

Antenna (radio)

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In radio and electronics, an **antenna** (plural **antennae** or **antennas**), or **aerial**, is an electrical device which converts electric power into radio waves, and vice versa.^[1] It is usually used with a radio transmitter or radio receiver. In transmission, a radio transmitter supplies an electric current oscillating at radio frequency (i.e. a high frequency alternating current (AC)) to the antenna's terminals, and the antenna radiates the energy from the current as electromagnetic waves (radio waves). In reception, an antenna intercepts some of the power of an electromagnetic wave in order to produce a tiny voltage at its terminals, that is applied to a receiver to be amplified.

Antennas are essential components of all equipment that uses radio. They are used in systems such as radio broadcasting, broadcast television, two-way radio, communications receivers, radar, cell phones, and satellite communications, as well as other devices such as garage door openers, wireless microphones, Bluetooth-enabled devices, wireless computer networks, baby monitors, and RFID tags on merchandise.

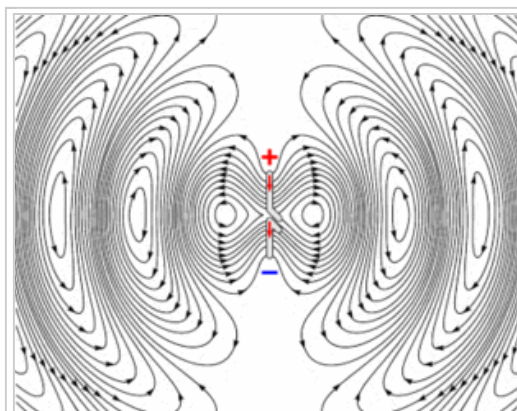
Typically an antenna consists of an arrangement of metallic conductors (elements), electrically connected (often through a transmission line) to the receiver or transmitter. An oscillating current of electrons forced through the antenna by a transmitter will create an oscillating magnetic field around the antenna elements, while the charge of the electrons also creates an oscillating electric field along the elements. These time-varying fields radiate away from the antenna into space as a moving transverse electromagnetic field wave. Conversely, during reception, the oscillating electric and magnetic fields of an incoming radio wave exert force on the electrons in the antenna elements, causing them to move back and forth, creating oscillating currents in the antenna.

Antennas can be designed to transmit and receive radio waves in all horizontal directions equally (omnidirectional antennas), or preferentially in a particular direction (directional or high gain antennas). In the latter case, an antenna may also include additional elements or surfaces with no electrical connection to the transmitter or receiver, such as parasitic elements, parabolic reflectors or horns, which serve to direct the radio waves into a beam or other desired radiation pattern.

The first antennas were built in 1888 by German physicist Heinrich Hertz 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 in *Annalen der Physik und Chemie* (vol. 36, 1889).

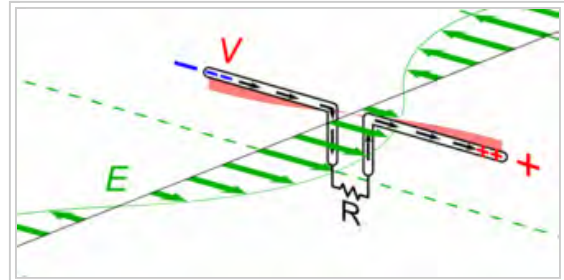
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Animation of a half-wave dipole antenna transmitting radio waves, showing the electric field lines. The antenna in the center is two vertical metal rods, with an alternating current applied at its center from a radio transmitter (*not shown*). The voltage charges the two sides of the antenna alternately positive (+) and negative (-). Loops of electric field (*black lines*) leave the antenna and travel away at the speed of light; these are the radio waves.

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Animated diagram of a half-wave dipole antenna receiving energy from a radio wave. The antenna consists of two metal rods connected to a receiver *R*. The electric field (*E*, green arrows) of the incoming wave pushes the electrons in the rods back and forth, charging the ends alternately positive (+) and negative (-). Since the length of the antenna is one half the wavelength of the wave, the oscillating field induces standing waves of voltage (*V*, represented by red band) and current in the rods. The oscillating currents (black arrows) flow down the transmission line and through the receiver (represented by the resistance *R*).

Terminology

The words *antenna* (plural: *antennas*^[2] in US English, although both "antennas" and "antennae" are used in International English^[3]) and *aerial* are used interchangeably. Occasionally the term "aerial" is used to mean a wire antenna. However, note the important international technical journal, the *IEEE Transactions on Antennas and Propagation*.^[4] In the United Kingdom and other areas where British English is used, the term aerial is sometimes used although 'antenna' has been universal in professional use for many years.

The origin of the word *antenna* relative to wireless apparatus is attributed to Italian radio pioneer Guglielmo Marconi. In the summer of 1895, Marconi began testing his wireless system outdoors on his father's estate near Bologna and soon began to experiment with long wire "aerials". Marconi discovered that by raising the "aerial" wire above the ground and connecting the other side of his transmitter to ground, the transmission range was increased.^[5] Soon he was able to transmit signals over a hill, a distance of approximately 2.4 kilometres (1.5 mi).^[6] In Italian a tent pole is known as *l'antenna centrale*, and the pole with the wire was simply called *l'antenna*. Until then wireless radiating transmitting and receiving elements were known simply as aerials or terminals.

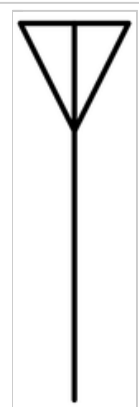
Because of his prominence, Marconi's use of the word *antenna* (Italian for *pole*) spread among wireless researchers, and later to the general public.^{[7][8][9]}

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 or mixer.

An antenna, in converting radio waves to electrical signals or vice versa, is a form of transducer.^[10]

Overview

Antennas are required by any radio receiver or transmitter to couple its electrical connection to the electromagnetic field. Radio waves are electromagnetic waves which carry signals through the air (or through space) at 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



Electronic symbol for an antenna

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).



Whip antenna on car, common example of an omnidirectional antenna

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

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.

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 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.



Half-wave dipole antenna

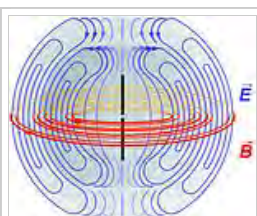


Diagram of the electric fields (*blue*) and magnetic fields (*red*) radiated by a dipole antenna (*black rods*) during transmission.

Antennas more complex 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. Antenna "gain" in this instance describes the concentration of radiated power into a particular solid angle of space, as opposed to the spherically uniform radiation of the ideal radiator. The increased power in the desired direction is at the expense of that in the undesired directions. Power is conserved, and there is no net power increase over that delivered from the power source (the transmitter.)

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



Antennas of the Atacama Large Millimeter submillimeter Array.^[11]

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 high directivity in an antenna depends on it being large compared to the wavelength, narrow beams of this type are more easily achieved at UHF and microwave frequencies.

At low frequencies (such as AM broadcast), arrays of vertical towers are used to achieve directionality ^[12] and they will occupy large areas of land. For reception, a long Beverage antenna can have significant directivity. For non directional portable use, a short vertical antenna or small loop antenna works well, 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 place of a (conductive) transmission line.



Cell phone base station antennas

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 and to present the transmitter or receiver with a standard resistive impedance that it expects to see for optimum operation.

Reciprocity

It is a fundamental property of antennas that the electrical 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.^{[13][14]} 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.^[14] 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 aforementioned 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 current or magnetic field 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.^{[13][14]} These can be used to give the antenna a different behavior on receiving than it has on transmitting,^[13] which can be useful in applications like radar.

Characteristics

Antennas are characterized by a number of performance measures which a user would be concerned with in selecting or designing an antenna for a particular application. Chief among these relate to the directional characteristics (as depicted in the antenna's *radiation pattern*) and the resulting *gain*. Even in omnidirectional (or weakly directional) antennas, the gain can often be increased by concentrating more of its power in the horizontal directions, sacrificing power radiated toward the sky and ground. The antenna's power gain (or simply "gain") also takes into account the antenna's efficiency, and is often the primary figure of merit.

Resonant antennas are expected to be used around a particular *resonant frequency*; an antenna must therefore be built or ordered to match the frequency range of the intended application. A particular antenna design will present a particular feedpoint impedance. While this may affect the choice of an antenna, an antenna's impedance can also be adapted to the desired impedance level of a system using a matching network while maintaining the other characteristics (except for a possible loss of efficiency).

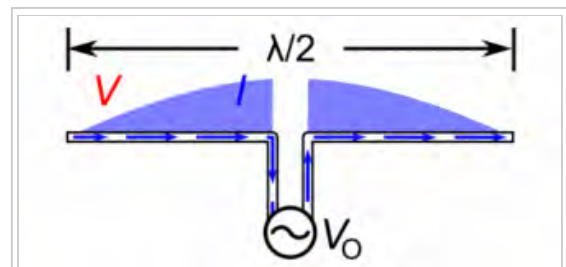
Although these parameters can be measured in principle, such measurements are difficult and require very specialized equipment. Beyond tuning a transmitting antenna using an SWR meter, the typical user will depend on theoretical predictions based on the antenna design or on claims of a vendor.

An antenna transmits and receives radio waves with a particular polarization which can be reoriented by tilting the axis of the antenna in many (but not all) cases. The physical size of an antenna is often a practical issue, particularly at lower frequencies (longer wavelengths). Highly directional antennas need to be significantly larger than the wavelength. Resonant antennas usually use a linear conductor (or *element*), or pair of such elements, each of which is about a quarter of the wavelength in length (an odd multiple of quarter wavelengths will also be resonant). Antennas that are required to be small compared to the wavelength sacrifice efficiency and cannot be very directional. Fortunately at higher frequencies (UHF, microwaves) trading off performance to obtain a smaller physical size is usually not required.

