# Practical Antennas and Transmission Lines

The Abdus Salam
International Centre
for Theoretical Physics



This talk covers antenna properties, transmission line characteristics, radio cable connectors and adapters, and shows examples of different kinds of commercial and do-it-yourself antennas.

# Goals

Antennas are the interface between guided waves (from a cable) and unguided waves (in space).

- To understand the various properties of antennas, so as to be able to choose the proper antenna for a particular application.
- Realize that not all kinds of cable are appropriate for use with wireless systems.
- Identify different kinds of cable connectors and understand when each kind is needed.





Antennas are very important for the overall wireless system performance, and there are many different types. It is crucial to understand the effect of their features to optimize the performance of the wireless system.

Transmission lines must couple the radio to the antenna introducing as little attenuation as possible.

# Transmission lines & antennas

- A ***transmission line*** is the device used to guide radio frequency (RF) energy from one point to another (for example a coaxial cable).
- An ***antenna*** is the structure associated with the region of transition from a guided wave to a free space wave, radiating RF energy.





Think of antennas as an interface between the guided wave in the transmission line and the unguided wave in space.

Antennas are passive devices. They cannot add power, they only focus it in a particular area.

# Bifilar transmission lines

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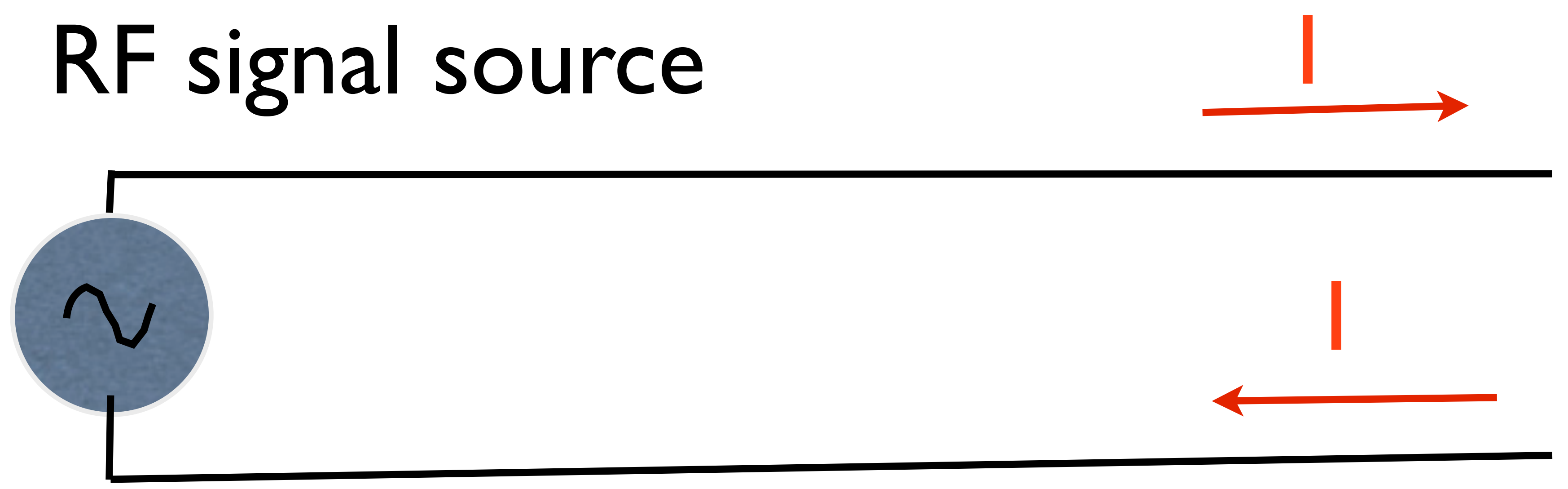
- ***Bifilar transmission lines*** are formed by two conducting wires separated by a dielectric. There can be an alternating current even in an open ended transmission line.





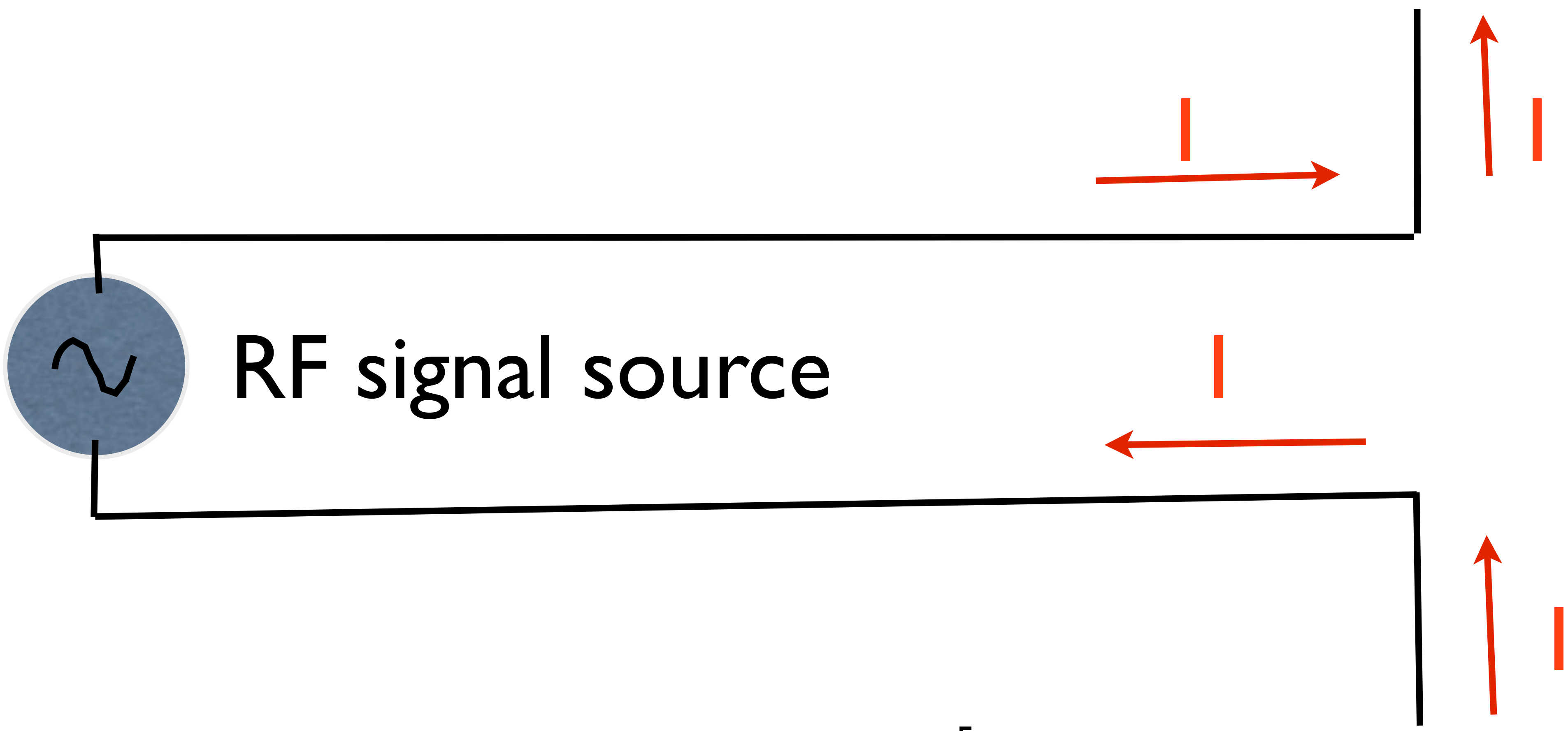



***Bifilar transmission lines*** are formed by two conducting wires separated by a dielectric. The dielectric can be air or a plastic like the one used for flat transmission lines used in TV antennas. A bifilar transmission line open at one end will not radiate because the current I in each wire has the same value but opposite direction, so the field they create on any given point at some distance from the line cancel.

Note that although the line is open, there is still a current because since we are applying a sinusoidal alternating voltage, electrons will simply change direction at the open end.

Since the two conductors are close, the field they create at some distance will be essentially equal in magnitude but opposed in phase, so they will cancel.
Nevertheless any metallic object near the the line will disturb this field cancellation and this is the reason why this type of line is rarely used.

# Bifilar transmission lines

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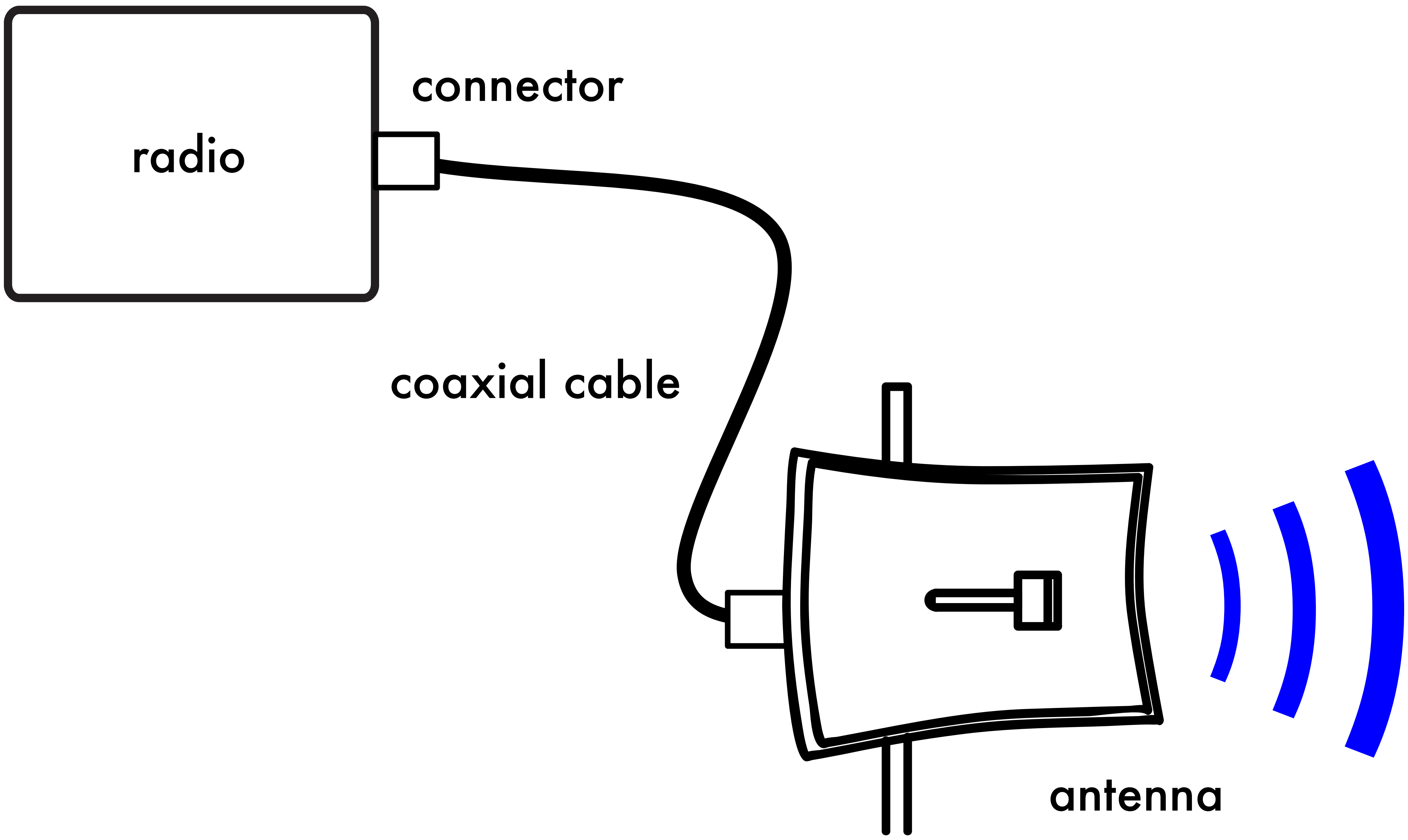
The length of the bent portion of the transmission line  will determine the antenna feature. If this length is chosen as a quarter of a wavelength we will have a half wave dipole antenna with a gain of 2.15 dBi.

This idea can be very easily demonstrated by using a piece of bifilar line commonly used for TV reception. Determine the wavelength of a local TV channel and  cut the plastic separating  the ending two pieces. Hold them in position with two isolators (a string will do) and attach the other end to the antenna connector of a TV receiver.  You should get a much stronger signal displayed. Experiment with a  TV Channel that it is not too strong in your area so that the effect of the antenna will be more noticeable.

Notice that we have just used the principle of reciprocity of every antenna.  For reception the signal source has been replaced by the signal sink, or in radio terminology, the transmitter has been replaced by the receiver.

# Wireless system connections





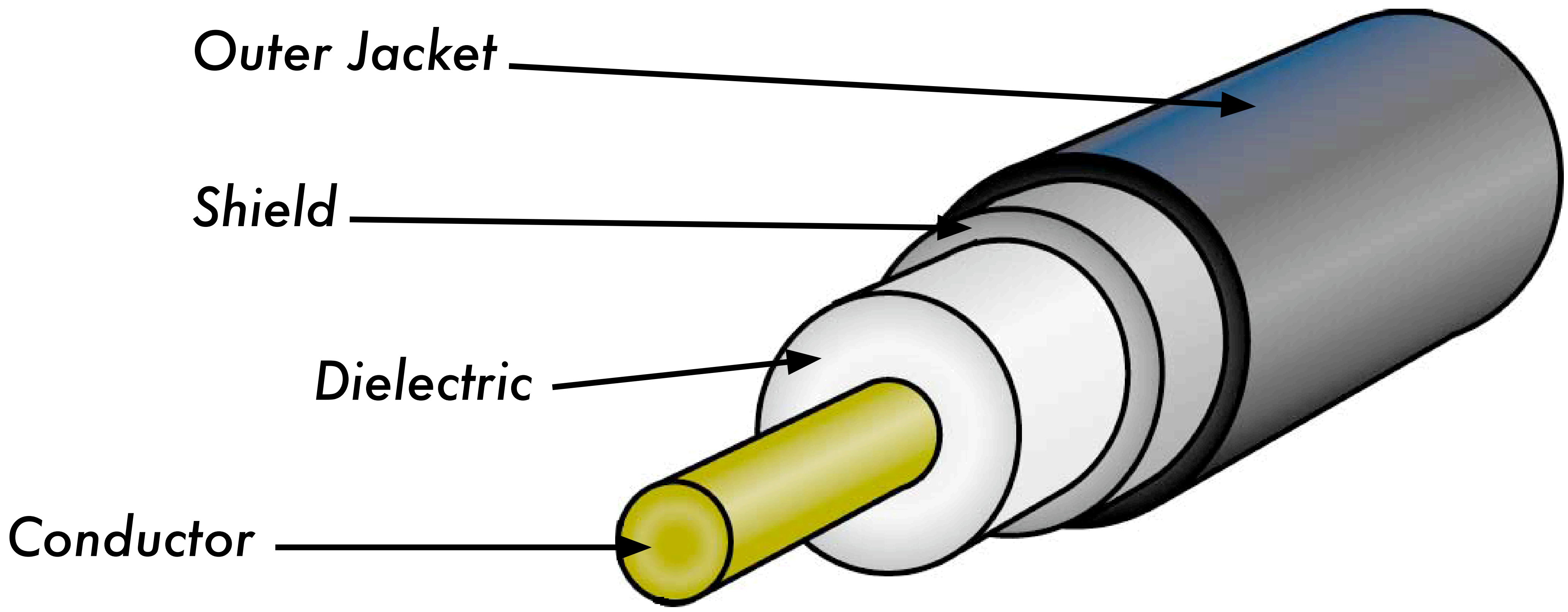



A wireless station consists of a radio that works as a transmitter, receiver, or often as both. A radio that both transmits and also receives is also called a transceiver.

