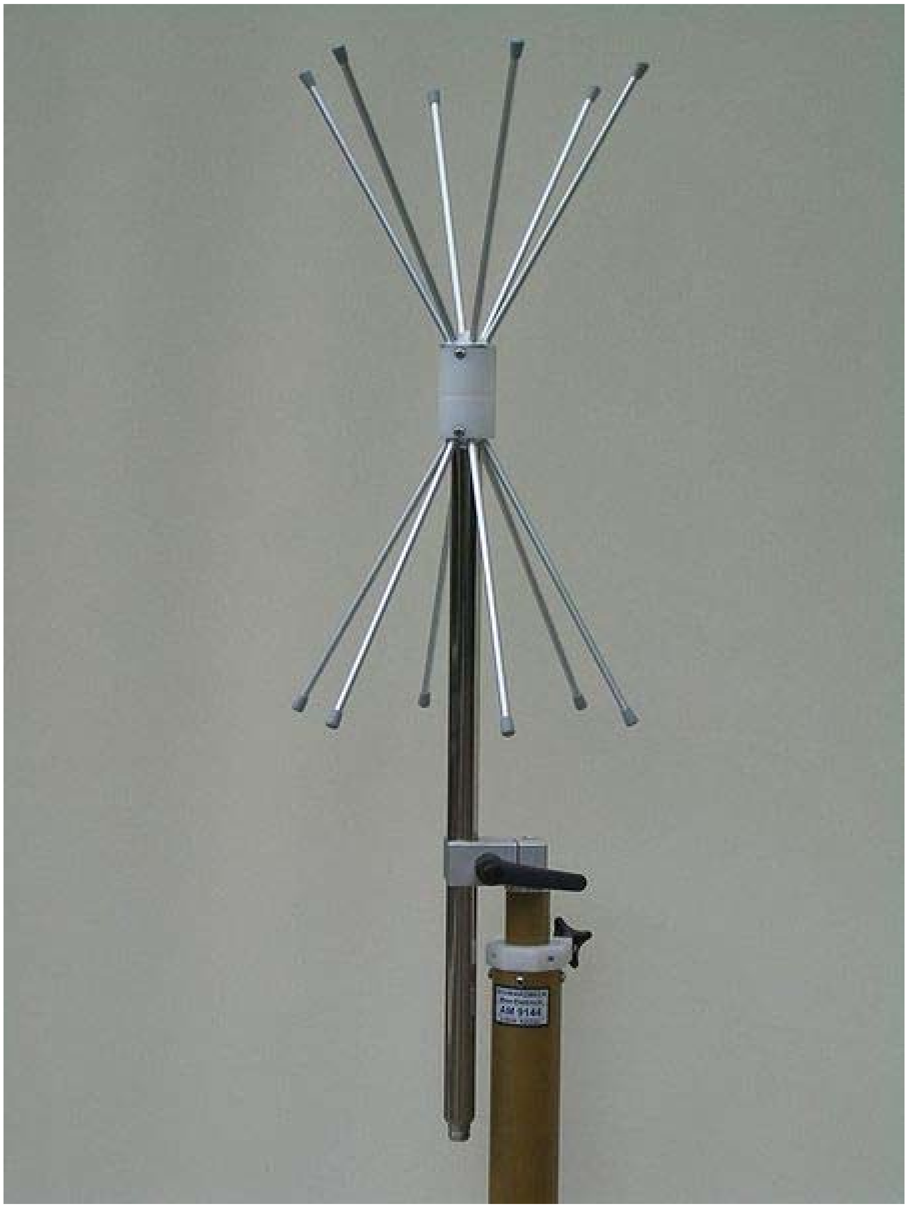
Types

Common types of low gain omnidirectional antennas are the whip antenna, "Rubber Ducky", ground plane antenna, vertically oriented dipole antenna, discone antenna, mast radiator and the horizontal loop antenna (or halo antenna) (Sometimes known colloquially as a 'circular aerial' because of the shape).

Higher gain omnidirectional antennas can also be built. "Higher gain" in this case means that the antenna radiates less energy at higher and lower elevation angles and more in the horizontal directions. High gain omnidirectional antennas are generally realized using collinear dipole arrays. These arrays consist of half-wavelength dipoles with a phase shifting method between each element that ensures the current in each dipole is in phase. The Coaxial Colinear or COCO antenna uses transposed coaxial sections to produce in-phase half-wavelength radiatiors. A Franklin Array uses short U-shaped half-wavelength sections whose radiation cancels in the far-field to bring each half-wavelength dipole section into equal phase.

Types of higher gain omnidirectional antennas are the Coaxial Colinear (COCO) antenna and Omnidirectional Microstrip Antenna (OMA).

Some planar antennas (constructed from printed circuit board) are omnidirectional antennas.



Vertical polarized VHF- UHF biconical antenna 170 – 1100 MHz with omni directional H-plane pattern.

Analysis

Omnidirectional radiation patterns are produced by the simplest practical antennas, monopole and dipole antennas, consisting of one or two straight rod conductors on a common axis. Antenna gain (G) is defined as antenna efficiency (e) multiplied by antenna directivity (D) which is expressed mathematically as: $G = eD$. A useful relationship between omnidirectional radiation pattern directivity (D) in decibels and half-power beamwidth (HPBW) based on the assumption of a $\sin b\theta \,/\, b\theta$ pattern shape is:

$$D = 10\log_{10}\left(\frac{101.5}{HPBW - 0.00272(HPBW)^2}\right)\ dB$$

Directional Antenna

Log-periodic dipole array

A **directional antenna** or **beam antenna** is an antenna which radiates greater power in one or more directions allowing for increased performance on transmit and receive and reduced interference from unwanted sources. Directional antennas like yagi antennas provide increased performance over dipole antennas when a greater concentration of radiation in a certain direction is desired.

All practical antennas are at least somewhat directional, although usually only the direction in the plane parallel to the earth is considered, and practical antennas can easily be omnidirectional in one plane.

The most common types are the yagi antenna, the log-periodic antenna, and the corner reflector, which are frequently combined and commercially sold as residential TV antennas. Cellular repeaters often make use of external directional antennas to give a far greater signal than can be obtained on a standard cell phone. Satellite Television receivers usually use parabolic antennas.

For long and medium wavelength frequencies, tower arrays are used in most cases as directional antennas.