Resonant antennas

The majority of antenna designs are based on the *resonance* principle. This relies on the behaviour of moving electrons, which reflect off surfaces where the dielectric constant changes, in a fashion similar to the way light reflects when optical properties change. In these designs, the reflective surface is created by the end of a conductor, normally a thin metal wire or rod, which in the simplest case has a *feed point* at one end where it is connected to a transmission line. The conductor, or *element*, is aligned with the electrical field of the desired signal, normally meaning it is perpendicular to the line from the antenna to the source (or receiver in the case of a broadcast antenna).^[15]

The radio signal's electrical component induces a voltage in the conductor. This causes an electrical current to begin flowing in the direction of the signal's instantaneous field. When the resulting current reaches the end of the conductor, it reflects, which is equivalent to a 180 degree change in phase. If the conductor is $\frac{1}{4}$ of a wavelength



Standing waves on a half wave dipole driven at its resonant frequency. The waves are shown graphically by bars of color (red for voltage, V and blue for current, I) whose width is proportional to the amplitude of the quantity at that point on the antenna.

long, current from the feed point will undergo 90 degree phase change by the time it reaches the end of the conductor, reflect through 180 degrees, and then another 90 degrees as it travels back. That means it has undergone a total 360 degree phase change, returning it to the original signal. The current in the element thus adds to the current being created from the source at that instant. This process creates a standing wave in the conductor, with the maximum current at the feed.^[16]

The ordinary half-wave dipole is probably the most widely used antenna design. This consists of two $\frac{1}{4}$ -wavelength elements arranged end-to-end, and lying along essentially the same axis (or *collinear*), each feeding one side of a two-conductor transmission wire. The physical arrangement of the two elements places them 180 degrees out of phase, which means that at any given instant one of the elements is driving current into the transmission line while the other is pulling it out. The monopole antenna is essentially one half of the half-wave dipole, a single $\frac{1}{4}$ -wavelength element with the other side connected to ground or an equivalent ground plane (or *counterpoise*). Monopoles, which are one-half the size of a dipole, are common for long-wavelength radio signals where a dipole would be impractically large. Another common design is the folded dipole, which is essentially two dipoles placed side-by-side and connected at their ends to make a single one-wavelength antenna.

The standing wave forms with this desired pattern at the design frequency, f_0 , and antennas are normally designed to be this size. However, feeding that element with $3f_0$ (whose wavelength is $\frac{1}{3}$ that of f_0) will also lead to a standing wave pattern. Thus, an antenna element is *also* resonant when its length is $\frac{3}{4}$ of a wavelength. This is true for all odd multiples of $\frac{1}{4}$ wavelength. This allows some flexibility of design in terms of antenna lengths and feed points. Antennas used in such a fashion are known to be *harmonically operated*.^[17]

Current and voltage distribution

The quarter-wave elements imitate a series-resonant electrical element due to the standing wave present along the conductor. At the resonant frequency, the standing wave has a current peak and voltage node (minimum) at the feed. In electrical terms, this means the element has minimum reactance, generating the maximum current for minimum voltage. This is the ideal situation, because it produces the maximum output for the minimum input, producing the highest possible efficiency. Contrary to an ideal (lossless) series-resonant circuit, a finite resistance remains (corresponding to the relatively small voltage at the feed-point) due to the antenna's radiation resistance as well as any actual electrical losses.

Recall that a current will reflect when there are changes in the electrical properties of the material. In order to efficiently send the signal into the transmission line, it is important that the transmission line has the same impedance as the elements, otherwise some of the signal will be reflected back into the antenna. This leads to the concept of impedance matching, the design of the overall system of antenna and transmission line so the impedance is as close as possible, thereby reducing these losses. Impedance matching between antennas and transmission lines is commonly handled through the use of a balun, although other solutions are also used in certain roles. An important measure of this basic concept is the standing wave ratio, which measures the magnitude of the reflected signal.

Consider a half-wave dipole designed to work with signals 1 m wavelength, meaning the antenna would be approximately 50 cm across. If the element has a length-to-diameter ratio of 1000, it will have an inherent resistance of about 63 ohms. Using the appropriate transmission wire or balun, we match that resistance to ensure minimum signal loss. Feeding that antenna with a current of 1 ampere will require 63 volts of RF, and the antenna will radiate 63 watts (ignoring losses) of radio frequency power. Now consider the case when the antenna is fed a signal with a wavelength of 1.25 m; in this case the reflected current would arrive at the feed out-of-phase with the signal, causing the net current to drop while the voltage remains the same. Electrically this appears to be a very high impedance. The antenna and transmission line no longer have the same impedance, and the signal will be reflected back into the antenna, reducing output. This could be addressed by changing the matching system between the antenna and transmission line, but that solution only works well at the new design frequency.

The end result is that the resonant antenna will efficiently feed a signal into the transmission line only when the source signal's frequency is close to that of the design frequency of the antenna, or one of the resonant multiples. This makes resonant antenna designs inherently narrowband, and they are most commonly used with a single target signal. They are particularly common on radar systems, where the same antenna is used for both broadcast and reception, or for radio and television *broadcasts*, where the antenna is working with a single frequency. They are less commonly used for reception where multiple channels are present, in which case additional modifications are used to increase the bandwidth, or entirely different antenna designs are used.

Electrically short antennas

It is possible to use simple impedance matching concepts to allow the use of monopole or dipole antennas substantially shorter than the $\frac{1}{4}$ or $\frac{1}{2}$ wavelength, respectively, at which they are resonant. As these antennas are made shorter (for a given frequency) their impedance becomes dominated by a series capacitive (negative) reactance; by adding a series inductance with the opposite (positive) reactance – a so-called loading coil – the antenna's reactance may be cancelled leaving only a pure resistance. Sometimes the resulting (lower) electrical resonant frequency of such a system (antenna plus matching network) is described using the concept of *electrical length*, so an antenna used at a lower frequency than its resonant frequency is called an *electrically short antenna*.

For example, at 30 MHz (10 m wavelength) a true resonant $\frac{1}{4}$ wavelength monopole would be almost 2.5 meters long, and using an antenna only 1.5 meters tall would require the addition of a loading coil. Then it may be said that the coil has lengthened the antenna to achieve an electrical length of 2.5 meters. However, the resulting resistive impedance achieved will be quite a bit lower than that of a true $\frac{1}{4}$ wave (resonant) monopole, often requiring further impedance matching (a transformer) to the desired transmission line. For ever shorter antennas (requiring greater "electrical lengthening") the radiation resistance plummets (approximately according to the square of the antenna length), so that the mismatch due to a net reactance away from the electrical resonance worsens. Or one could as well say that the equivalent resonant circuit of the antenna system has a higher Q factor and thus a reduced bandwidth, which can even become inadequate for the transmitted signal's spectrum. Resistive losses due to the loading coil, relative to the decreased radiation resistance, entail a reduced electrical efficiency, which can be of great concern for a transmitting antenna, but bandwidth is the major factor that sets the size of antennas at 1 MHz and lower frequencies.

Arrays and reflectors

The amount of signal received from a distant transmission source is essentially geometric in nature due to the inverse-square law, and this leads to the concept of *effective area*. This measures the performance of an antenna by comparing the amount of power it generates to the amount of power in the original signal, measured in terms of the signal's power density in Watts per square metre. A half-wave dipole has an effective area of $0.13 \lambda^2$. If more performance is needed, one cannot simply make the antenna larger. Although this would intercept more energy from the signal, due to the considerations above, it would decrease the output significantly due to it moving away from the resonant length. In roles where higher performance is needed, designers often use multiple elements combined together.

Returning to the basic concept of current flows in a conductor, consider what happens if a half-wave dipole is not connected to a feed point, but instead shorted out. Electrically this forms a single $\frac{1}{2}$ -wavelength element. But the overall current pattern is the same; the current will be zero at the two ends, and reach a maximum in the center. Thus signals near the design frequency will continue to create a standing wave pattern. Any varying electrical current, like the standing wave in the element, will radiate a signal. In this case, aside from resistive losses in the element, the rebroadcast signal will be significantly similar to the original signal in both magnitude and shape. If this element is placed so its signal reaches the main dipole in-phase, it will reinforce the original signal, and increase the current in the dipole. Elements used in this way are known as *passive elements*.

A Yagi-Uda array uses passive elements to greatly increase gain. It is built along a support boom that is pointed toward the signal, and thus sees no induced signal and does not contribute to the antenna's operation. The end closer to the source is referred to as the front. Near the rear is a single active element, typically a half-wave dipole or folded dipole. Passive elements are arranged in front (*directors*) and behind (*reflectors*) the active element along the boom. The Yagi has the inherent quality that it becomes increasingly directional, and thus has higher gain, as the number of elements increases. However, this also makes it increasingly sensitive to changes in frequency; if the signal frequency changes, not only does the active element receive less energy directly, but all of the passive elements adding to that signal also decrease their output as well and their signals no longer reach the active element in-phase.



Rooftop television Yagi-Uda antennas like these are widely used at VHF and UHF frequencies.

It is also possible to use multiple active elements and combine them together with transmission lines to produce a similar system where the phases add up to reinforce the output. The antenna array and very similar reflective array antenna consist of multiple elements, often half-wave dipoles, spaced out on a plane and wired together with transmission lines with specific phase lengths to produce a single in-phase signal at the output. The log-periodic antenna is a more complex design that uses multiple in-line elements similar in appearance to the Yagi-Uda but using transmission lines between the elements to produce the output.

Reflection of the original signal also occurs when it hits an extended conductive surface, in a fashion similar to a mirror. This effect can also be used to increase signal through the use of a *reflector*, normally placed behind the active element and spaced so the reflected signal reaches the element in-phase. Generally the reflector will remain highly reflective even if it is not solid; gaps less than $\frac{1}{10}$ generally have little effect on the outcome. For this reason, reflectors often take the form of wire meshes or rows of passive elements, which makes them lighter and less subject to wind. The parabolic reflector is perhaps the best known example of a reflector-based antenna, which has an effective area far greater than the active element alone.

Bandwidth

Although a resonant antenna has a purely resistive feed-point impedance at a particular frequency, many (if not most) applications require using an antenna over a range of frequencies. The frequency range or *bandwidth* over which an antenna functions well can be very wide (as in a log-periodic antenna) or narrow (in a resonant antenna); outside this range the antenna impedance becomes a poor match to the transmission line and transmitter (or receiver). Also in the case of the Yagi-Uda and other end-fire arrays, use of the antenna well away from its design frequency affects its radiation pattern, reducing its directive gain; the usable bandwidth is then limited regardless of impedance matching.