The radio attaches to an antenna by means of a cable with connectors. Although the cable ore common to use a coaxial cable.There are a variety of connectors in use, of different sizes, mechanical and electrical properties.The connector must be appropriate for the radio and the cable. Sometimes adapters are required to interface different types of connectors.

A coaxial cable carries the signal from the radio to the antenna and vice-versa.The antenna couples the signal from the cable to the free space for transmission, and the other way around for reception.

# Coaxial transmission lines

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***Coaxial transmission lines*** (or ***coax*** for short) have a core conductor wire surrounded by a non-conductive material called dielectric. The dielectric is then surrounded by shielding made of braided wire or solid tubing. The shield is protected by a tough outer jacket, usually made of PVC.

Cables are not perfect conductors. Some amount of signal passing through a transmission cable will always be lost. This fading is known as attenuation, and for transmission lines it is measured in decibels per meter (dB/m). The rate of attenuation is a function of the signal frequency and the physical construction of the cable itself. As the signal frequency increases, so does its attenuation.

The thicker the cable, the less it attenuates (a bigger pipe has smaller losses).

The quality of the dielectric affects the attenuation, as does the type of shielding . The shielding is often a braid, for flexibility and ease of installation, but this introduces some losses.

Low loss RF cables are rigid. A very flexible cable like RG8 will have great losses at frequencies above 2GHz.

To minimize attenuation, use the shortest practical transmission line made from the best possible cable. Always use cable designed for microwave frequencies (such as LMR or Heliax). Avoid common cables such as RG-58 and RG-213, as these are extremely lossy at microwave frequencies.
You can avoid the RF cable losses altogether by attaching the antenna directly to the radio. This means installing the radio outside and feeding it by means of a data cable, which will exhibit much lower losses because it operates at lower frequencies.

# Coaxial transmission lines

The loss (or ***attenuation***) of a coaxial cable depends on the construction of the cable and the operating frequency. The total amount of loss is proportional to the length of the cable.

| Cable Type | Diameter | Attenuation @ 2.4 GHz | Attenuation @ 5.3 GHz |
|---|---|---|---|
| RG-58 | 4.95 mm | 0.846 dB/m | 1.472 dB/m |
| RG-213 | 10.29 mm | 0.475 dB/m | 0.829 dB/m |
| LMR-400 | 10.29 mm | 0.217 dB/m | 0.341 dB/m |
| LDF4-50A | 16 mm | 0.118 dB/m | 0.187 dB/m |

*http://www.ocarc.ca/coax.htm*



Always avoid RG-58. It is intended for thin Ethernet networking, CB or VHF radio, not for microwave.

Always avoid RG-213. It is intended for CB and HF radio. In this case the cable diameter does not imply a high quality, or low attenuation.

Whenever possible, use LMR-400 (or thicker) or Heliax (LDF, also called foam core).

# Impedance

All materials will oppose the flow of an alternating current to some extent. This opposition is called ***impedance***, and is analogous to resistance in DC circuits.

Most commercial communication antennas have an impedance of 50 ohms, while TV antennas and cables are usually 75 ohms.

Make sure that the characteristic impedance of the cable between the radio and the antenna is 50 ohms. Any mismatch will cause undesired reflections and power loss.





Impedance is often represented by the letter Z, and in general it is a complex quantity formed by a resistance **R** and a reactance **X.**

The impedance is the ratio between the voltage and the current in a given element.

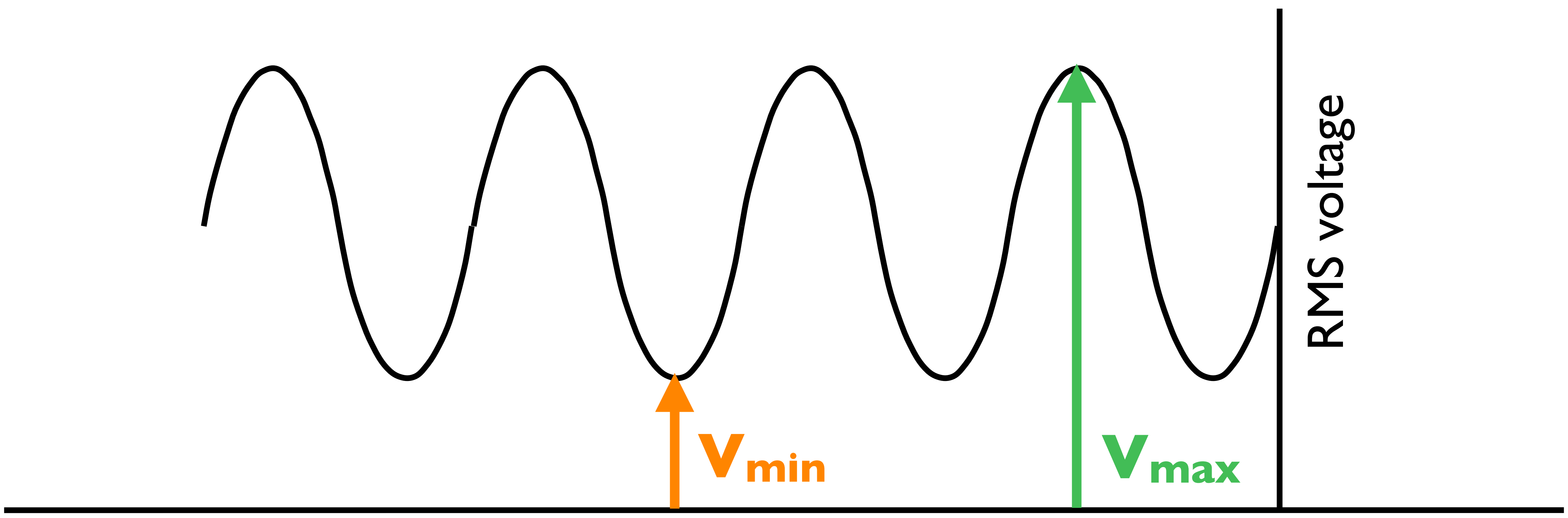
**Z = V/I**

Reflections build up in the transmission line or waveguide as stationary wave with peaks and troughs.

Communication antennas have 50 ohm impedance.

# Reflections and VSWR

Impedance mismatch causes reflections and increased VSWR.




$$\text{Voltage Standing Wave Ratio VSWR} = \frac{V_{max}}{V_{min}}$$



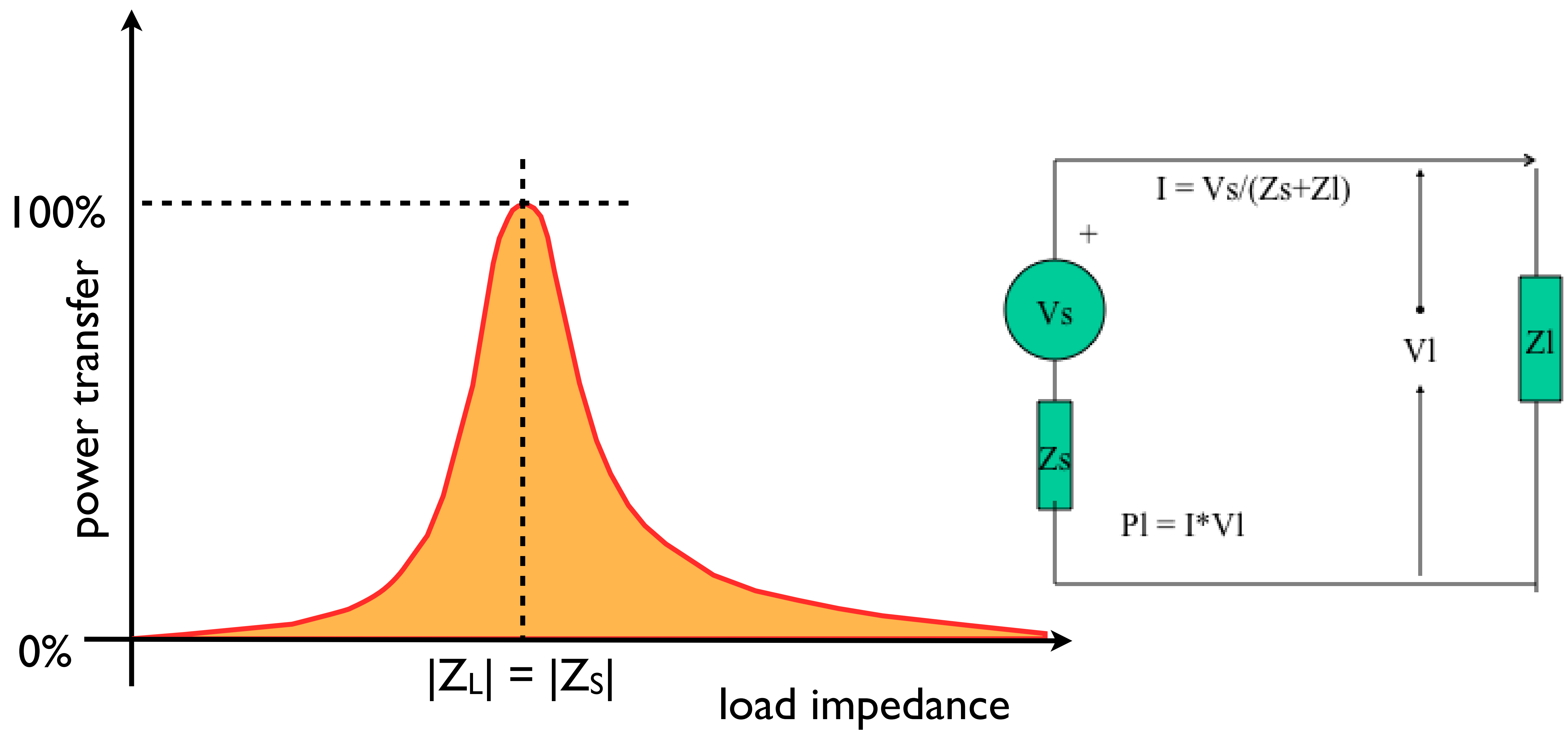


Input impedance is defined as the impedance presented by the antenna at its terminals or the ratio of the voltage to current at its terminals. If the antenna is perfectly matched to the transmission line (impedance presented by the antenna is the same as the characteristic impedance of the transmission line), then all the energy that reaches the antenna is radiated. If the two are not matched, the antenna will not accept all the power from the transmission line. The part it does not accept is reflected back and forth between the transmitter and the antenna. This sets up a fixed wave pattern along the line which we can measure and which is called the **voltage standing wave ratio (VSWR).**

The minimum value of the VSWR is 1, which is achieved in a perfect transmission line that will transfer all of the signal power to the antenna with zero reflection Vmax=Vmin.

In practice a good system will have VSWR < 1.5

# Matched impedance = maximum power transfer

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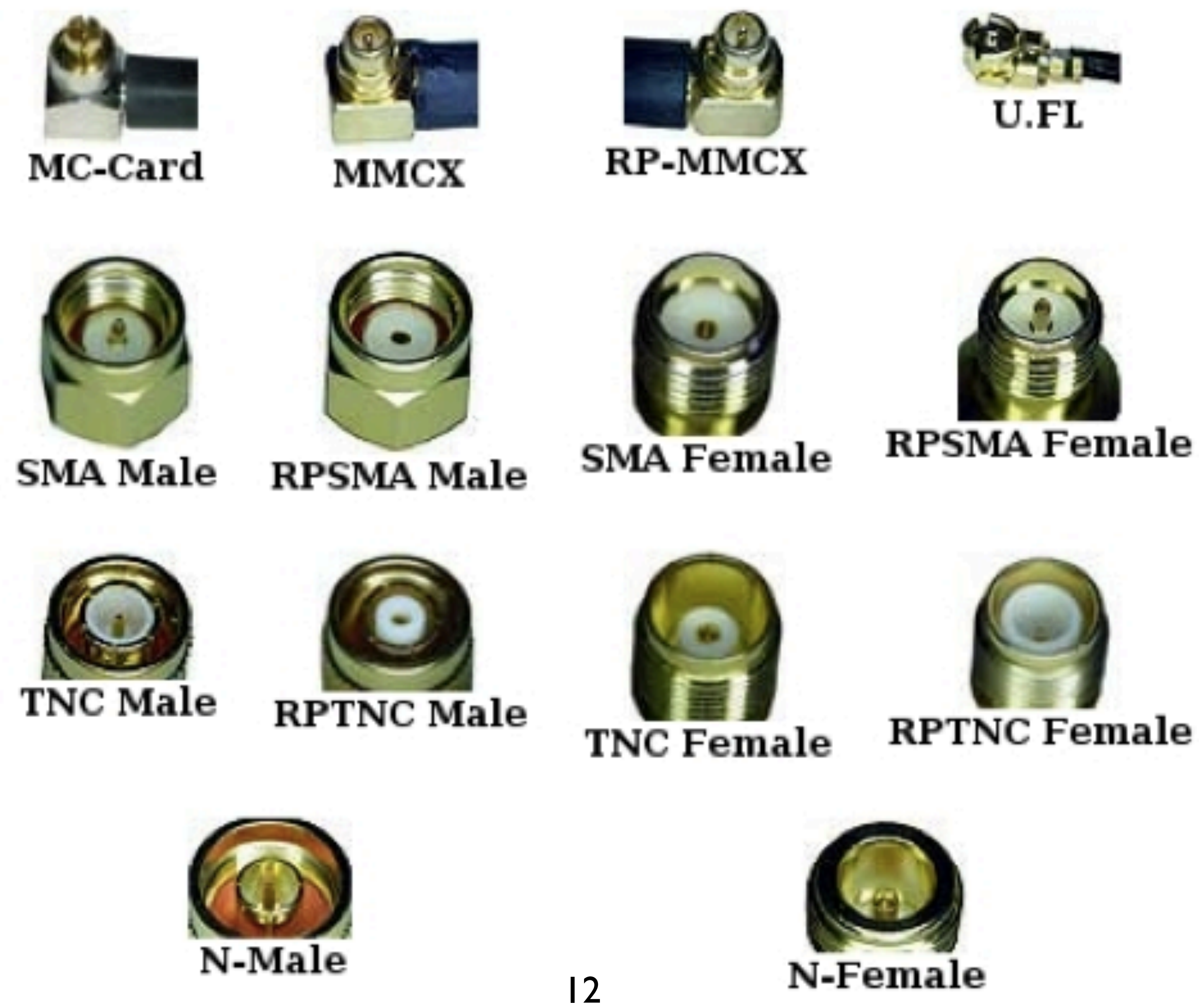
Electrical power is voltage times current. At a short circuit (zero impedance), current is maximum but voltage is zero, so you have zero power. An open circuit (infinite impedance) will yield the maximum voltage, but the current is zero, so you have zero power. The maximum power will therefore be obtained between those two limits, and from circuit on the right, it can be shown that it will happen when the input impedance is the complex conjugate of the transmission line characteristic impedance.