Except for the latter concern, the resonant frequency of an antenna system can always be altered by adjusting a suitable matching network. This is most efficiently accomplished using a matching network at the site of the antenna, since simply adjusting a matching network at the transmitter (or receiver) would leave the transmission line with a poor standing wave ratio.

Instead, it is often desired to have an antenna whose impedance does not vary so greatly over a certain bandwidth. It turns out that the amount of reactance seen at the terminals of a resonant antenna when the frequency is shifted, say, by 5%, depends very much on the diameter of the conductor used. A long thin wire used as a half-wave dipole (or quarter wave monopole) will have a reactance significantly greater than the resistive impedance it has at resonance, leading to a poor match and generally unacceptable performance. Making the element using a tube of a diameter perhaps $\frac{1}{50}$ of its length, however, results in a reactance at this altered frequency which is not so great, and a much less serious mismatch and effect on the antenna's net performance. Thus rather thick tubes are often used for the elements; these also have reduced parasitic resistance (loss).

Rather than just using a thick tube, there are similar techniques used to the same effect such as replacing thin wire elements with *cages* to simulate a thicker element. This widens the bandwidth of the resonance. On the other hand, it is desired for amateur radio antennas to operate at several bands which are widely separated from each other (but not in between). This can often be accomplished simply by connecting elements resonant at those different frequencies in parallel. Most of the transmitter's power will flow into the resonant element while the others present a high (reactive) impedance, thus drawing little current from the same voltage. Another popular solution uses so-called *traps* consisting of parallel resonant circuits which are strategically placed in breaks along each antenna element. When used at one particular frequency band the trap presents a very high impedance (parallel resonance) effectively truncating the element at that length, making it a proper resonant antenna. At a lower frequency the trap allows the full length of the element to be employed, albeit with a shifted resonant frequency due to the inclusion of the trap's net reactance at that lower frequency.

The bandwidth characteristics of a resonant antenna element can be characterized according to its *Q*, just as one uses to characterize the sharpness of an L-C resonant circuit. A common mistake is to assume that there is an advantage in an antenna having a high *Q* (the so-called "quality factor"). In the context of electronic circuitry a low *Q* generally signifies greater loss (due to unwanted resistance) in a resonant L-C circuit, and poorer receiver selectivity. However this understanding does not apply to resonant antennas where the resistance involved is the radiation resistance, a desired quantity which removes energy from the resonant element in order to radiate it (the purpose of an antenna, after all!). The *Q* of an L-C-R circuit is defined as the ratio of the inductor's (or capacitor's) reactance to the resistance, so for a certain radiation resistance (the radiation resistance at resonance does not vary greatly with diameter) the greater reactance off-resonance causes the poorer bandwidth of an antenna employing a very thin conductor. The *Q* of such a narrowband antenna can be as high as 15. On the other hand, the reactance at the same off-resonant frequency of one using thick elements is much less, consequently resulting in a *Q* as low as 5. These two antennas may perform equivalently at the resonant frequency, but the second antenna will perform over a bandwidth 3 times as wide as the antenna consisting of a thin conductor.

Antennas for use over much broader frequency ranges are achieved using further techniques. Adjustment of a matching network can, in principle, allow for any antenna to be matched at any frequency. Thus the loop antenna built into most AM broadcast (medium wave) receivers has a very narrow bandwidth, but is tuned using a parallel capacitance which is adjusted according to the receiver tuning. On the other hand, log-periodic antennas are *not* resonant at any frequency but can be built to attain similar characteristics (including feedpoint impedance) over any frequency range. These are therefore commonly used (in the form of directional log-periodic dipole arrays) as television antennas.

Gain

Gain is a parameter which measures the degree of directivity of the antenna's radiation pattern. A high-gain antenna will radiate most of its power in a particular direction, while a low-gain antenna will radiate over a wider angle. The *antenna gain*, or *power gain* of an antenna is defined as the ratio of the intensity (power per unit surface area) I radiated by the antenna in the direction of its maximum output, at an arbitrary distance, divided by the intensity I_{iso} radiated at the same distance by a hypothetical isotropic antenna which radiates equal power in all directions. This dimensionless ratio is usually expressed logarithmically in decibels, these units are called "decibels-isotropic" (dBi)

$$G_{\text{dBi}} = 10 \log \frac{I}{I_{\text{iso}}}$$

A second unit used to measure gain is the ratio of the power radiated by the antenna to the power radiated by a half-wave dipole antenna I_{dipole} ; these units are called "decibels-dipole" (dBd)

$$G_{\text{dBd}} = 10 \log \frac{I}{I_{\text{dipole}}}$$

Since the gain of a half-wave dipole is 2.15 dBi and the logarithm of a product is additive, the gain in dBi is just 2.15 decibels greater than the gain in dBd

$$G_{\text{dBi}} = G_{\text{dBd}} + 2.15$$

High-gain antennas have the advantage of longer range and better signal quality, but must be aimed carefully at the other antenna. An example of a high-gain antenna is a parabolic dish such as a satellite television antenna. Low-gain antennas have shorter range, but the orientation of the antenna is relatively unimportant. An example of a low-gain antenna is the whip antenna found on portable radios and cordless phones. Antenna gain should not be confused with amplifier gain, a separate parameter measuring the increase in signal power due to an amplifying device.

Effective area or aperture

The *effective area* or effective aperture of a receiving antenna expresses the portion of the power of a passing electromagnetic wave which it delivers to its terminals, expressed in terms of an equivalent area. For instance, if a radio wave passing a given location has a flux of $1 \text{ pW} / \text{m}^2$ (10^{-12} watts per square meter) and an antenna has an effective area of 12 m^2 , then the antenna would deliver 12 pW of RF power to the receiver (30 microvolts rms at 75 ohms). Since the receiving antenna is not equally sensitive to signals received from all directions, the effective area is a function of the direction to the source.

Due to reciprocity (discussed above) the gain of an antenna used for transmitting must be proportional to its effective area when used for receiving. Consider an antenna with no loss, that is, one whose electrical efficiency is 100%. It can be shown that its effective area averaged over all directions must be equal to $\lambda^2/4\pi$, the wavelength squared divided by 4π . Gain is defined such that the average gain over all directions for an antenna with 100% electrical efficiency is equal to 1. Therefore, the effective area A_{eff} in terms of the gain G in a given direction is given by:

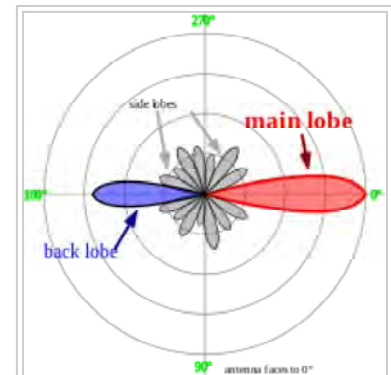
$$A_{\text{eff}} = \frac{\lambda^2}{4\pi} G$$

For an antenna with an efficiency of less than 100%, both the effective area and gain are reduced by that same amount. Therefore, the above relationship between gain and effective area still holds. These are thus two different ways of expressing the same quantity. A_{eff} is especially convenient when computing the power that would be received by an antenna of a specified gain, as illustrated by the above example.

Radiation pattern

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 "*principal axis*" or "*boresight axis*".



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.

Field regions

The space surrounding an antenna can be divided into three concentric regions: the reactive near-field, the radiating near-field (Fresnel region) and the far-field (Fraunhofer) regions. These regions are useful to identify the field structure in each, although there are no precise boundaries.

In the far-field region, we are far enough from the antenna to neglect its size and shape. We can assume that the electromagnetic wave is purely a radiating plane wave (electric and magnetic fields are in phase and perpendicular to each other and to the direction of propagation). This simplifies the mathematical analysis of the radiated field.

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,^[18] 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 of a transmitting antenna is the ratio of power actually radiated (in all directions) to the power absorbed by the antenna terminals. The power supplied to the antenna terminals which is not radiated is converted into heat. This is usually through loss resistance in the antenna's conductors, but can also be due to dielectric or magnetic core losses in antennas (or antenna systems) using such components. Such loss effectively robs power from the transmitter, requiring a stronger transmitter in order to transmit a signal of a given strength.

For instance, if a transmitter delivers 100 W into an antenna having an efficiency of 80%, then the antenna will radiate 80 W as radio waves and produce 20 W of heat. In order to radiate 100 W of power, one would need to use a transmitter capable of supplying 125 W to the antenna. Note that antenna efficiency is a separate issue from impedance matching, which may also

reduce the amount of power radiated using a given transmitter. If an SWR meter reads 150 W of incident power and 50 W of reflected power, that means that 100 W have actually been absorbed by the antenna (ignoring transmission line losses). How much of that power has actually been radiated cannot be directly determined through electrical measurements at (or before) the antenna terminals, but would require (for instance) careful measurement of field strength. Fortunately the loss resistance of antenna conductors such as aluminum rods can be calculated and the efficiency of an antenna using such materials predicted.

However loss resistance will generally affect the feedpoint impedance, adding to its resistive (real) component. That resistance will consist of the sum of the radiation resistance R_r and the loss resistance R_{loss} . If an rms current I is delivered to the terminals of an antenna, then a power of $I^2 R_r$ will be radiated and a power of $I^2 R_{\text{loss}}$ will be lost as heat. Therefore, the efficiency of an antenna is equal to $R_r / (R_r + R_{\text{loss}})$. Of course only the total resistance $R_r + R_{\text{loss}}$ can be directly measured.

According to reciprocity, the efficiency of an antenna used as a receiving antenna is identical to the efficiency as defined above. The power that an antenna will deliver to a receiver (with a proper impedance match) is reduced by the same amount. In some receiving applications, the very inefficient antennas may have little impact on performance. At low frequencies, for example, atmospheric or man-made noise can mask antenna inefficiency. For example, CCIR Rep. 258-3 indicates man-made noise in a residential setting at 40 MHz is about 28 dB above the thermal noise floor. Consequently, an antenna with a 20 dB loss (due to inefficiency) would have little impact on system noise performance. The loss within the antenna will affect the intended signal and the noise/interference identically, leading to no reduction in signal to noise ratio (SNR).

This is fortunate, since antennas at lower frequencies which are not rather large (a good fraction of a wavelength in size) are inevitably inefficient (due to the small radiation resistance R_r of small antennas). Most AM broadcast radios (except for car radios) take advantage of this principle by including a small loop antenna for reception which has an extremely poor efficiency. Using such an inefficient antenna at this low frequency (530–1650 kHz) thus has little effect on the receiver's net performance, but simply requires greater amplification by the receiver's electronics. Contrast this tiny component to the massive and very tall towers used at AM broadcast stations for transmitting at the very same frequency, where every percentage point of reduced antenna efficiency entails a substantial cost.

The definition of antenna gain or *power gain* already includes the effect of the antenna's efficiency. Therefore, if one is trying to radiate a signal toward a receiver using a transmitter of a given power, one need only compare the gain of various antennas rather than considering the efficiency as well. This is likewise true for a receiving antenna at very high (especially microwave) frequencies, where the point is to receive a signal which is strong compared to the receiver's noise temperature. However, in the case of a directional antenna used for receiving signals with the intention of *rejecting* interference from different directions, one is no longer concerned with the antenna efficiency, as discussed above. In this case, rather than quoting the antenna gain, one would be more concerned with the *directive gain* which does *not* include the effect of antenna (in)efficiency. The directive gain of an antenna can be computed from the published gain divided by the antenna's efficiency.

Polarization

The *polarization* of an antenna refers to 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; note that this designation is totally distinct from the antenna's directionality. Thus, a simple straight wire antenna will have one polarization when mounted vertically, and a different polarization when mounted horizontally. As a transverse wave, the magnetic field of a radio wave is at right angles to that of the electric field, but by convention, talk of an antenna's "polarization" is understood to refer to the direction of the electric field.

Reflections generally affect polarization. For radio waves, one important reflector is the ionosphere which can change the wave's polarization. Thus for signals received following reflection by the ionosphere (a skywave), a consistent polarization cannot be expected. For line-of-sight communications or ground wave propagation, horizontally or vertically polarized transmissions generally remain in about the same polarization state at the receiving location. Matching the receiving antenna's polarization to that of the transmitter can make a very substantial difference in received signal strength.

Polarization is predictable from an antenna's geometry, although in some cases it is not at all obvious (such as for the quad antenna). An antenna's linear polarization is generally along the direction (as viewed from the receiving location) of the antenna's currents when such a direction can be defined. For instance, a vertical whip antenna or Wi-Fi antenna vertically oriented will transmit and receive in the vertical polarization. Antennas with horizontal elements, such as most rooftop TV

antennas in the United States, are horizontally polarized (broadcast TV in the U.S. usually uses horizontal polarization). Even when the antenna system has a vertical orientation, such as an array of horizontal dipole antennas, the polarization is in the horizontal direction corresponding to the current flow. The polarization of a commercial antenna is an essential specification.

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) as we have discussed above, and circular polarization (in which the two axes of the ellipse are equal). In linear polarization the electric field of the radio wave oscillates back and forth along one direction; this can be affected by the mounting of the antenna but usually the desired direction is either horizontal or vertical polarization. In circular polarization, the electric field (and magnetic field) of the radio wave rotates at the radio frequency circularly around the axis of propagation. Circular or elliptically polarized radio waves are designated as right-handed or left-handed using the "thumb in the direction of the propagation" rule. Note that for circular polarization, optical researchers use the opposite right hand rule from the one used by radio engineers.

It is best for the receiving antenna to match the polarization of the transmitted wave for optimum reception. Intermediate matchings will lose some signal strength, but not as much as a complete mismatch. A circularly polarized antenna can be used to equally well match vertical or horizontal linear polarizations. Transmission from a circularly polarized antenna received by a linearly polarized antenna (or vice versa) entails a 3 dB reduction in signal-to-noise ratio as the received power has thereby been cut in half.

Impedance matching

Maximum power transfer requires matching the impedance of an antenna system (as seen looking into the transmission line) to the complex conjugate of the impedance of the receiver or transmitter. In the case of a transmitter, however, the desired matching impedance might not correspond to the dynamic output impedance of the transmitter as analyzed as a source impedance but rather the design value (typically 50 ohms) required for efficient and safe operation of the transmitting circuitry. The intended impedance is normally resistive but a transmitter (and some receivers) may have additional adjustments to cancel a certain amount of reactance in order to "tweak" the match. When a transmission line is used in between the antenna and the transmitter (or receiver) one generally would like an antenna system whose impedance is resistive and near the characteristic impedance of that transmission line in order to minimize the standing wave ratio (SWR) and the increase in transmission line losses it entails, in addition to supplying a good match at the transmitter or receiver itself.

Antenna tuning generally refers to cancellation of any reactance seen at the antenna terminals, leaving only a resistive impedance which might or might not be exactly the desired impedance (that of the transmission line). Although an antenna may be designed to have a purely resistive feedpoint impedance (such as a dipole 97% of a half wavelength long) this might not be exactly true at the frequency that it is eventually used at. In some cases the physical length of the antenna can be "trimmed" to obtain a pure resistance. On the other hand, the addition of a series inductance or parallel capacitance can be used to cancel a residual capacitive or inductive reactance, respectively.

In some cases this is done in a more extreme manner, not simply to cancel a small amount of residual reactance, but to resonate an antenna whose resonance frequency is quite different from the intended frequency of operation. For instance, a "whip antenna" can be made significantly shorter than 1/4 wavelength long, for practical reasons, and then resonated using a so-called loading coil. This physically large inductor at the base of the antenna has an inductive reactance which is the opposite of the capacitive reactance that such a vertical antenna has at the desired operating frequency. The result is a pure resistance seen at feedpoint of the loading coil; unfortunately that resistance is somewhat lower than would be desired to match commercial coax.

So an additional problem beyond canceling the unwanted reactance is of matching the remaining resistive impedance to the characteristic impedance of the transmission line. In principle this can always be done with a transformer, however the turns ratio of a transformer is not adjustable. A general matching network with at least two adjustments can be made to correct both components of impedance. Matching networks using discrete inductors and capacitors will have losses associated with those components, and will have power restrictions when used for transmitting. Avoiding these difficulties, commercial antennas are generally designed with fixed matching elements or feeding strategies to get an approximate match to standard coax, such as 50 or 75 Ohms. Antennas based on the dipole (rather than vertical antennas) should include a balun in between the transmission line and antenna element, which may be integrated into any such matching network.

Another extreme case of impedance matching occurs when using a small loop antenna (usually, but not always, for receiving) at a relatively low frequency where it appears almost as a pure inductor. Resonating such an inductor with a capacitor at the frequency of operation not only cancels the reactance but greatly magnifies the very small radiation resistance of such a loop. This is implemented in most AM broadcast receivers, with a small ferrite loop antenna resonated by a capacitor which is varied along with the receiver tuning in order to maintain resonance over the AM broadcast band

Antenna types

Antennas can be classified in various ways. The list below groups together antennas under common operating principles, following the way antennas are classified in many engineering textbooks.^{[19][20][21]}

Isotropic: An isotropic antenna (isotropic radiator) is a *hypothetical* antenna that radiates equal signal power in all directions. It is a mathematical model that is used as the base of comparison to calculate the gain of real antennas. No real antenna can have an isotropic radiation pattern. However *approximately* isotropic antennas, constructed with multiple elements, are used in antenna testing.

The first four groups below are usually resonant antennas; when driven at their resonant frequency their elements act as resonators. Waves of current and voltage bounce back and forth between the ends, creating standing waves along the elements.

Dipole



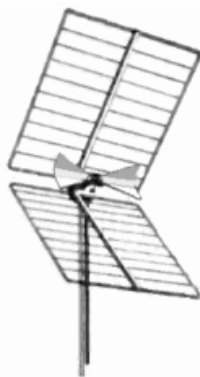
"Rabbit ears" dipole variant for VHF television reception



Yagi-Uda television antenna for analog channels 2-4, 47-68 MHz



Log-periodic dipole array covering 140-470 MHz



Corner reflector UHF TV antenna with "bowtie" dipole driven element



Two-element turnstile antenna for reception of weather satellite data, 137 MHz. Has circular polarization.

The dipole is the prototypical antenna on which a large class of antennas are based. A basic dipole antenna consists of two conductors (usually metal rods or wires) arranged symmetrically, with one side of the balanced feedline from the transmitter or receiver attached to each.^{[20][22]} The most common type, the half-wave dipole, consists of two resonant elements just under a quarter wavelength long. This antenna radiates maximally in directions perpendicular to the antenna's axis, giving it a small directive gain of 2.15 dBi (practically the lowest directive gain of any antenna). Although half-wave dipoles are used alone as omnidirectional antennas, they are also a building block of many other more complicated directional antennas.

- *Yagi-Uda* - One of the most common directional antennas at HF, VHF, and UHF frequencies. Consists of multiple half wave dipole elements in a line, with a single driven element and multiple parasitic elements which serve to create a uni-directional or beam antenna. These typically have gains between 10 and 20 dBi depending on the number of elements used, and are very narrowband (with a usable bandwidth of only a few percent) though there are derivative designs which relax this limitation. Used for rooftop television antennas, point-to-point communication links, and long distance shortwave communication using skywave ("skip") reflection from the ionosphere.
- *Log-periodic dipole array* - Often confused with the Yagi-Uda, this consists of many dipole elements along a boom with gradually increasing lengths, all connected to the transmission line with alternating polarity. It is a directional antenna with a wide bandwidth. This makes it ideal for use as a rooftop television antenna, although its gain is much less than a Yagi of comparable size.
- *Turnstile* - Two dipole antennas mounted at right angles, fed with a phase difference of 90°. This antenna is unusual in that it radiates in *all* directions (no nodes in the radiation pattern), with horizontal polarization in directions coplaner with the elements, circular polarization normal to that plane, and elliptical polarization in other directions. Used for receiving signals from satellites, as circular polarization is transmitted by many satellites.
- *Corner reflector* - A directive antenna with moderate gain of about 8 dBi often used at UHF frequencies. Consists of a dipole mounted in front of two reflective metal screens joined at an angle, usually 90°. Used as a rooftop UHF television antenna and for point-to-point data links.
- *Patch (microstrip)* - A type of antenna with elements consisting of metal sheets mounted over a ground plane. Similar to dipole with gain of 6 - 9 dBi. Integrated into surfaces such as aircraft bodies. Their easy fabrication using PCB techniques have made them popular in modern wireless devices. Often used in arrays.