Z = R +jX, The impedance has a real part which is the resistance (R) and an imaginary part which is the reactance (X). The reactance could be zero in particular cases, but in general it is positive for inductive loads and negative for capacitive loads.

# Connectors

Connectors come in a huge variety of shapes and sizes. In addition to standard types, connectors may be ***reverse polarity*** (genders swapped) or ***reverse threaded***.








The US Federal Commission of Communications (FCC) discourages the user connectable antennas, for fear that they would cause interference to other users. For this reason, they require the use of non-standard connectors in consumer radios. That is the reason of proliferation of reverse polarity, reverse thread and other differentiating features in connectors.

The other reason is size. One cannot accommodate an N connector in a PCCARD or mini-PCI card. Pigtails are used for the transformation from the N connector, which is a standard for antennas, to a small size connector on the radio side. The pigtail also relieves the mechanical stress that a thick coaxial cable would impose on the radio.

# Adapters & Pigtails

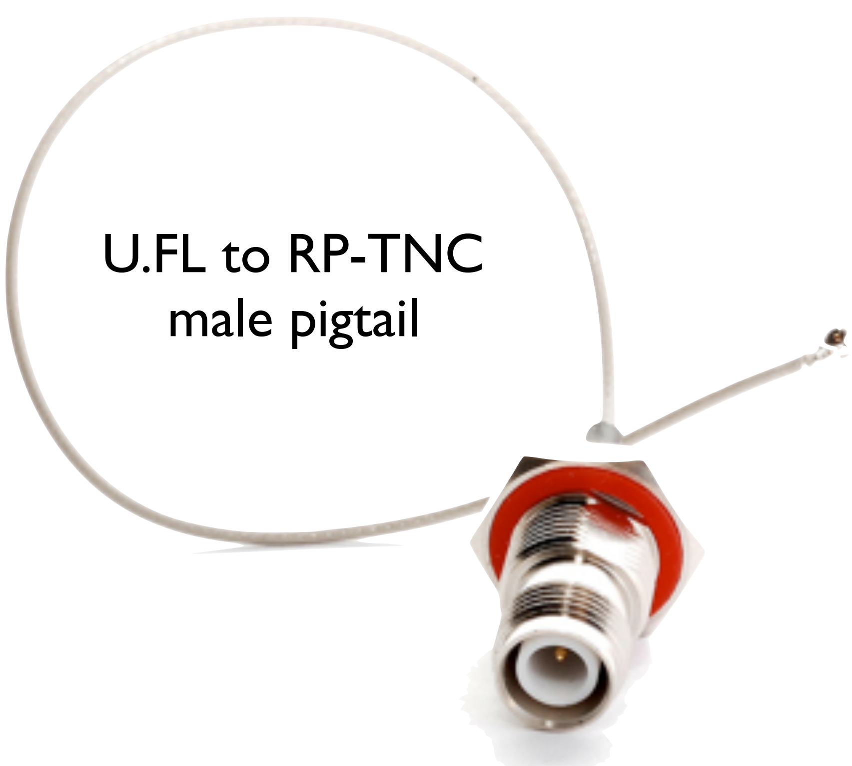
Adapters and pigtails are used to interconnect different kinds of cable or devices.

SMA female to N male

N male to N male

N female to N female

SMA male to TNC male



U.FL to RP-TNC male pigtail

U.FL to N male pigtail

SMA male to N female





A pigtail is a flexible cable that is used to reduce the mechanical strain that a rigid cable would impose in the small connector used in many modern radios.

There are many kinds of adapters and pigtails available. They are typically used to match cables of different sizes, or to mate components with incompatible connectors. Adapters are used to match the gender, polarity and thread orientation of connecter.

But rather than rely on adapters, it is best to purchase commercial cables terminated with the proper connector whenever possible. This helps to avoid the point of potential failure and signal loss introduced by the adapter.

# Theory: isotropic antennas

An ***isotropic antenna*** radiates the energy fed into it equally in every direction in space. It is only an ideal model and cannot be built.

Real-world antennas are characterized by their ability to radiate more strongly in some directions than in others; this is called ***directivity***.

When taking the efficiency of the antenna into account, this preference for a direction of radiation is referred to as ***gain***.





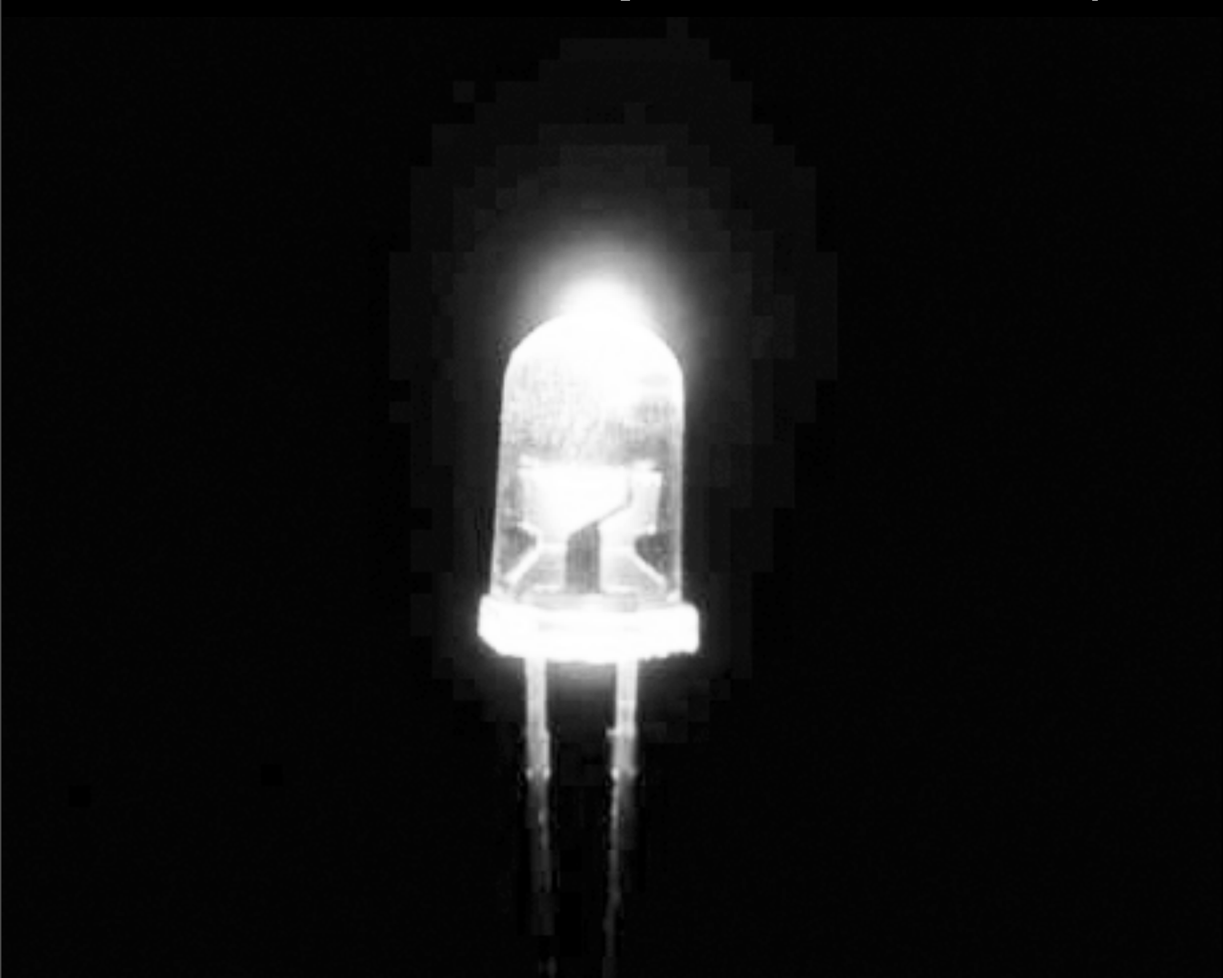
An isotropic radiator is an idealized model of an antenna that radiates power equally in all directions. By comparing the operating characteristics of real-world antennas to the isotropic model, we have a meaningful unit that can allow us to compare different kinds of antennas.

An approximation of an isotropic source is a lightbulb that will shed light in **almost** all directions with the same intensity. Another approximate example of an isotropic radiator would be the sun, or a star.

# dBi

Antennas do not add power. They direct available power in a particular direction.

The gain of an antenna is measured in ***dBi*** (decibels relative to an isotropic radiator).





The directivity of an antenna is simply the ratio of the maximum power density to the average power density.

To express the directivity in dBi (that is, dB relative to an isotropic radiator), find the common log of this ratio and multiply it by ten.

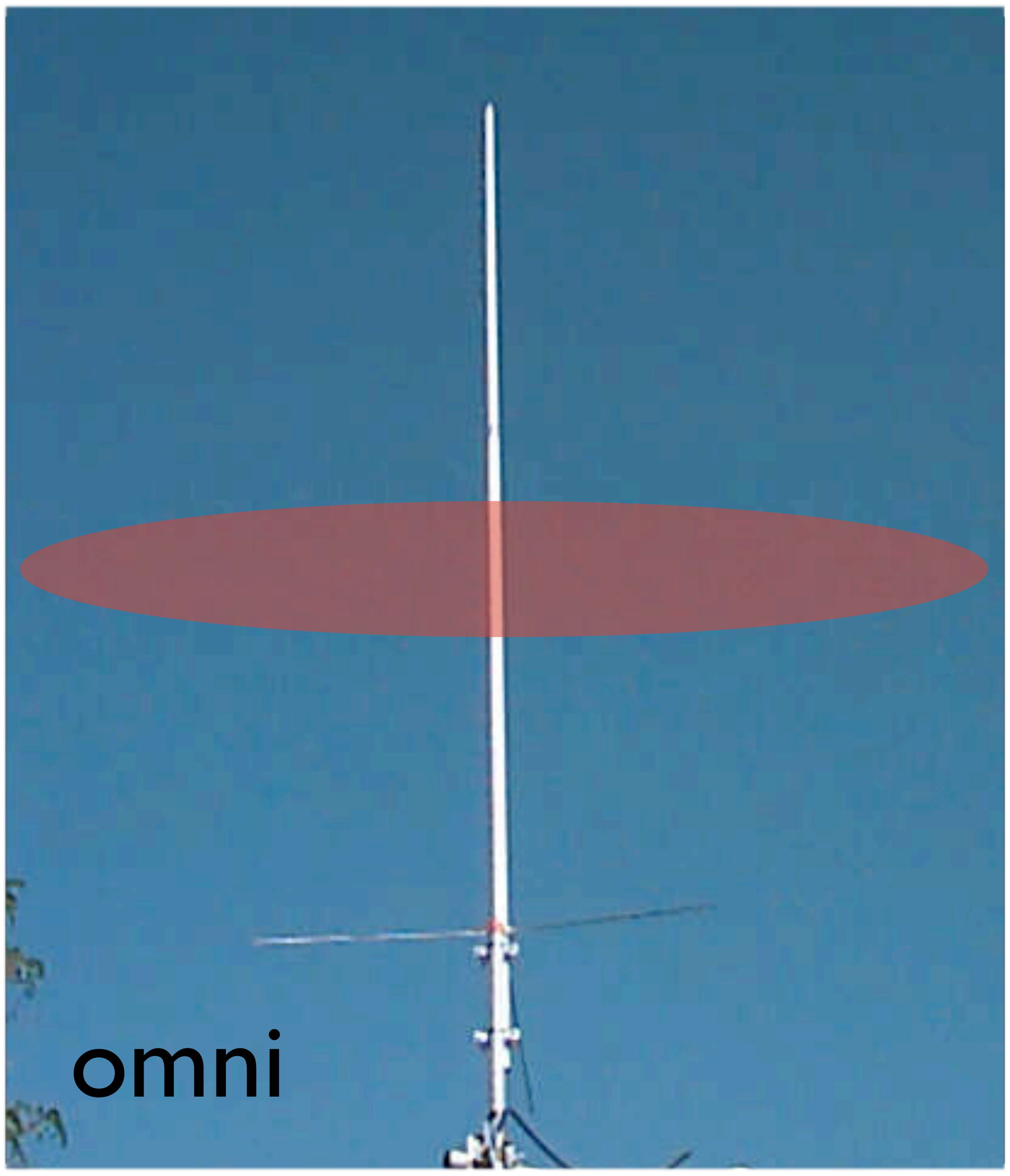
$$D[dBi] = 10\log_{10} (P_{max} / P_{av})$$

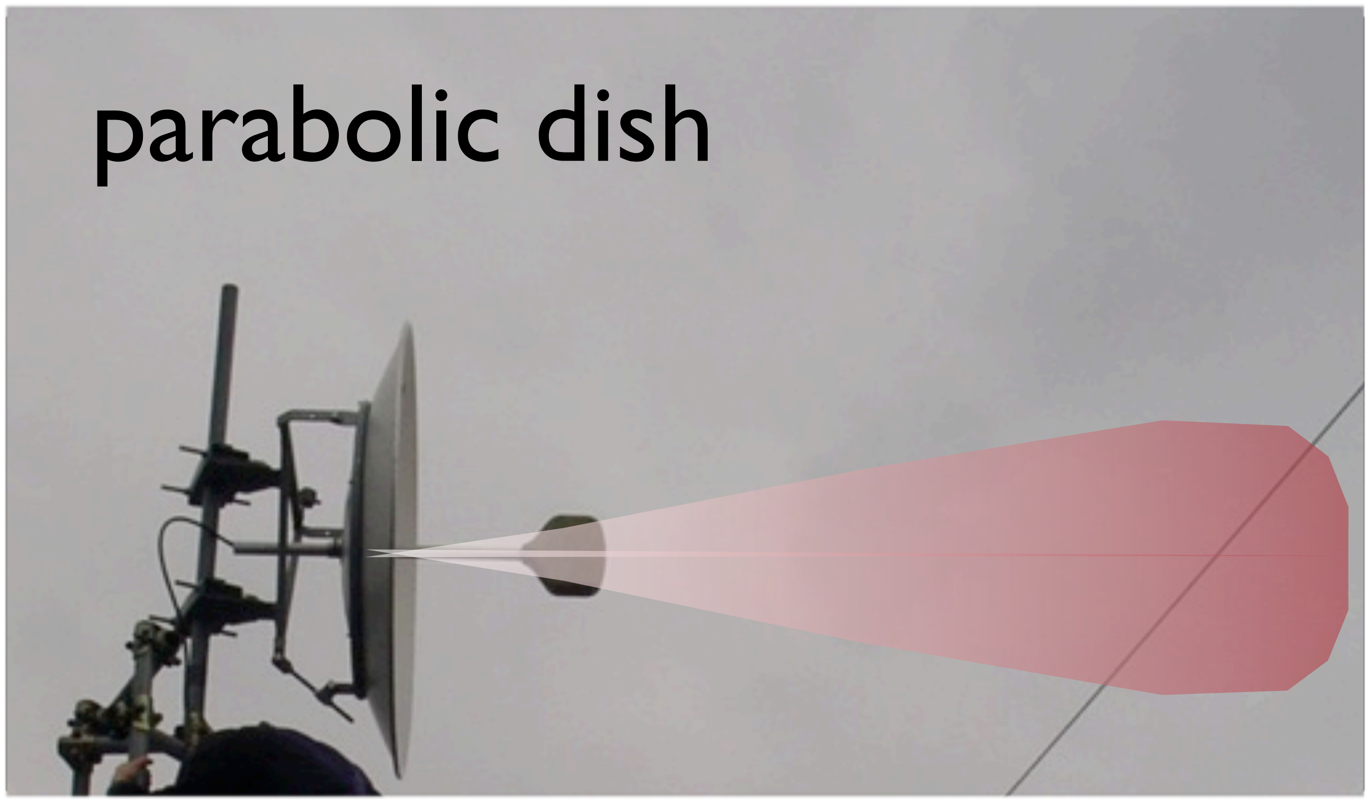
The gain is closely related to directivity: in this case you have to take into account the efficiency η of the antenna:

$$G[dBi] = 10\log_{10} \eta(P_{max} / P_{av})$$

Typical efficiency is between 0.5 and 0.9, depending on the quality of the construction and the conductivity of the metal used.