Monopole



Quarter-wave whip antenna on an FM radio for 88-108 MHz



Rubber Ducky antenna on UHF 446 MHz walkie talkie with rubber cover removed.



VHF ground plane antenna



Mast radiator antenna of medium wave AM radio station, Germany



T antenna of amateur radio station, 80 ft high, used at 1.5 MHz.

Monopole antennas consist of a single conductor such as a metal rod, mounted over the ground or an artificial conducting surface (a so-called *ground plane*).^{[20][23]} One side of the feedline from the receiver or transmitter is connected to the conductor, and the other side to ground and/or the artificial ground plane. The monopole is best understood as a dipole antenna in which one conductor is omitted; the radiation is generated as if the second arm of the dipole were present due to the effective image current seen as a reflection of the monopole from the ground. Since all of the equivalent dipole's radiation is concentrated in a half-space, the antenna has twice (3 dB increase of) the gain of a similar dipole, not considering losses in the ground plane.

The most common form is the quarter-wave monopole which is one-quarter of a wavelength long and has a gain of 5.12 dBi when mounted over a ground plane. Monopoles have an omnidirectional radiation pattern, so they are used for broad coverage of an area, and have vertical polarization. The ground waves used for broadcasting at low frequencies must be vertically polarized, so large vertical monopole antennas are used for broadcasting in the MF, LF, and VLF bands. Small monopoles are used as nondirectional antennas on portable radios in the HF, VHF, and UHF bands.

- *Whip* - Type of antenna used on mobile and portable radios in the VHF and UHF bands such as boom boxes, consists of a flexible rod, often made of telescoping segments.
 - *Rubber Duck* - Most common antenna used on portable two way radios and cordless phones due to its compactness, consists of an electrically short wire helix. The helix adds inductance to cancel the capacitive reactance of the short radiator, making it resonant. Very low gain.
 - *Ground plane* - a whip antenna with several rods extending horizontally from base of whip attached to the ground side of the feedline. Since whips are mounted above ground, the horizontal rods form an artificial ground plane under the antenna to increase its gain. Used as base station antennas for land mobile radio systems such as police, ambulance and taxi dispatchers.
- *Mast radiator* - A radio tower in which the tower structure itself serves as the antenna. Common form of transmitting antenna for AM radio stations and other MF and LF transmitters. At its base the tower is usually, but not necessarily, mounted on a ceramic insulator to isolate it from the ground.
- *T and inverted L* - Consist of a long horizontal wire suspended between two towers with insulators, with a vertical wire hanging down from it, attached to a feedline to the receiver or transmitter. Used on LF and VLF bands. The vertical wire serves as the radiator. Since at these frequencies the vertical wire is electrically short, much shorter than a quarter wavelength, the horizontal wire(s) serve as a capacitive "hat" to increase the current in the vertical radiator, increasing the gain. Very narrow bandwidth, requires loading coil to tune out the capacitive reactance and make it resonant. Requires low resistance ground (electricity)
- *Inverted F* - Combines the advantages of the inverted-L antenna and the F-type antenna of, respectively, compactness and good matching. The antenna is grounded at the base and fed at some intermediate point. The position of the feed point determines the antenna impedance. Thus, matching can be achieved without the need for an extraneous matching network.
- *Umbrella* - Very large wire transmitting antennas used on VLF bands. Consists of a central mast radiator tower attached at the top to multiple wires extending out radially from the mast to ground, like a tent or umbrella, insulated at the ends. Extremely narrow bandwidth, requires large loading coil and low resistance counterpoise ground. Used for long range military communications.

Array



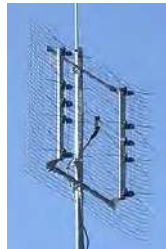
VHF collinear array of folded dipoles



Sector antennas (*white bars*) on cell phone tower. Collinear arrays of dipoles, these radiate a flat, fan-shaped beam.



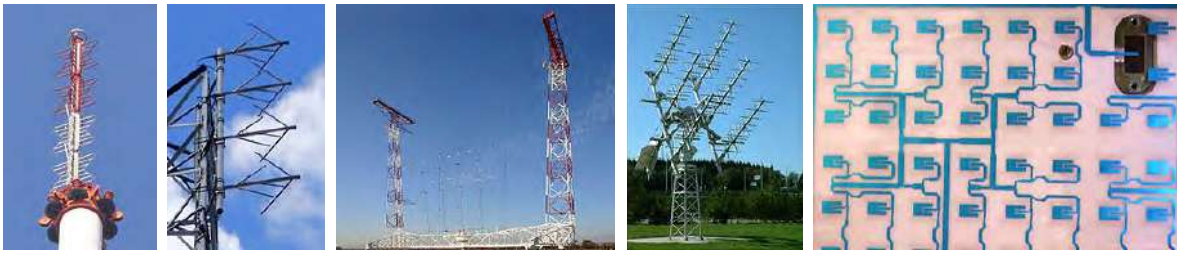
108 MHz reflective array antenna of AN-270 radar used during WW2.



Reflective array UHF TV antenna, with bowtie dipoles to cover the UHF 470-890 MHz band



US Air Force PAVE PAWS phased array radar antenna for ballistic missile detection, Alaska. The two circular arrays are composed of thousands of crossed dipole antennas.



Batwing VHF television broadcasting antenna

Crossed-dipole FM radio broadcast antenna

Curtain array shortwave transmitting antenna, Austria. Wire dipoles suspended between towers

Turnstile antenna array used for satellite communication

Flat microstrip array antenna for satellite TV reception.

Array antennas consist of multiple antennas working as a single antenna. Typically they consist of arrays of identical driven elements, usually dipoles fed in phase, giving increased gain over that of a single dipole.^{[20][24][25]}

- *Collinear* - Consist of a number of dipoles in a vertical line. It is a high gain omnidirectional antenna, meaning more of the power is radiated in horizontal directions and less into the sky or ground and wasted. Gain of 8 to 10 dBi. Used as base station antennas for land mobile radio systems such as police, fire, ambulance, and taxi dispatchers, and sector antennas for cellular base stations.
- *Reflective array* - multiple dipoles in a two-dimensional array mounted in front of a flat reflecting screen. Used for radar and UHF television transmitting and receiving antennas.
- *Phased array* - A high gain antenna used at UHF and microwave frequencies which is electronically steerable. It consists of multiple dipoles in a two-dimensional array, each fed through an electronic phase shifter, with the phase shifters controlled by a computer control system. The beam can be instantly pointed in any direction over a wide angle in front of the antenna. Used for military radar and jamming systems.
- *Curtain array* - Large directional wire transmitting antenna used at HF by shortwave broadcasting stations. It consists of a vertical rectangular array of wire dipoles suspended in front of a flat reflector screen consisting of a vertical "curtain" of parallel wires, all supported between two metal towers. It radiates a horizontal beam of radio waves into the sky above the horizon, which is reflected by the ionosphere to Earth beyond the horizon
- *Batwing or superturnstile* - A specialized antenna used in television broadcasting consisting of perpendicular pairs of dipoles with radiators resembling bat wings. Multiple batwing antennas are stacked vertically on a mast to make VHF television broadcast antennas. Omnidirectional radiation pattern with high gain in horizontal directions. The batwing shape gives them wide bandwidth.
- *microstrip* - an array of patch antennas on a substrate fed by microstrip feedlines. Microwave antenna that can achieve large gains in compact space. Ease of fabrication by PCB techniques have made them popular in modern wireless devices. Beamwidth and polarization can be actively reconfigurable.

Loop



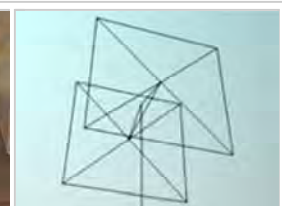
Loopstick antenna from an AM broadcast radio, about 4 in (10 cm) long. The antenna is inductive and, in conjunction with a variable capacitor, forms the tuned circuit at the input stage of the receiver.



Loop antenna for transmitting at high frequencies, 2m diameter



Separate loop antenna for AM radio



A two-element quad antenna used by an amateur radio station

Loop antennas consist of a loop (or coil) of wire.^{[20][26][27]} Loops with circumference of a wavelength (or integer multiple of the wavelength) are resonant and act somewhat similarly to the half-wave dipole. However a loop small in comparison to the wavelength, also called a magnetic loop, performs quite differently. This antenna interacts directly with the magnetic field of

the radio wave, making it relatively insensitive to nearby electrical noise. However it has a very small radiation resistance, typically much smaller than the loss resistance, making it inefficient and thus undesirable for transmitting. They are used as receiving antennas at low frequencies, and also as direction finding antennas.

- *Ferrite (loopstick)* - These are used as the receiving antenna in most consumer AM radios operating in the medium wave broadcast band (and lower frequencies), a notable exception being car radios. Wire is coiled around a ferrite core which greatly increases the coil's inductance. Radiation pattern is maximum at directions normal to the ferrite stick.
- *Quad* - consists of multiple wire loops in a line with one functioning as the driven element, and the others as parasitic elements. Used as a directional antenna on the HF bands for shortwave communication.

Aperture



NASA Cassegrain parabolic spacecraft communication antenna, Australia. Uses X band, 8 – 12 GHz. Extremely high gain ~70 dBi.



Microwave horn antenna bandwidth 0.8–18 GHz



X band marine radar slot antenna on ship, 8 – 12 GHz.

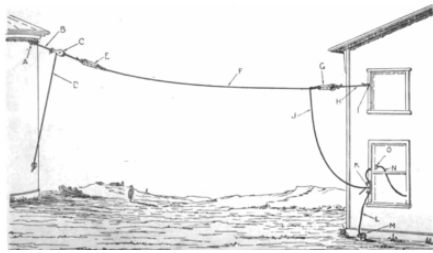


Dielectric lens antenna used in millimeter wave radio telescope

Aperture antennas are the main type of directional antennas used at microwave frequencies and above.^{[20][28]} They consist of a small dipole or loop feed antenna inside a three-dimensional guiding structure large compared to a wavelength, with an aperture to emit the radio waves. Since the antenna structure itself is nonresonant they can be used over a wide frequency range by replacing or tuning the feed antenna.

- *Parabolic* - The most widely used high gain antenna at microwave frequencies and above. Consists of a dish-shaped metal parabolic reflector with a feed antenna at the focus. It can have some of the highest gains of any antenna type, up to 60 dBi, but the dish must be large compared to a wavelength. Used for radar antennas, point-to-point data links, satellite communication, and radio telescopes
- *Horn* - Simple antenna with moderate gains of 15 to 25 dBi consists of a flaring metal horn attached to a waveguide. Used for applications such as radar guns, radiometers and as feed antennas for parabolic dishes.
- *Slot* - Consist of a waveguide with one or more slots cut in it to emit the microwaves. Linear slot antennas emit narrow fan-shaped beams. Used as UHF broadcast antennas and marine radar antennas.
- *Dielectric resonator* - consists of small ball or puck-shaped piece of dielectric material excited by aperture in waveguide Used at millimeter wave frequencies

Traveling wave



A typical random wire antenna for shortwave reception, strung between two buildings.



Quadrant antenna, similar to rhombic, at an Austrian shortwave broadcast station. Radiates horizontal beam at 5-9 MHz, 100 kW



Array of four axial-mode helical antennas used for satellite tracking, France

Unlike the above antennas, traveling wave antennas are nonresonant so they have inherently broad bandwidth.^{[20][29]} They are typically wire antennas multiple wavelengths long, through which the voltage and current waves travel in one direction, instead of bouncing back and forth to form standing waves as in resonant antennas. They have linear polarization (except for the helical antenna). Unidirectional traveling wave antennas are terminated by a resistor at one end equal to the antenna's characteristic resistance, to absorb the waves from one direction. This makes them inefficient as transmitting antennas.

- *Random wire* - This describes the typical antenna used to receive shortwave radio, consisting of a random length of wire either strung outdoors between supports or indoors in a zigzag pattern along walls, connected to the receiver at one end. Can have complex radiation patterns with several lobes at angles to the wire.
- *Beverage* - Simplest unidirectional traveling wave antenna. Consists of a straight wire one to several wavelengths long, suspended near the ground, connected to the receiver at one end and terminated by a resistor equal to its characteristic impedance, 400 to 800Ω at the other end. Its radiation pattern has a main lobe at a shallow angle in the sky off the terminated end. It is used for reception of skywaves reflected off the ionosphere in long distance "skip" shortwave communication.
- *Rhombic* - Consists of four equal wire sections shaped like a rhombus. It is fed by a balanced feedline at one of the acute corners, and the two sides are connected to a resistor equal to the characteristic resistance of the antenna at the other. It has a main lobe in a horizontal direction off the terminated end of the rhombus. Used for skywave communication on shortwave bands.
- *Helical (axial mode)* - Consists of a wire in the shape of a helix mounted above a reflecting screen. It radiates circularly polarized waves in a beam off the end, with a typical gain of 15 dBi. It is used at VHF and UHF frequencies for communication with satellites and animal tracking transmitters, which use circular polarization because it is insensitive to the relative orientation of the antennas.
- *Leaky wave* - Microwave antennas consisting of a waveguide or coaxial cable with a slot or apertures cut in it so it radiates continuously along its length.

Effect of ground

Ground reflections is one of the common types of multipath.^{[30][31][32]}

The radiation pattern and even the driving point impedance of an antenna can be influenced by the dielectric constant and especially conductivity of nearby objects. For a terrestrial antenna, the ground is usually one such object of importance. The antenna's height above the ground, as well as the electrical properties (permittivity and conductivity) of the ground, can then be important. Also, in the particular case of a monopole antenna, the ground (or an artificial ground plane) serves as the return connection for the antenna current thus having an additional effect, particularly on the impedance seen by the feed line.

When an electromagnetic wave strikes a plane surface such as the ground, part of the wave is transmitted into the ground and part of it is reflected, according to the Fresnel coefficients. If the ground is a very good conductor then almost all of the wave is reflected (180° out of phase), whereas a ground modeled as a (lossy) dielectric can absorb a large amount of the wave's power. The power remaining in the reflected wave, and the phase shift upon reflection, strongly depend on the wave's angle of incidence and polarization. The dielectric constant and conductivity (or simply the complex dielectric constant) is dependent on the soil type and is a function of frequency.

For very low frequencies to high frequencies (<30 MHz), the ground behaves as a lossy dielectric,^[33] Thus the ground is characterized both by a conductivity^[34] and permittivity (dielectric constant) which can be measured for a given soil (but is influenced by fluctuating moisture levels) or can be estimated from certain maps. At lower frequencies the ground acts mainly as a good conductor, which AM middle wave broadcast (.5 - 1.6 MHz) antennas depend on.

At frequencies between 3 and 30 MHz, a large portion of the energy from a horizontally polarized antenna reflects off the ground, with almost total reflection at the grazing angles important for ground wave propagation. That reflected wave, with its phase reversed, can either cancel or reinforce the direct wave, depending on the antenna height in wavelengths and elevation angle (for a sky wave).

On the other hand, vertically polarized radiation is not well reflected by the ground except at grazing incidence or over very highly conducting surfaces such as sea water.^[35] However the grazing angle reflection important for ground wave propagation, using vertical polarization, is *in phase* with the direct wave, providing a boost of up to 6 db, as is detailed below.

At VHF and above (>30 MHz) the ground becomes a poorer reflector. However it remains a good reflector especially for horizontal polarization and grazing angles of incidence. That is important as these higher frequencies usually depend on horizontal line-of-sight propagation (except for satellite communications), the ground then behaving almost as a mirror.

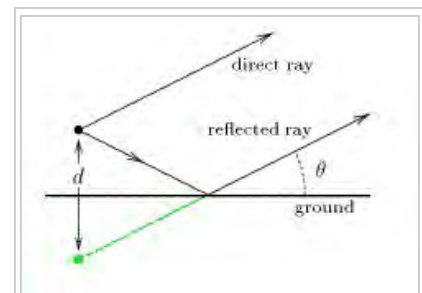
The net quality of a ground reflection depends on the topography of the surface. When the irregularities of the surface are much smaller than the wavelength, we are in the regime of specular reflection, and the receiver sees both the real antenna and an image of the antenna under the ground due to reflection. But if the ground has irregularities not small compared to the wavelength, reflections will not be coherent but shifted by random phases. With shorter wavelengths (higher frequencies), this is generally the case.

Whenever both the receiving or transmitting antenna are placed at significant heights above the ground (relative to the wavelength), waves specularly reflected by the ground will travel a longer distance than direct waves, inducing a phase shift which can sometimes be significant. When a sky wave is launched by such an antenna, that phase shift is always significant unless the antenna is very close to the ground (compared to the wavelength).

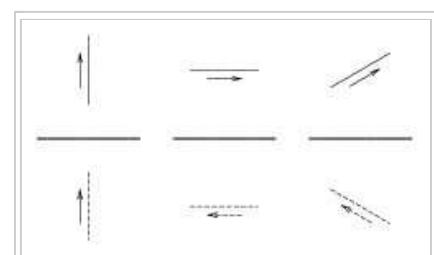
The phase of reflection of electromagnetic waves depends on the polarization of the incident wave. Given the larger refractive index of the ground (typically $n=2$) compared to air ($n=1$), the phase of horizontally polarized radiation is reversed upon reflection (a phase shift of π radians or 180°). On the other hand, the vertical component of the wave's electric field is reflected at grazing angles of incidence approximately *in phase*. These phase shifts apply as well to a ground modelled as a good electrical conductor.

This means that a receiving antenna "sees" an image of the antenna but with reversed currents. That current is in the same absolute direction as the actual antenna if the antenna is vertically oriented (and thus vertically polarized) but opposite the actual antenna if the antenna current is horizontal.

The actual antenna which is *transmitting* the original wave then also may *receive* a strong signal from its own image from the ground. This will induce an additional current in the antenna element, changing the current at the feedpoint for a given feedpoint voltage. Thus the antenna's impedance, given by the ratio of feedpoint voltage to current, is altered due to the antenna's proximity to the ground. This can be quite a significant effect when the antenna is within a wavelength or two of the ground. But as the antenna height is increased, the reduced power of the reflected wave (due to the inverse square law) allows the antenna to approach its asymptotic feedpoint impedance given by theory. At lower heights, the effect on the antenna's impedance is *very* sensitive to the exact distance from the ground, as this affects the phase of the reflected wave relative to the currents in the antenna. Changing the antenna's height by a quarter wavelength, then changes the phase of the reflection by 180° , with a completely different effect on the antenna's impedance.



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



The currents in an antenna appear as an image in *opposite* phase when reflected at grazing angles. This causes a phase reversal for waves emitted by a horizontally polarized antenna (left) but not a vertically polarized antenna (center).