# Directional vs. Omnidirectional








Commercial antennas are generally classified in two groups, ***omnidirectional*** antennas and ***directional*** antennas.

Omnidirectional antennas (or ***omni*** for short) transmit with the same power in every direction of the horizontal plane, at the expense of reduced radiation in the vertical plane. Directional antennas focus most of the radiation in a specific direction at the expense of all others.

# Antenna features

When buying an antenna, what features are important to consider?

- Usable frequency range (bandwidth)
- Radiation pattern (beamwidth, sidelobes, backlobe, front-to-back ratio, location of nulls)
- Maximum gain
- Input impedance
- Physical size and wind resistance
- Cost





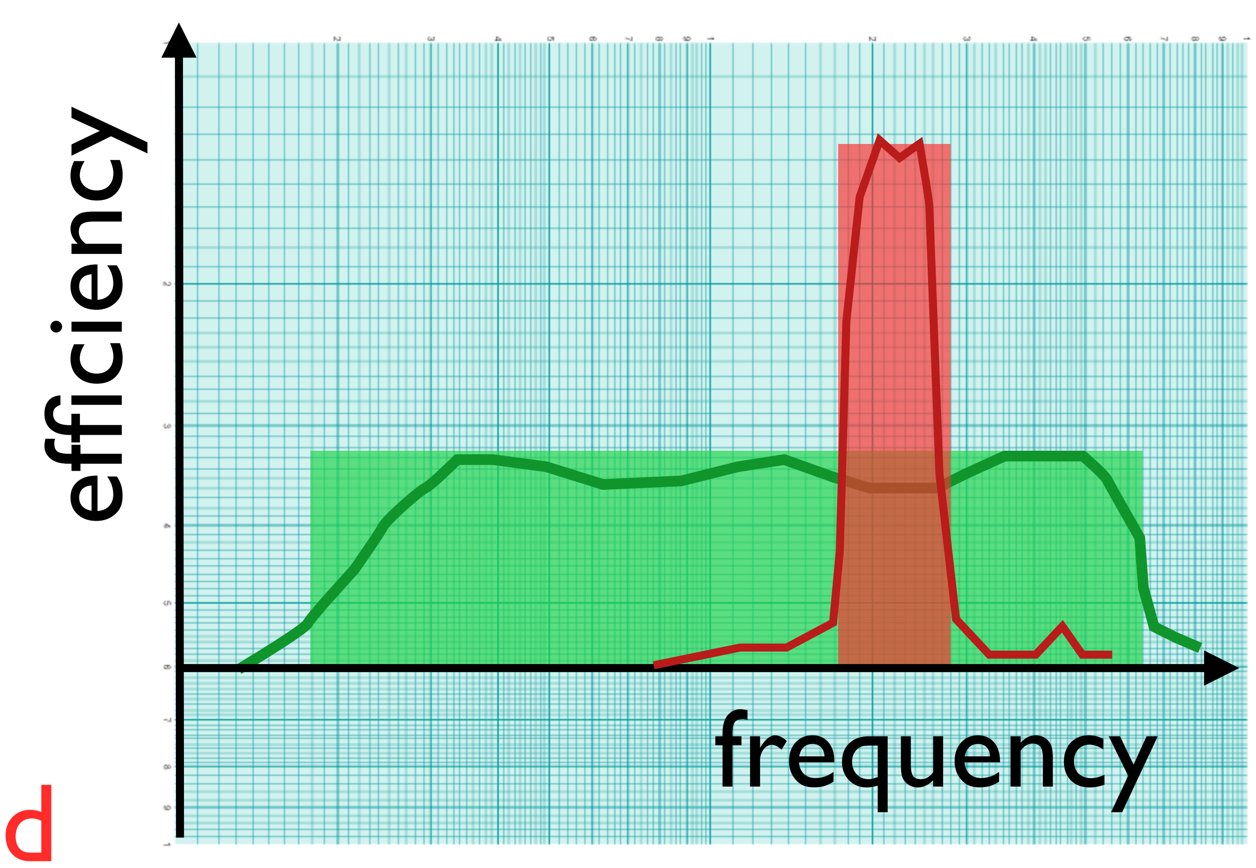
The non-mechanical properties of an antenna (i.e. all those on this list, except for Polarization and Wind load) are strongly frequency dependent, so they should be specified over the applicable frequency range.

The aperture of an antenna is easily visualized in the case of a parabolic dish, in which it basically coincides with its front section. For a wire antenna, in which the physical dimension is very small, the aperture can be derived mathematically.

# Bandwidth

The ***bandwidth*** refers to the range of frequencies over which the antenna can operate correctly.

You must choose an antenna that works well for the frequencies you intend to use (for example, use a 2.4 GHz antenna for 802.11 b/g, and a 5 GHz antenna for 802.11a).




narrow band

wide band





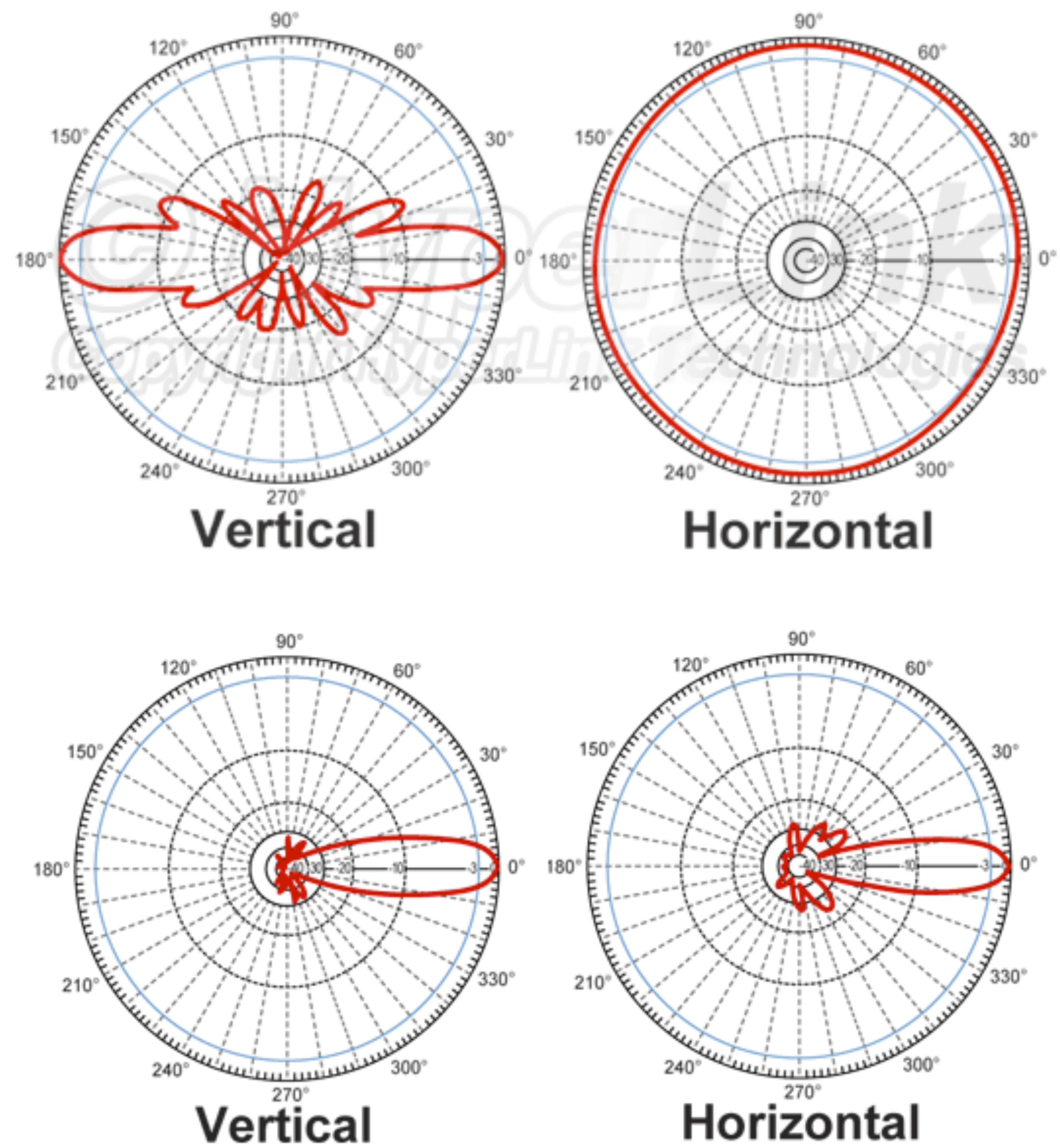
The bandwidth of an antenna refers to the range of frequencies over which the antenna can operate satisfactorily.

The effective bandwidth is usually defined by the frequencies for which the input impedance matches the transmission line (VSWR bandwidth). It can also be defined by pattern features such as gain, sidelobes, beamwidth, etc.  All these pattern features change over the range of frequencies used by an antenna.

# Radiation pattern

The ***radiation pattern*** of an antenna is a pictorial representation of the distribution of the power radiated from, or received by, the antenna. This is presented as a function of direction angles centered on the antenna.

Radiation patterns usually use a polar projection.