The ground reflection has an important effect on the net far field radiation pattern in the vertical plane, that is, as a function of elevation angle, which is thus different between a vertically and horizontally polarized antenna. Consider an antenna at a height h above the ground, transmitting a wave considered at the elevation angle θ . For a vertically polarized transmission the magnitude of the electric field of the electromagnetic wave produced by the direct ray plus the reflected ray is:

$$|E_V| = 2 |E_0| \left| \cos\left(\frac{2\pi h}{\lambda} \sin \theta\right) \right|$$

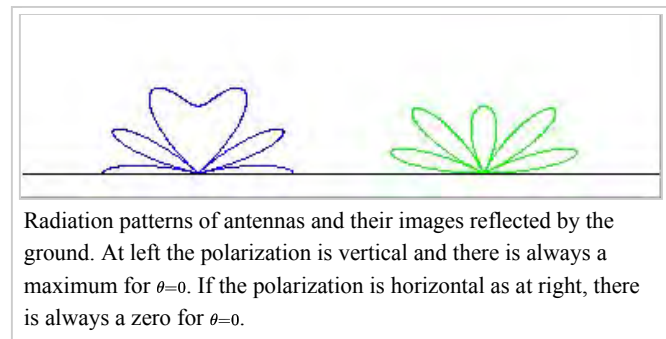
Thus the *power* received can be as high as 4 times that due to the direct wave alone (such as when $\theta=0$), following the *square* of the cosine. The sign inversion for the reflection of horizontally polarized emission instead results in:

$$|E_H| = 2 |E_0| \left| \sin\left(\frac{2\pi h}{\lambda} \sin \theta\right) \right|$$

where:

- E_0 is the electrical field that would be received by the direct wave if there were no ground.
- θ is the elevation angle of the wave being considered.
- λ is the wavelength.
- h is the height of the antenna (half the distance between the antenna and its image).

For horizontal propagation between transmitting and receiving antennas situated near the ground reasonably far from each other, the distances traveled by the direct and reflected rays are nearly the same. There is almost no relative phase shift. If the emission is polarized vertically, the two fields (direct and reflected) add and there is maximum of received signal. If the signal is polarized horizontally, the two signals subtract and the received signal is largely cancelled. The vertical plane radiation patterns are shown in the image at right. With vertical polarization there is always a maximum for $\theta=0$, horizontal propagation (left pattern). For horizontal polarization, there is cancellation at that angle.



Note that the above formulae and these plots assume the ground as a perfect conductor. These plots of the radiation pattern correspond to a distance between the antenna and its image of 2.5λ . As the antenna height is increased, the number of lobes increases as well.

The difference in the above factors for the case of $\theta=0$ is the reason that most broadcasting (transmissions intended for the public) uses vertical polarization. For receivers near the ground, horizontally polarized transmissions suffer cancellation. For best reception the receiving antennas for these signals are likewise vertically polarized. In some applications where the receiving antenna must work in any position, as in mobile phones, the base station antennas use mixed polarization, such as linear polarization at an angle (with both vertical and horizontal components) or circular polarization.

On the other hand, classical (analog) television transmissions are usually horizontally polarized, because in urban areas buildings can reflect the electromagnetic waves and create ghost images due to multipath propagation. Using horizontal polarization, ghosting is reduced because the amount of reflection of electromagnetic waves in the p polarization (horizontal polarization off the side of a building) is generally less than s (vertical, in this case) polarization. Vertically polarized analog television has nevertheless been used in some rural areas. In digital terrestrial television such reflections are less problematic, due to robustness of binary transmissions and error correction.

Mutual impedance and interaction between antennas

Current circulating in one antenna generally induces a voltage across the feedpoint of nearby antennas or antenna elements. The mathematics presented below are useful in analyzing the electrical behaviour of antenna arrays, where the properties of the individual array elements (such as half wave dipoles) are already known. If those elements were widely separated and driven in a certain amplitude and phase, then each would act independently as that element is known to. However, because of the mutual interaction between their electric and magnetic fields due to proximity, the currents in each element are *not* simply a function of the applied voltage (according to its driving point impedance), but depend on the currents in the other nearby elements. Note

that this now is a near field phenomenon which could not be properly accounted for using the Friis transmission equation for instance. This near field effect creates a different set of currents at the antenna terminals resulting in distortions in the far field radiation patterns; however, the distortions may be removed using a simple set of network equations.^[36]

The elements' feedpoint currents and voltages can be related to each other using the concept of **mutual impedance** Z_{ji} between every pair of antennas just as the mutual impedance $j\omega M$ describes the voltage induced in one inductor by a current through a nearby coil coupled to it through a mutual inductance M . The mutual impedance Z_{21} between two antennas is defined^[37] as:

$$Z_{ji} = \frac{v_j}{i_i}$$

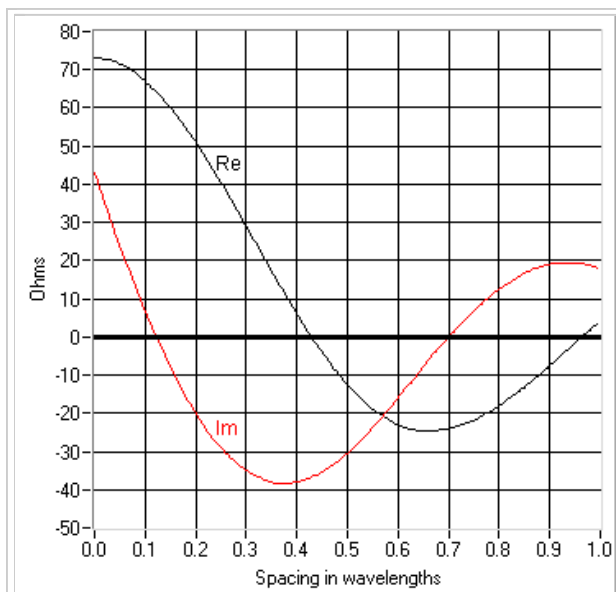
where i_i is the current flowing in antenna i and v_j is the voltage induced at the open-circuited feedpoint of antenna j due to i_1 when all other currents i_k are zero. The mutual impedances can be viewed as the elements of a symmetric square impedance matrix \mathbf{Z} . Note that the diagonal elements, $Z_{ii} = \frac{v_i}{i_i}$, are simply the driving point impedances of each element.

Using this definition, the voltages present at the feedpoints of a set of coupled antennas can be expressed as the multiplication of the impedance matrix times the vector of currents. Written out as discrete equations, that means:

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

where:

- v_i is the voltage at the terminals of antenna i
- i_i is the current flowing between the terminals of antenna i
- Z_{ii} is the driving point impedance of antenna i
- Z_{ij} is the mutual impedance between antennas i and j .



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

As is the case for mutual inductances,

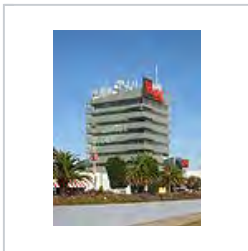
$$Z_{ij} = Z_{ji}.$$

This is a consequence of Lorentz reciprocity. For an antenna element i not connected to anything (open circuited) one can write $i_i = 0$. But for an element i which is short circuited, a current is generated across that short but no voltage is allowed, so the corresponding $v_i = 0$. This is the case, for instance, with the so-called parasitic elements of a Yagi-Uda antenna where the solid rod can be viewed as a dipole antenna shorted across its feedpoint. Parasitic elements are unpowered elements that absorb and reradiate RF energy according to the induced current calculated using such a system of equations.

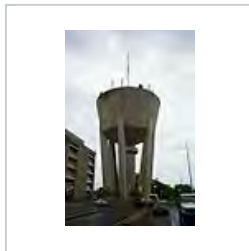
With a particular geometry, it is possible for the mutual impedance between nearby antennas to be zero. This is the case, for instance, between the crossed dipoles used in the turnstile antenna.

Gallery

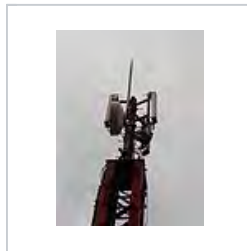
Antennas and supporting structures



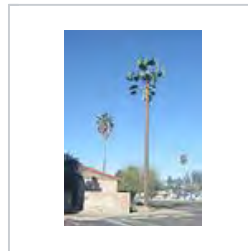
A building rooftop supporting numerous dish and sectored mobile telecommunications antennas (Doncaster, Victoria, Australia).



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

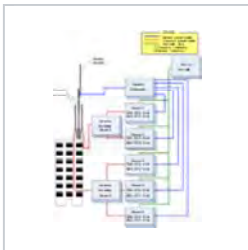


A three-sector telephone site in Mexico City.

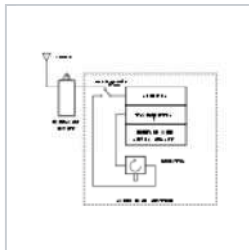


Telephone site concealed as a palm tree.

Diagrams as part of a system



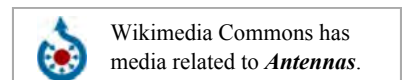
Antennas may be connected through a multiplexing arrangement in some applications like this trunked two-way radio example.



Antenna network for an emergency medical services base station.