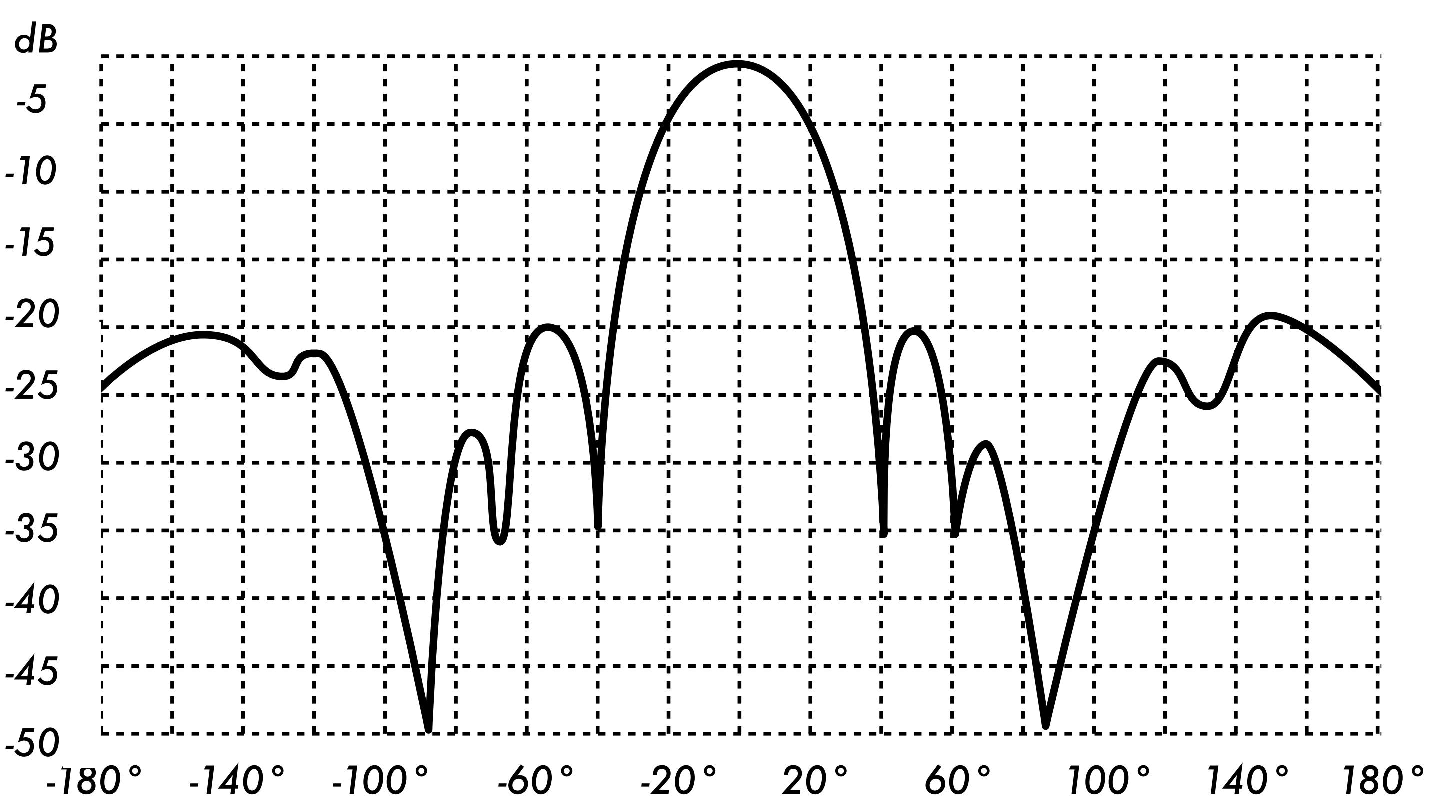


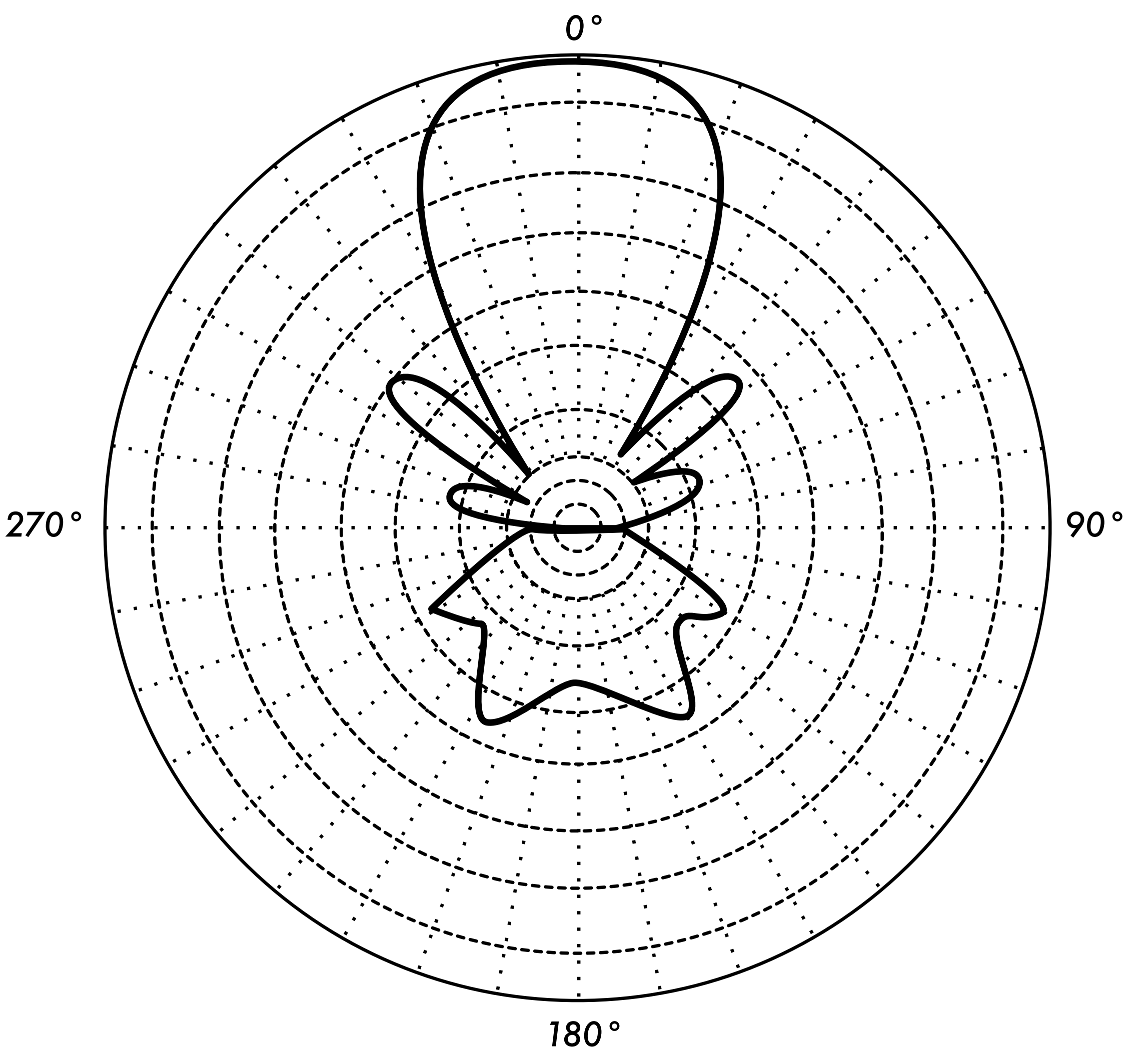

Although the radiation pattern is a volume, it is customary to characterize it by means of two graphs, the vertical radiation pattern and the horizontal radiation pattern. The diagram on top shows the radiation pattern of an omnidirectional antenna. The diagram on bottom shows the pattern of a parabolic dish.

Notice also that some energy is always radiated in undesired directions, constituting sidelobes and the backlobe.

# Radiation pattern

This is a ***rectangular plot*** and a ***polar plot*** of the same antenna (in a single plane). Polar coordinate systems are far more common than rectangular plots, since they give a better visual representation of antenna performance in every direction.



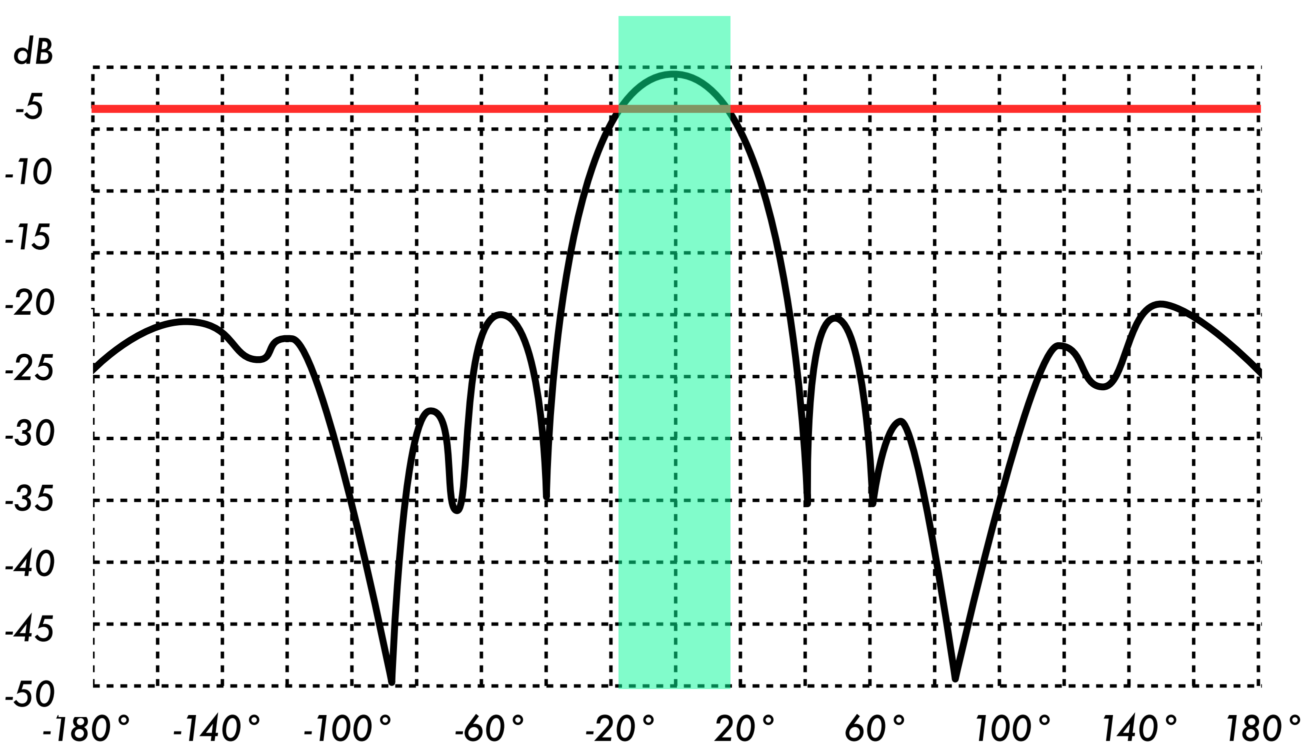




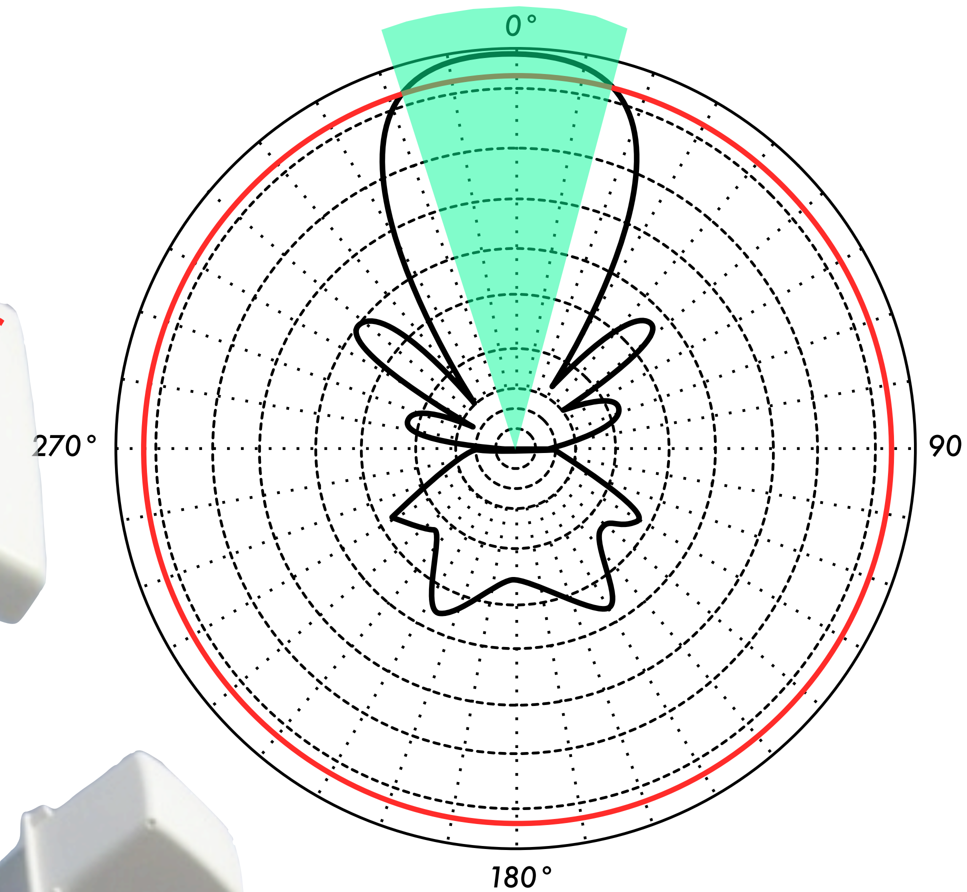

Here we have a rectangular plot and a polar plot of the same antenna. Polar coordinate systems are more common than rectangular plots, since they give a better visual representation of antenna performance in every direction.

# Beamwidth

The ***beamwidth*** of an antenna is the angular measure of that part of the space where the radiated power is greater than or equal to the half of its maximum value.











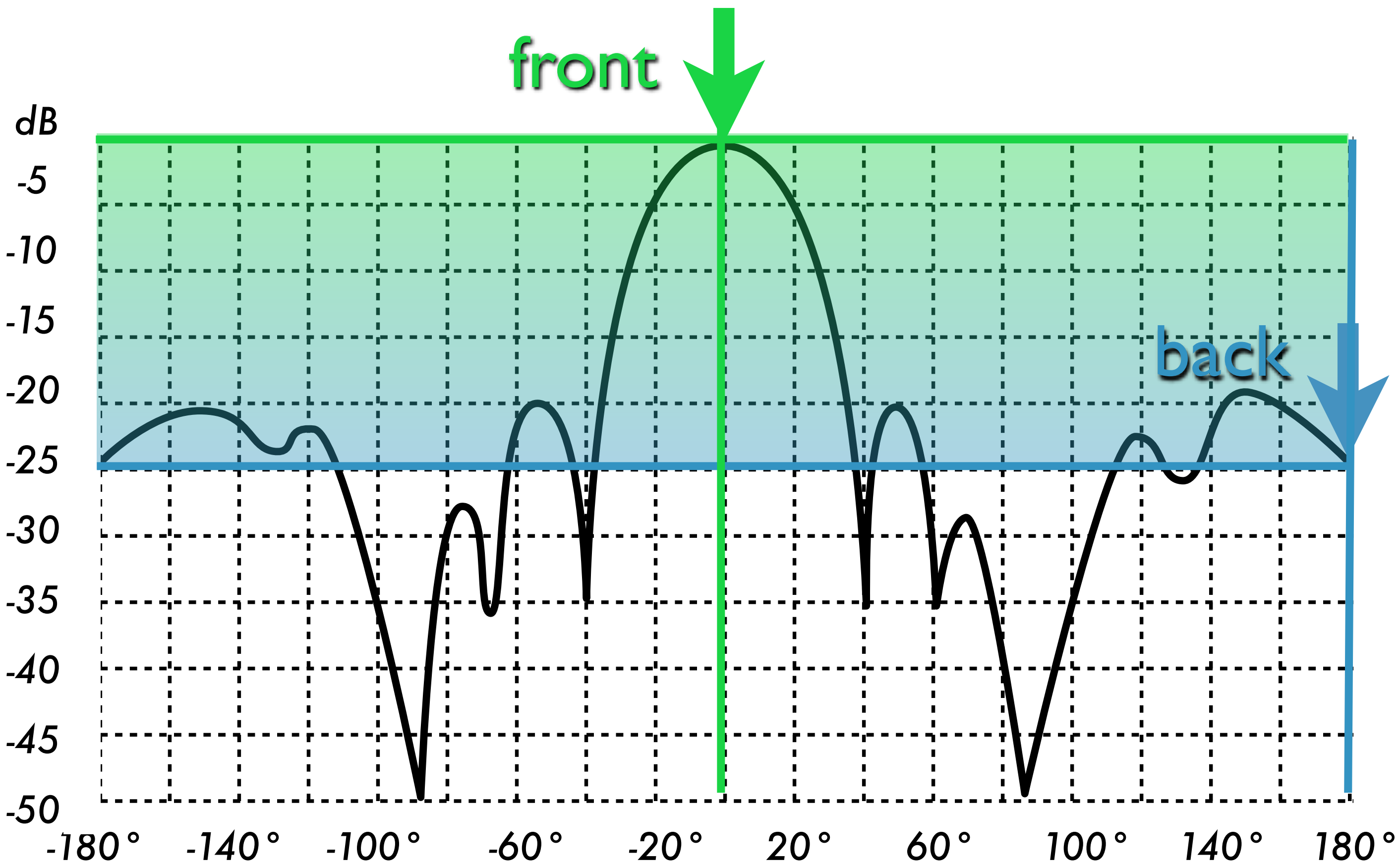

The peak radiation intensity is found, and then the points on either side of the peak which represent half the power of the peak intensity are located. The angular distance between the half power points is defined as the beamwidth.
The narrower the beamwidth the higher the gain, because the energy is more tightly focused. The greater the gain of the antenna, the narrower the beamwidth.

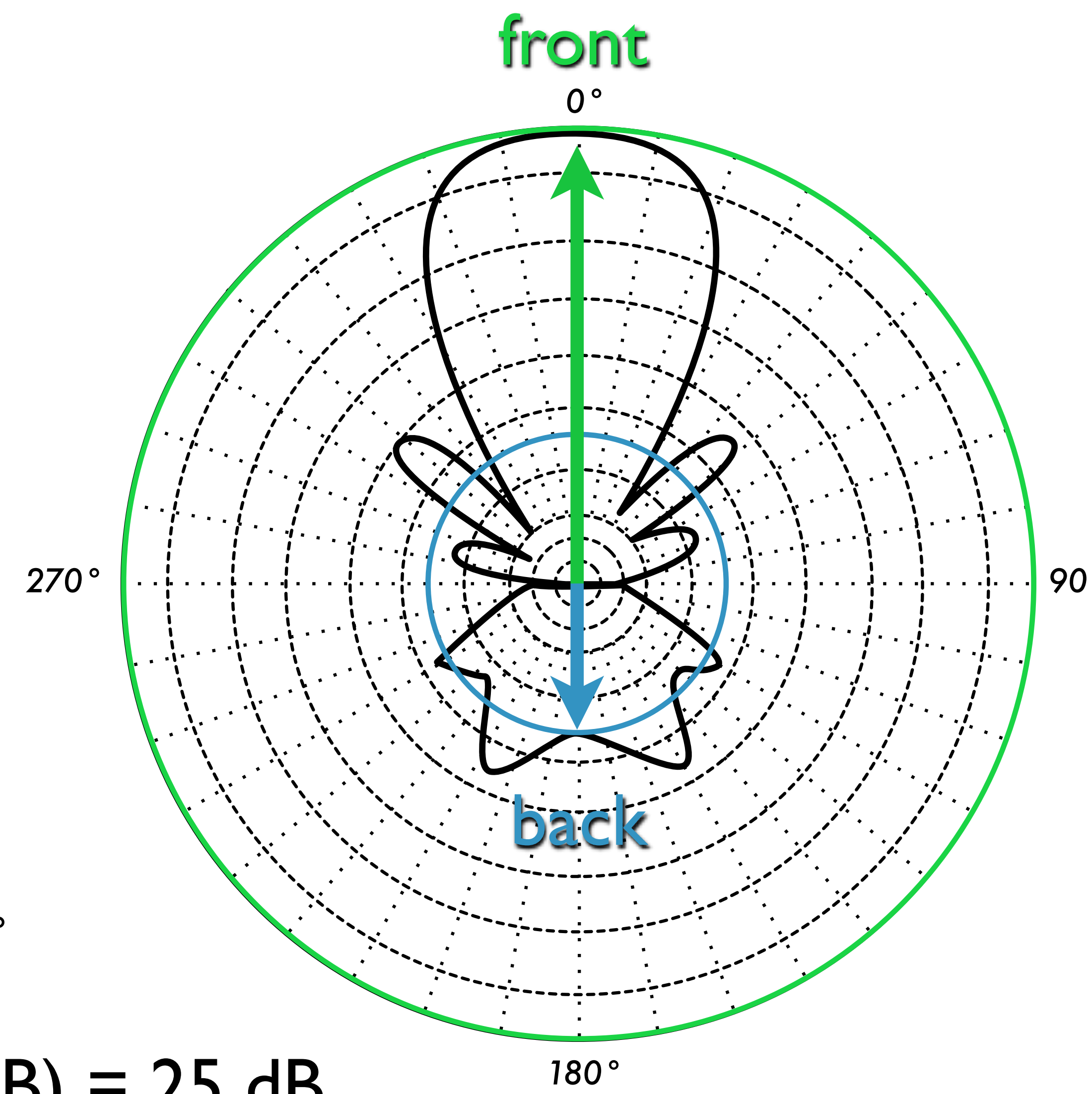
Remember that the radiation pattern is a three-dimensional volume, and therefore there is a **vertical beamwidth** and a **horizontal beamwidth**, that are usually different.

A very high gain antenna can have a beamwidth of a few degrees and will have to be pointed very carefully in order to hit the target.

# Front-to-back ratio

The ***front-to-back ratio*** of a directional antenna is the ratio of the maximum directivity of the antenna to its directivity in the opposite direction.




In this example the f/b ratio is: 0 dB - (-25 dB) = 25 dB

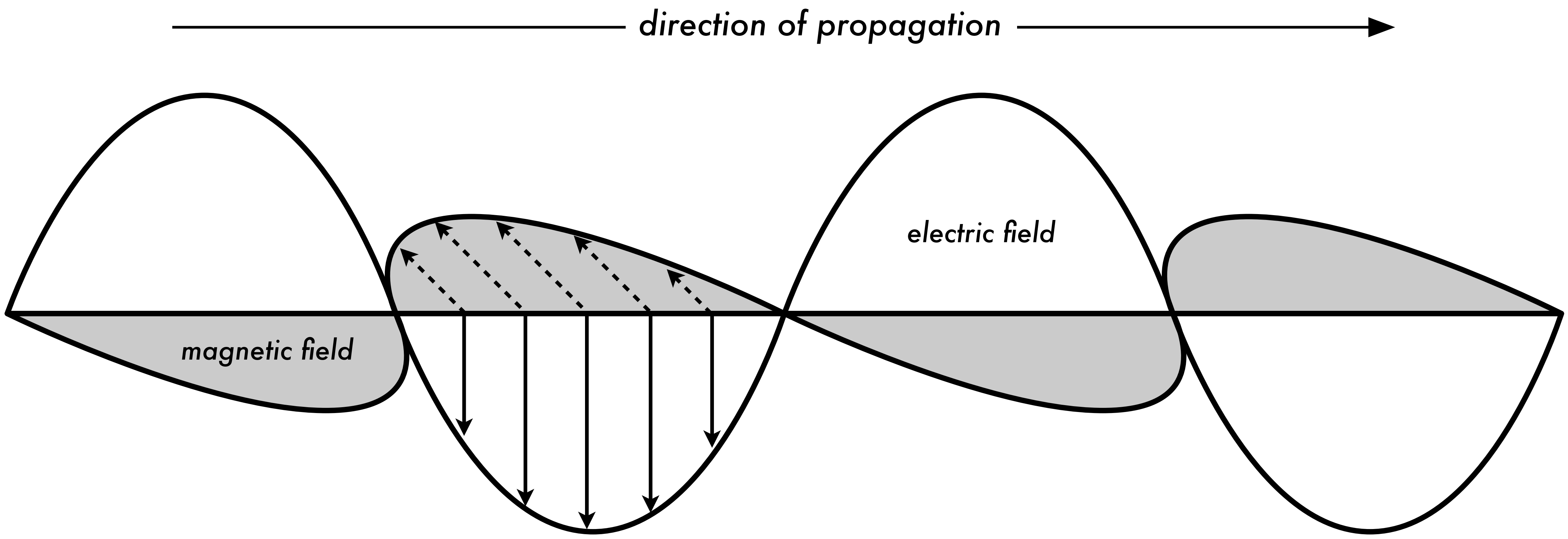




The front-to-back ratio is quite important in backbone networks built with repeaters. The backward radiation can cause problems with the previous stage's receiver, so for this application antennas with large front-to-back ratio are preferred.

# Polarization

- Electromagnetic waves have electrical and magnetic components.
- The polarization of transmitting and receiving antennas **MUST MATCH** for optimum communications.








Another important quality of electromagnetic waves is ***polarization***. Polarization describes the direction of the electrical field vector.

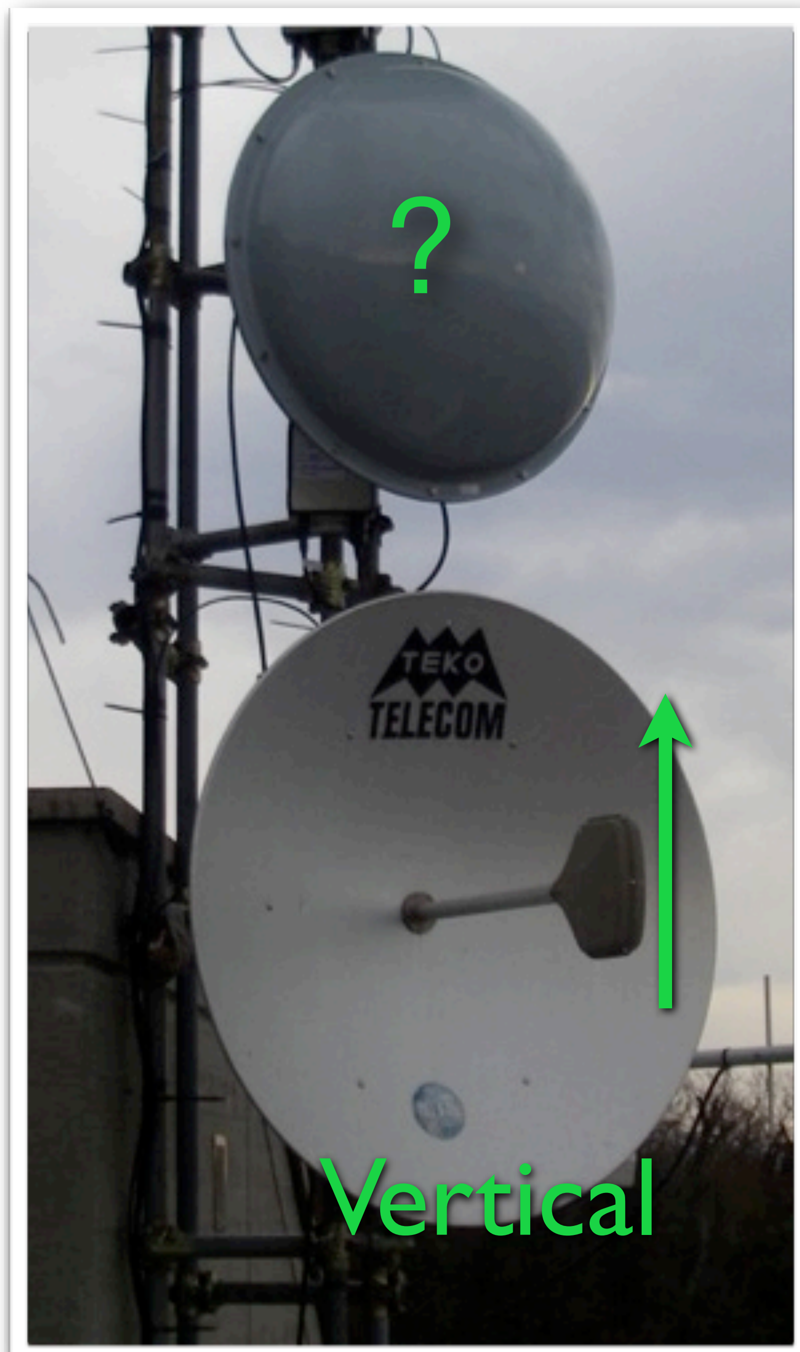
If you imagine a vertically aligned dipole antenna (a straight piece of wire), electrons only move up and down, not sideways (because there is no room to move) and thus electrical fields only ever point up or down, vertically. The energy leaving the wire and traveling as a wave has a strict linear (and in this case, vertical) polarization. If we put the antenna flat on the ground, we would find horizontal linear polarization.

Most WiFi antennas we work with are linearly polarized, but circularly polarized antennas are also sometimes used (for special purposes).

Polarization mismatch can cause 20dB or more of attenuation.

Polarization mismatch can be exploited to send two different signals on the same frequency at the same time, thus doubling the throughput of the link. Special antennas that have dual feeds can be used for this purpose. Real life throughput is somewhat lower than twice the single antenna throughput because of the inevitable cross polarization interference.

# Antenna polarization







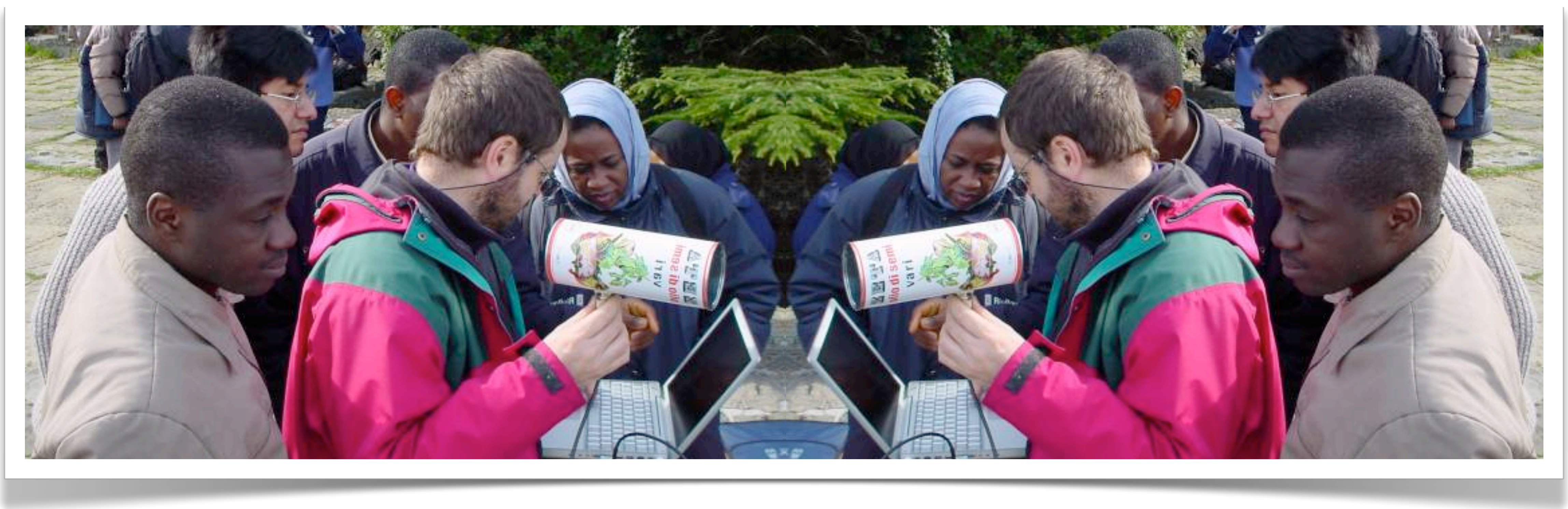
The polarization of an antenna can sometimes be inferred by the orientation of the feed. Radomes make this more difficult. Antennas nearly always have a mark indicating the polarization, but sometimes you must consult the manufacturer's datasheet!

Most omnidirectional antennas are vertically polarized. By choosing to use a horizontally polarized antenna, you can avoid some man-made interference (since most devices use vertical polarization). But horizontally polarized waves might lose power over long distances due to interactions with the surface of the earth. This effect is more pronounced when making links over water.

# Reciprocity

Antenna characteristics like gain, beamwidth, efficiency, polarization, and impedance are independent of the antenna's use for either transmitting or receiving.

Another way to state this is that an antenna's transmitting and receiving characteristics are ***reciprocal***.







The concept of reciprocity is very powerful and is used very often. Many properties of an antenna are easier to visualize in terms of a receiving antenna, and by reciprocity these properties can be applied to a transmitting antenna and vice-versa.

# Wind load

Parabolic Antenna with Radome

Sector Antenna

Parabolic Grid Antenna

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Wind load is a significant factor that can cause the destruction of the antenna and even of the mast to which it is attached.

One way to diminish the wind resistance is to use a grill as a reflector. As long as the separation between the grid elements is a fraction of the wavelength, the grid will behave almost like a solid surface, while offering a much reduced wind load.

Another way to reduce the drag of the wind is by covering the antenna with a curved surfaced dielectric material transparent to radio waves called a Radome (Radar dome).