See also

- Category:Radio frequency antenna types
- Category:Radio frequency propagation



- Cellular repeater
- DXing
- Electromagnetism
- Mobile broadband modem
- Numerical Electromagnetics Code
- Radial (radio)
- Radio masts and towers
- RF connector
- Smart antenna
- TETRA

References

1. Graf, Rudolf F. (1999). *Modern Dictionary of Electronics*. Newnes. p. 29. ISBN 0750698667.
2. In the context of electrical engineering and physics, the plural of *antenna* is *antennas*, and it has been this way since about 1950 (or earlier), when a cornerstone textbook in this field, *Antennas*, was published by the physicist and electrical engineer John D. Kraus of The Ohio State University. Besides in the title, Dr. Kraus noted this in a footnote on the first page of his book. Insects may have "antennae", but this form is not used in the context of electronics or physics.
3. For example <http://www.telegraph.co.uk/science/science-news/7810454/British-scientists-launch-major-radio-telescope.html>; <http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf09377.html>; "Archived copy". Archived from the original on 2013-10-20. Retrieved 2013-10-19.
4. "IEEE Transactions on Antennas and Propagation".
5. Marconi, "Wireless Telegraphic Communication: Nobel Lecture, 11 December 1909. (http://nobelprize.org/nobel_prizes/physics/laureates/1909/marconi-lecture.html)" Nobel Lectures. Physics 1901–1921. Amsterdam: Elsevier Publishing Company, 1967: 196–222. p. 206.
6. "The Nobel Prize in Physics 1909".
7. Slyusar, Vadym (20–23 September 2011). "To history of radio engineering's term "antenna" " (PDF). *VIII International Conference on Antenna Theory and Techniques (ICATT'11)*. Kyiv, Ukraine. pp. 83–85.
8. Slyusar, Vadym (21–24 February 2012). "An Italian period on the history of radio engineering's term "antenna" " (PDF). *11th International Conference Modern Problems of Radio Engineering, Telecommunications and Computer Science (TCSET'2012)*. Lviv-Slavske, Ukraine. p. 174.
9. Slyusar, Vadym (June 2011). "Антенна: история радиотехнического термина" [The Antenna: A History of Radio Engineering's Term] (PDF). *ПЕРВАЯ МИЛЛИЯ Last mile: Electronics: Science, Technology, Business* (in Russian). ? (6): 52–64.
10. Schantz, Hans Gregory (2003), "Introduction to ultra-wideband antennas" (PDF), *Proceedings of the 2003 IEEE UWBST Conference*.
11. "Media Advisory: Apply Now to Attend the ALMA Observatory Inauguration". *ESO Announcement*. Retrieved 4 December 2012.
12. Carl Smith (1969). *Standard Broadcast Antenna Systems*, p. 2-1212. Cleveland, Ohio: Smith Electronics, Inc.
13. Lonngren, Karl Erik; Savov, Sava V.; Jost, Randy J. (2007). *Fundamentals of Electromagnetics With Matlab, 2nd Ed.* SciTech Publishing. p. 451. ISBN 1891121588.
14. Stutzman, Warren L.; Thiele, Gary A. (2012). *Antenna Theory and Design, 3rd Ed.* John Wiley & Sons. pp. 560–564. ISBN 0470576642.
15. Hall, Gerald (1991). *The ARRL Antenna Book (15th edition)*. ARRL. p. 24. ISBN 0-87259-206-5.
16. Hall 1991, p. 25.
17. Hall 1991, pp. 31-32.
18. Impedance is caused by the same physics as refractive index in optics, although impedance effects are typically one-dimensional, where effects of refractive index is three-dimensional.
19. Bevelaqua, Peter J. "Types of Antennas". *Antenna Theory*. Antenna-theory.com Peter Bevelaqua's private website. Retrieved June 28, 2015.
20. Aksoy, Serkan (2008). "Antennas" (PDF). *Lecture Notes-v.1.3.4*. Electrical Engineering Dept., Gebze Technical University, Gebze, Turkey. Retrieved June 29, 2015.
21. Balanis, Constantine A. (2005). *Antenna Theory: Analysis and Design*. **1** (3rd ed.). John Wiley and Sons. p. 4. ISBN 047166782X.
22. Bevelaqua, *Dipole Antenna*, Antenna-Theory.com (<http://www.antenna-theory.com/antennas/dipole.php>)
23. Bevelaqua, *Monopole Antenna*, Antenna-Theory.com (<http://www.antenna-theory.com/antennas/monopole.php>)
24. Bevelaqua, *Antenna Arrays*, Antenna-Theory.com (<http://www.antenna-theory.com/arrays/main.php>)
25. Balanis 2005, pp. 283–371
26. Bevelaqua, *Loop Antennas*, Antenna-Theory.com (<http://www.antenna-theory.com/antennas/smallLoop.php>)
27. Balanis 2005, pp. 231–275
28. Balanis 2005, pp. 653–728
29. Balanis 2005, pp. 549–602
30. *Fixed Broadband Wireless System Design* (<https://books.google.com/books?id=M8NOGnp2IRwC&pg=PA130>), p. 130, at Google Books
31. *Monopole Antennas* (https://books.google.com/books?id=62_WpVcU8GIC&pg=PA340), p. 340, at Google Books
32. *Wireless and Mobile Communication* (<https://books.google.com/books?id=rKVq0C5jsX8C&pg=PA37>), p. 37, at Google Books

33. Silver, H. Ward, ed. (2011). *ARRL Antenna Book*. Newington, Connecticut: American Radio Relay League. p. 3-2. ISBN 978-0-87259-694-8.
34. <http://www.fcc.gov/encyclopedia/m3-map-effective-ground-conductivity-united-states-wall-sized-map-am-broadcast-stations>
35. Silver 2011, p. 3-23
36. Chakravorty, Pragnan; Mandal, Durbadal (2016). "Radiation Pattern Correction in Mutually Coupled Antenna Arrays Using Parametric Assimilation Technique". *IEEE Transactions on Antennas and Propagation*. **PP** (99): 1–1. doi:10.1109/TAP.2016.2578307. ISSN 0018-926X.
37. Kai Fong Lee (1984). *Principles of Antenna Theory*. John Wiley and Sons Ltd. ISBN 0-471-90167-9.

Further reading

General

- Antenna Theory (3rd edition), by C. Balanis, Wiley, 2005, ISBN 0-471-66782-X;
- Antenna Theory and Design (2nd edition), by W. Stutzman and G. Thiele, Wiley, 1997, ISBN 0-471-02590-9;
- Antennas (4th edition), by J. Kraus and R. Marhefka, McGraw-Hill, 2001, ISBN 0-07-232103-2;
- Antennenbuch, by Karl Rothammel, publ. Franck'sche Verlagshandlung Stuttgart, 1991, ISBN 3-440-05853-0; other editions (<http://www.worldcat.org/oclc/65969707?tab=editions>) (in German)
- Antennas for portable Devices (<http://www1.i2r.a-star.edu.sg/~chenzn>), Zhi Ning Chen (edited), John Wiley & Sons in March 2007
- Broadband Planar Antennas: Design and Applications, Zhi Ning Chen and M. Y. W. Chia, John Wiley & Sons in February 2006

Practical design

- *Antenna Theory* antenna-theory.com (<http://www.antenna-theory.com>)
- *Antennas* Antenna types (<http://www.dxzone.com/catalog/Antennas/>)
- *Patch Antenna: From Simulation to Realization* EM Talk (http://www.emtalk.com/mwt_mpa.htm)
- *Why Antennas Radiate*, Stuart G. Downs, WY6EE (<http://www.arrl.org/files/file/QEX%20Binaries/0105downs.pdf>) (PDF)
- *Understanding electromagnetic fields and antenna radiation takes (almost) no math*, Ron Schmitt, EDN Magazine, March 2 2000 (<http://www.classicstela.com/download/emfields.pdf>) (PDF)
- *Antennas: Generalities, Principle of operation, As electronic component, Hertz Marconi and Other types Antennas etc etc* (http://www.ilmondodeltelecomunicazioni.it/argomento.php?id_lezione=45&lang=en)

Theory and simulations

- AN-SOF, "Antenna Simulation Software (https://web.archive.org/web/20120304222913/http://www.antennasoftware.com.ar:80/1_5_PRODUCTS.html)". Program system for the modeling of antennas and scatterers.
- <http://www.dipoleanimator.com>
- EM Talk, "Microstrip Patch Antenna (http://www.emtalk.com/tut_1.htm)", (Theory and simulation of microstrip patch antenna)
- "[1] (<http://www.jampro.com/calculatorsconverters.html>)" Formulas for simulating and optimizing Antenna specs and placement
- "Microwave Antenna Design Calculator (<https://web.archive.org/web/20080829160009/http://www.q-par.com/capabilities/software/microwave-antenna-design-calculator>)" Provides quick estimation of antenna size required for a given gain and frequency. 3 dB and 10 dB beamwidths are also derived; the calculator additionally gives the far-field range required for a given antenna.
- Sophocles J. Orfanidis, "Electromagnetic Waves and Antennas (<http://www.ece.rutgers.edu/~orfanidi/ewa/>)", Rutgers University (20 PDF Chaps. Basic theory, definitions and reference)
- Hans Lohninger, "Learning by Simulations: Physics: Coupled Radiators (http://www.vias.org/simulations/simusoftware_twoaerials.html)". vias.org, 2005. (ed. Interactive simulation of two coupled antennas)
- NEC Lab (<http://www.ingenierias.ugto.mx/profesores/sledesma/documentos/index.htm>) - NEC Lab is a tool that uses Numerical Electromagnetics Code and Artificial Intelligence to design and simulate antennas.
- Justin Smith "Aerials (<http://www.aerialsandtv.com/aerials.html>)". A.T.V (Aerials and Television), 2009. (ed. Article on the (basic) theory and use of FM, DAB & TV aerials)

- Antennas Research Group, "Virtual (Reality) Antennas (<http://www.antennas.gr>)". Democritus University of Thrace, 2005.
- "Support > Knowledgebase > RF Basics > Antennas / Cables > dBi vs. dBd detail (<http://www.maxstream.net/helpdesk/article-27>)". MaxStream, Inc., 2005. (ed. How to measure antenna gain) (New location: <http://www.digi.com/support/kbase/kbaseresultdetl?id=2146> Note: to skip the registration form click the link below it)
- Yagis and Log Periodics, Astrosurf article. (<http://www.astrosurf.com/luxorion/qs1-antenna4.htm>)
- Raines, J. K., "Virtual Outer Conductor for Linear Antennas," Microwave Journal, Vol. 52, No. 1, January, 2009, pp. 76–86
- Tests of FM/VHF receiving antennas. (<http://www.aerialsandtv.com/fmanddabradio.html#FMandDABaerialTests>)

Effect of ground


- Electronic Radio and Engineering. F.E. Terman. McGraw-Hill
- Lectures on physics. Feynman, Leighton and Sands. Addison-Wesley
- Classical Electricity and Magnetism. W. Panofsky and M. Phillips. Addison-Wesley

Patents and USPTO

- CLASS 343 (<http://www.uspto.gov/go/classification/uspc343/defs343.htm>), Communication: Radio Wave Antenna

Base station

- Antennas for Base Stations in Wireless Communications, edited by Zhi Ning Chen and Kwai-Man Luk, McGraw-Hill Companies, Inc, USA in May 2009

 The dictionary definition of antenna at Wiktionary

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Categories: Antennas (radio) | Radio electronics

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