Smaller antennas, such as sector and patch antennas, can provide a lot of gain in a very small package, reducing the problems caused by wind load.

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# Weather effects

parabolic grid

parabolic grid
(covered by snow)





Ice affects the performance of all antennas to some degree and the problem gets more serious at higher frequencies. The impedance of free space is 377 ohms. If the air immediately surrounding the dipole elements is replaced by ice which has a lower impedance than air, then the impedance match and radiation patterns of the antenna will change. These changes become progressively worse as the ice loading increases.

Antenna elements are usually encased in a plastic protective housing (radome). This provides an air space between the elements and ice casing so that the lower impedance of the ice layer has only a small effect on the radiators. Detuning is greatly reduced but radiation pattern distortion may still be encountered (detuning reduces usable antenna bandwidth). For a given ice thickness, deviation from nominal performance values become worse as frequency increases.

In areas where severe icing and wet snow are common, it is prudent to install a full radome over solid parabolic antennas, to use panel antennas instead of corner reflectors, and to stay away from grid parabolics.

# Weatherproofing antennas

Most antenna problems are caused by coaxial cable connections that loosen due to vibration, allowing moisture to penetrate the connector interface.

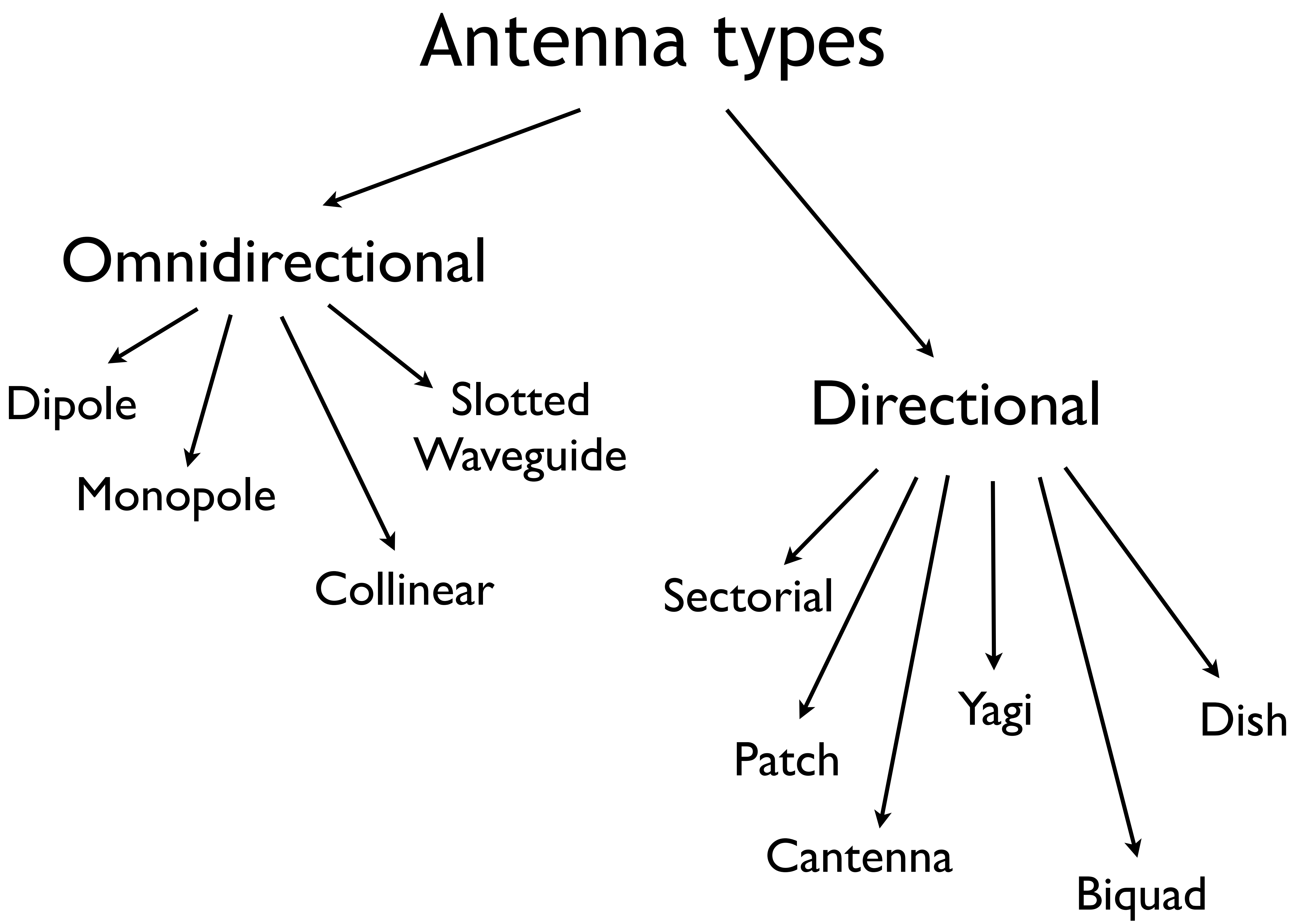
Weatherproof all outdoor connections.



Weatherproofing can be done by applying several layers of rubber vulcanizing tape over the connection and then covering that with good (low temperature, UV resistant) electrical tape.

Drainage is very important with unpressurized radomes. Make sure that the drain hole is on the bottom and that it has not been blocked during installation.

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These antennas are listed from left to right in order of increasing directionality and gain.

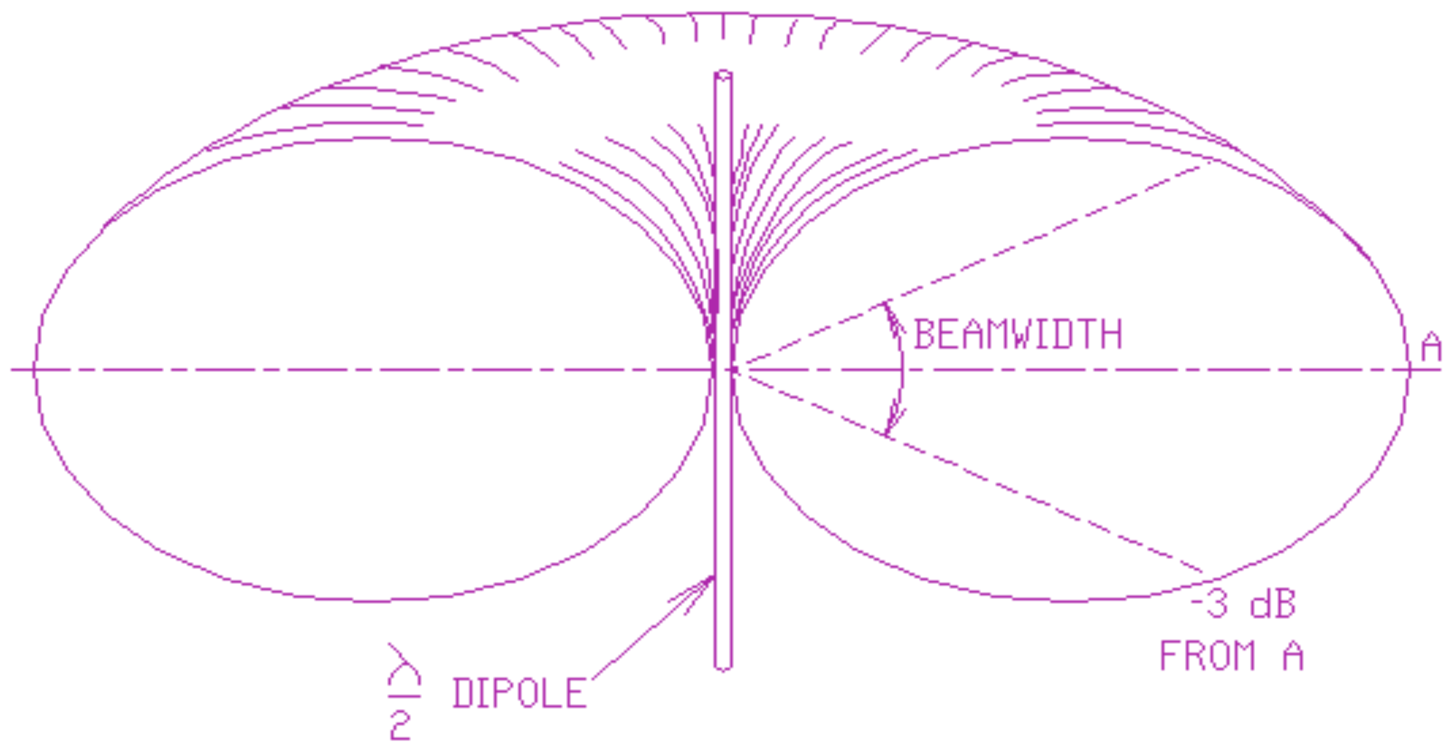
The most common dipole is made with two wires of a quarter wavelength and is called a half wave dipole. This is a practical low-gain antenna that approximates an isotropic radiator (except in the vertical plane).

The gain of a dipole can be increased by stacking several radiating elements if they are fed in alternate phase to obtain a collinear antenna.

Directional antennas are further subdivided into high gain antennas meant for point to point applications and sectorial antennas, which normally have beamwidths of 60°, 90° or 120° and are commonly combined to provide 360° coverage from a base station. Sectorial antennas typically have a higher gain than an omnidirectional antenna. If each sector is fed by a different radio, higher throughput can also be obtained compared to using a single omni.

Examples of point to point antennas are waveguide and horn antennas, Yagis, corner reflectors, parabolic reflectors and patch antennas.

# Half Wavelength Dipole




- Two 1/4 λ elements
- Very easy to build over a wide frequency range
- Omnidirectional in the plane perpendicular to the elements
- 2.15 dBi gain
- 72 ohm input impedance nearly matches the 50 ohm coax



Can be used as feed for parabolic or corner reflectors.

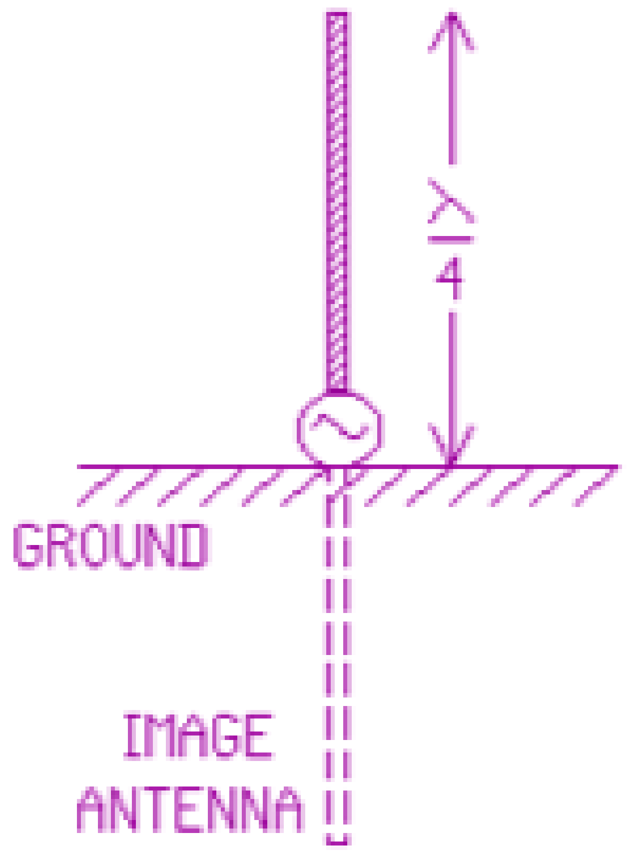
It can be center fed as shown or fed at other points which will change the input impedance.

The dipole can be folded which will increase 4 times the impedance thus providing 288 ohm, very close to the characteristic impedance of the flat twin line used in antenna receivers.

You can easily build a half wavelength dipole using a flat antenna TV cable by splitting a quarter wave section at the end in two halves and fixing them horizontally with insulators.

# Monopole or Marconi antenna

- Vertical element 1/4 λ
- A good ground plane is required
- omnidirectional in the horizontal plane
- 5.15 dBi
- ~ 36 Ω impedance



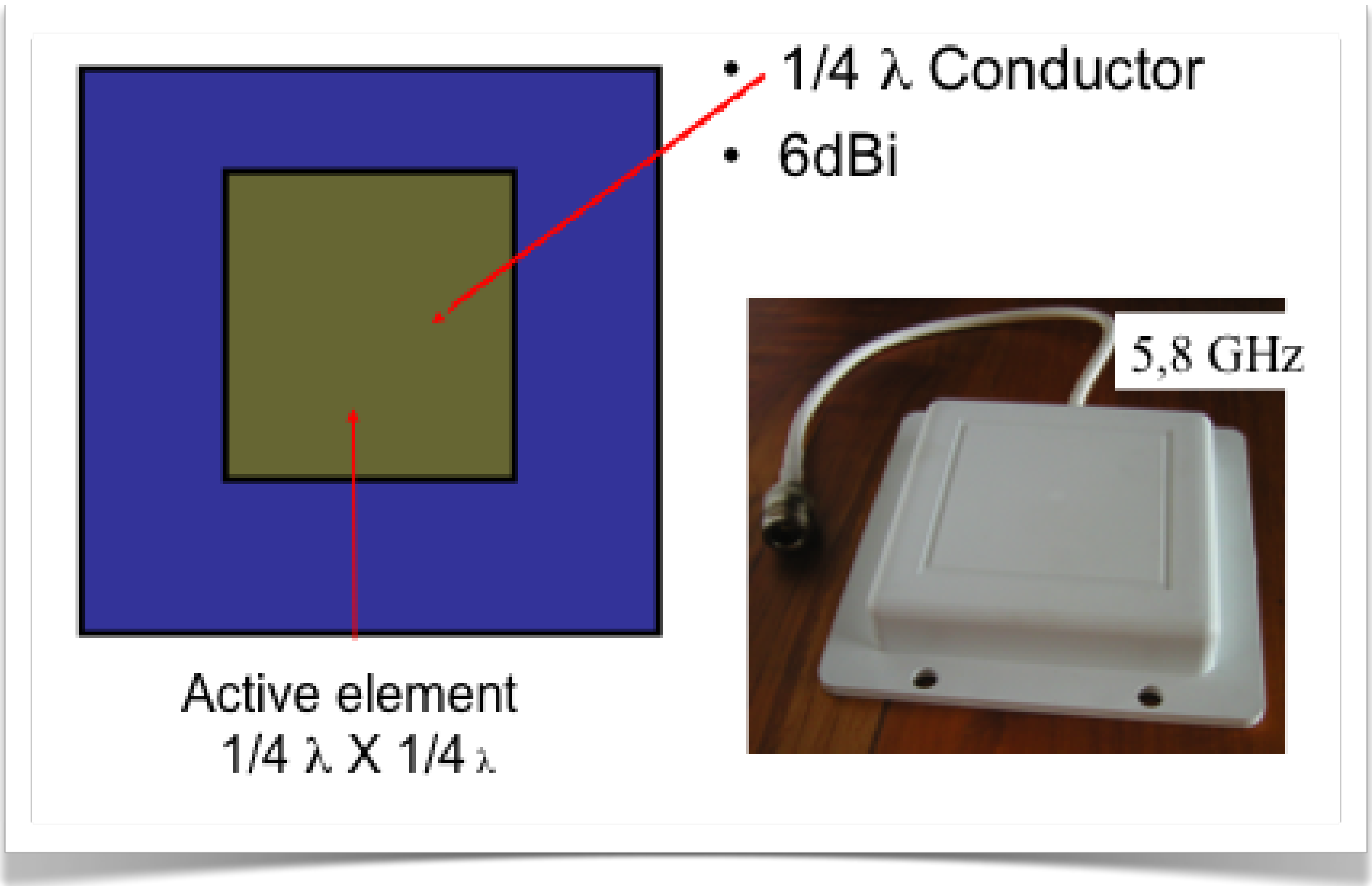





The ground plane can be implemented by wire radials a quarter wavelength long.
The monopole has half the input impedance of a dipole and twice the gain (that is, 3 dB more). This is because only half of the voltage is required to drive the same amount of current as in the dipole, and because the lower half of the radiation pattern is not active due to the ground plane.

The monopole can also be used as a probe for more complex antennas, like the "cantenna". In this case the ground plane is the wall of the can.

# Patch antenna








The advantage of the patch antenna is that is less visually obtrusive than a parabolic antenna.
Several elements can be combined and fed with the proper phase to increase the gain.

# Antenna types

parabolic reflector


panel antennas

# Do-it-yourself reflector

You can make your own reflector using an aluminum sheet, cardboard or thick paper, scissors and glue.







The cheapest "do it yourself" antenna is a simple parabolic reflector added to an omni antenna. It adds a small amount of gain (3 to 6 dBi, depending on the size of the reflector) thus providing some directivity.

# Parabolic reflectors

- Parabolic dish/grid shape. Corner reflectors also work well.
- Gain =~ $(D / \lambda)^2$
- Beamwidth =~ $\lambda / D$
- It must have the right feed, positioned at the focal point of the reflector
- Off-center feeds (e.g. for satellite TV) are difficult to align





Offset feeds usually look as though they are pointing "too low".

Parabolics can provide high gain, and are easily available as surplus in most countries. The parabolic reflector is not actually an antenna, but it can be added to any other antenna to increase the gain.

A complete transceiver (e.g. a USB radio) can be located at the focus for a very cost effective long distance communication system.

# Do-it-yourself cantenna

Cheap and effective antennas can be made from food cans.

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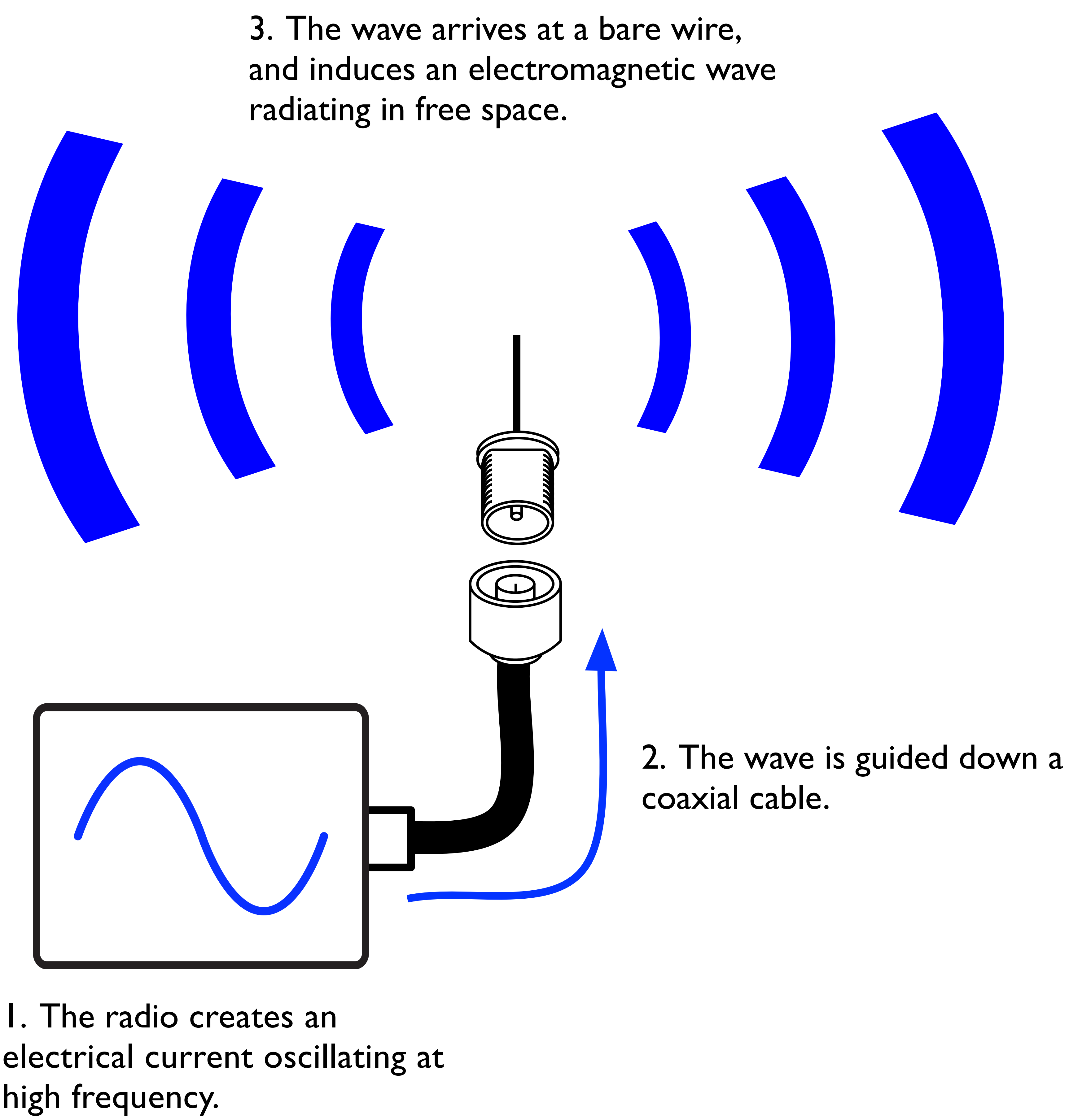
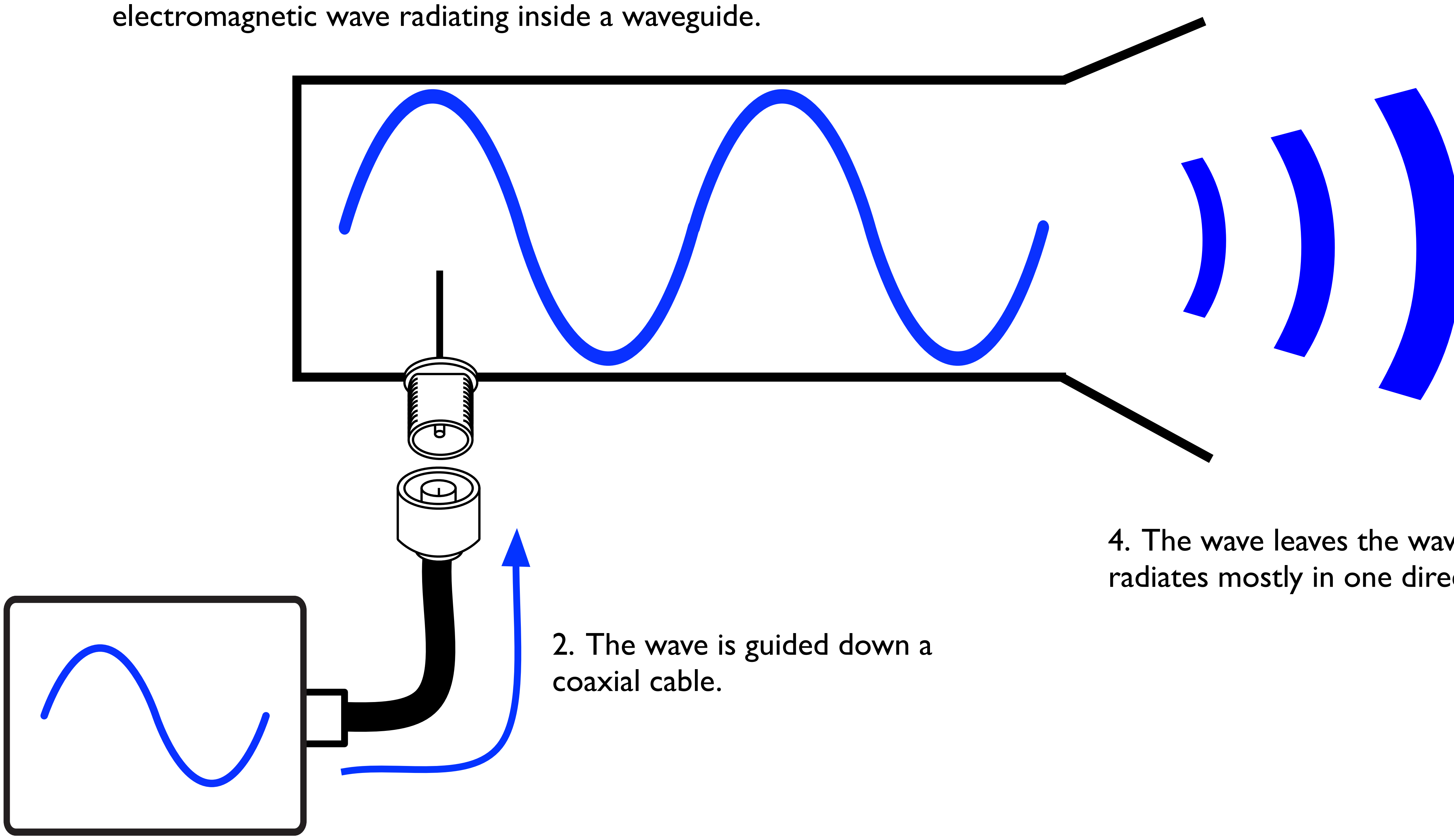
Inexpensive WiFi antennas can be made using ordinary food cans. This kind of antenna is called a “waveguide antenna”. The WNDW book has a detailed description on how to build this and other kind of antennas.







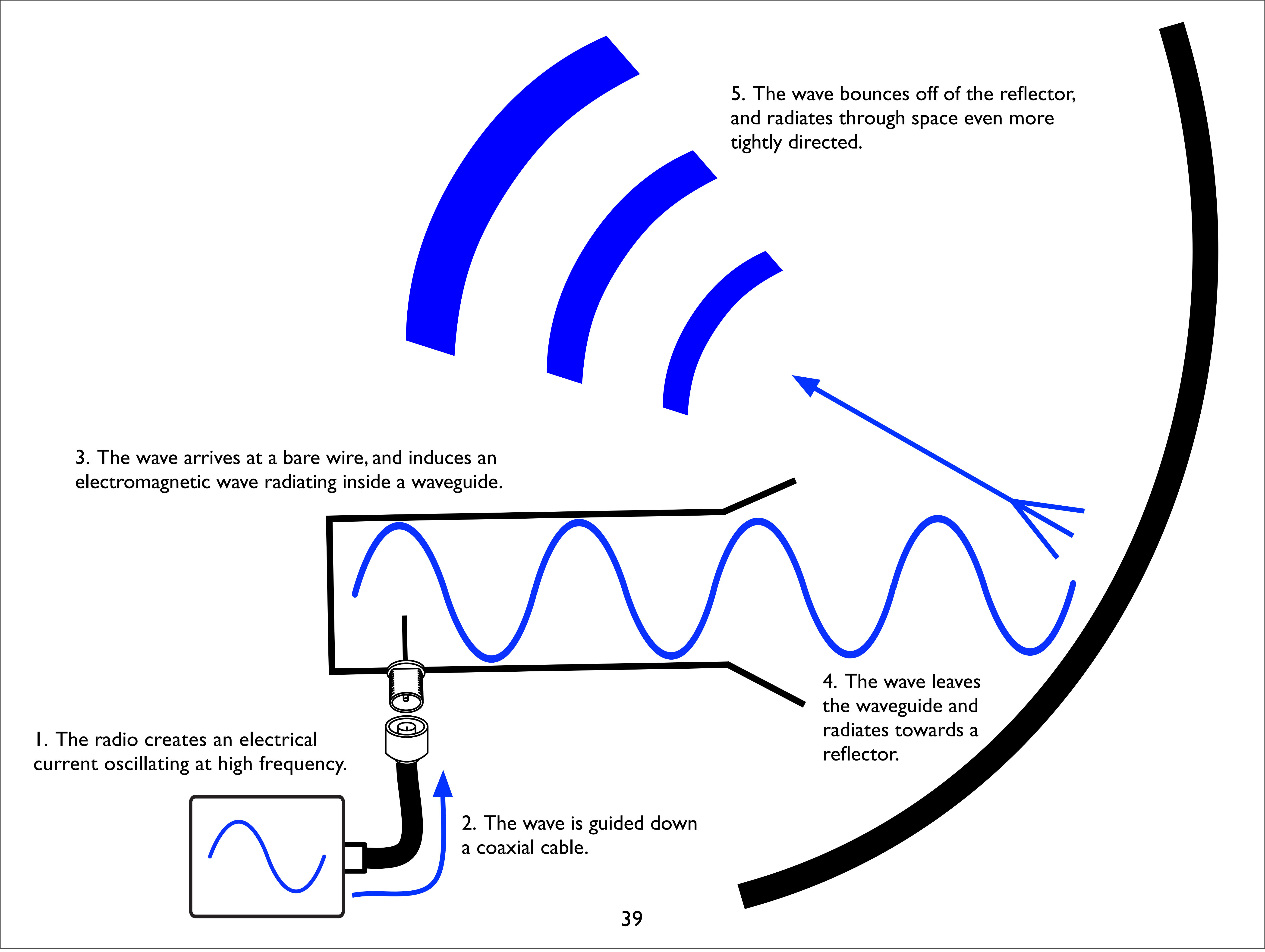

The antenna is the point at which a moving current in a wire is transformed into an electromagnetic wave radiating in space.








The wave leaving the wire can be further guided to travel mostly one direction.







The guided wave can be further directed to radiate very strongly in one direction, as in the case of a waveguide feeding a parabolic reflector.

# Conclusions

- Antennas are the interface between guided and unguided waves.
- Antenna come in all shapes and sizes.
- The size of the antenna must be at least a fraction of the wavelength it handles.
- Antenna impedance must match the transmission line.
- There is no “best antenna” for every application; the choice is always a trade-off between reaching long distances and covering a wide area.
- Use high gain antennas to reach long distances, and omni or sectorial antennas to cover wide areas.

# Thank you for your attention

For more details about the topics presented in this lecture, please see the book ***Wireless Networking in the Developing World***, available as free download in many languages at:

*http://wndw.net/*




See Chapter 5 of the book for more detailed information about the material covered in this talk.