Reference Material

UNITS:

Submultiples			Multiples		
Value	**SI symbol**	**Name**	**Value**	**SI symbol**	**Name**
10^{-1} Hz	dHz	decihertz	10^{1} Hz	daHz	decahertz
10^{-2} Hz	cHz	centihertz	10^{2} Hz	hHz	hectohertz
10^{-3} Hz	mHz	millihertz	10^{3} Hz	**kHz**	**kilohertz**
10^{-6} Hz	µHz	microhertz	10^{6} Hz	**MHz**	**megahertz**
10^{-9} Hz	nHz	nanohertz	10^{9} Hz	**GHz**	**gigahertz**
10^{-12} Hz	pHz	picohertz	10^{12} Hz	**THz**	**terahertz**
10^{-15} Hz	fHz	femtohertz	10^{15} Hz	PHz	petahertz
10^{-18} Hz	aHz	attohertz	10^{18} Hz	EHz	exahertz
10^{-21} Hz	zHz	zeptohertz	10^{21} Hz	ZHz	zettahertz
10^{-24} Hz	yHz	yoctohertz	10^{24} Hz	YHz	yottahertz
Common prefixed units are in bold.					

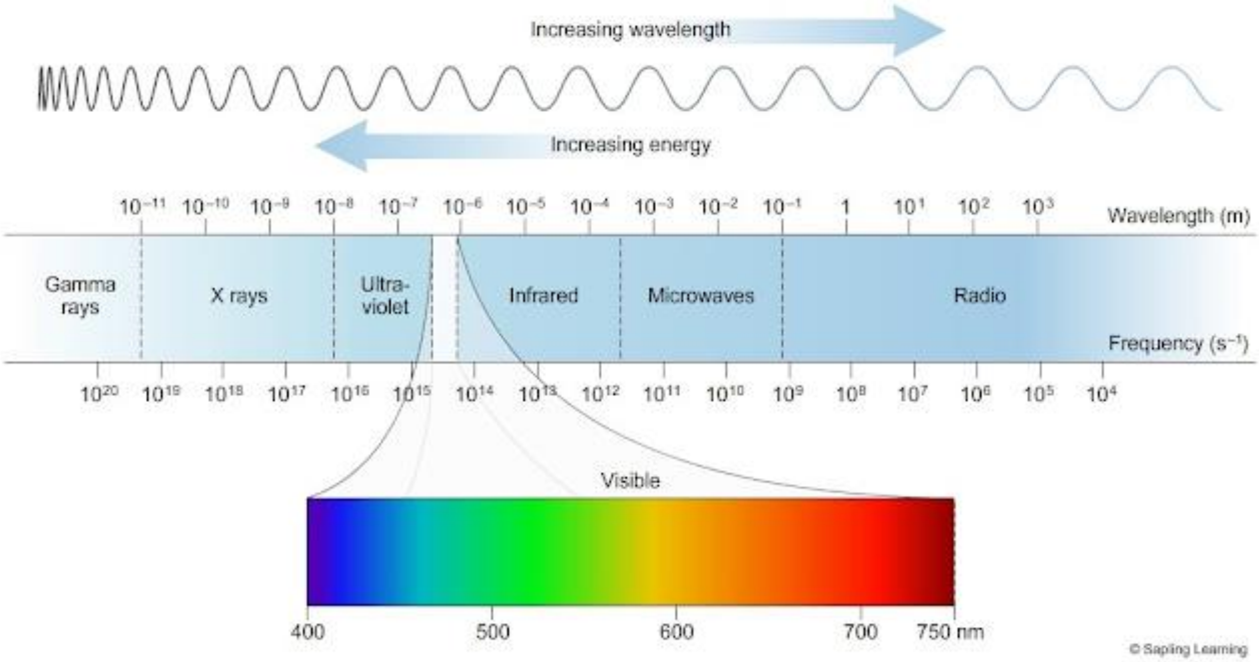
SI Base Units

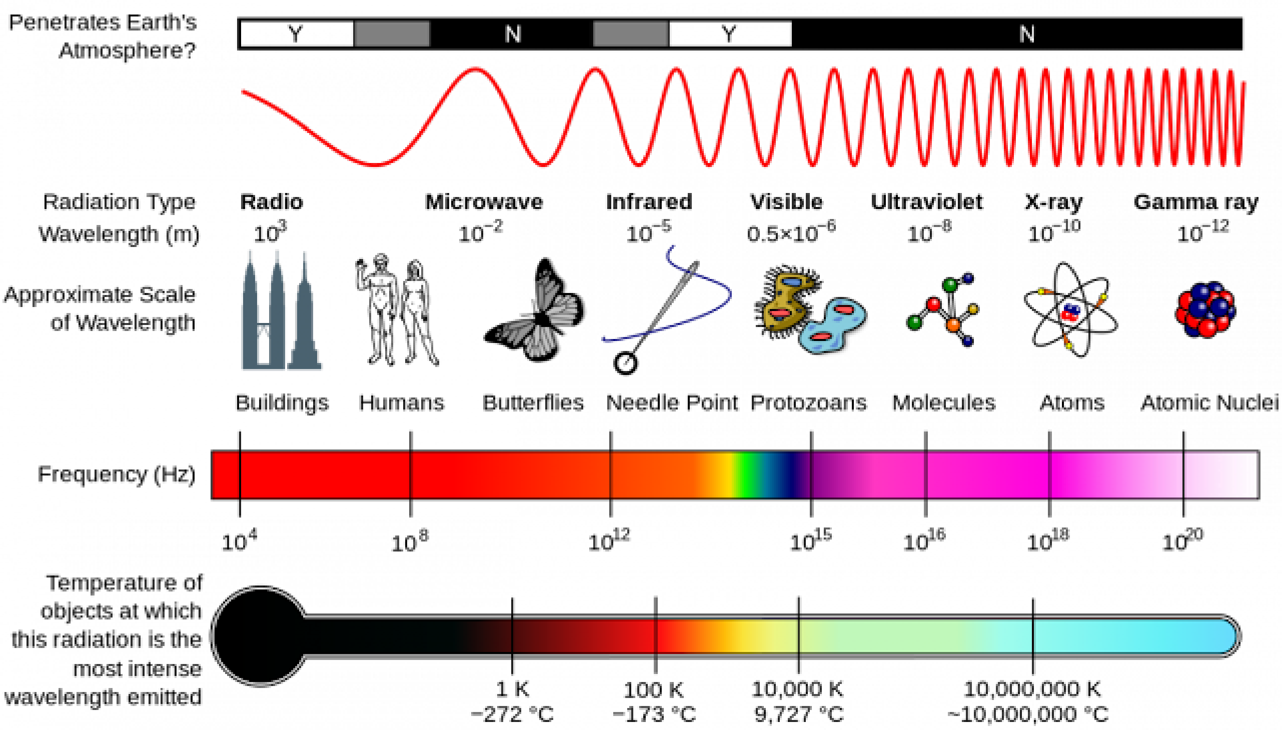
Name	Symbol	Quantity
meter	m	length
kilogram	kg	mass
second	s	time
ampere	A	electric current
Kelvin	K	temperature
candela	cd	luminous intensity
mole	mol	amount of substance

SI Derived Units

Name	Symbol	Quantity	In terms of other SI
joule	J	energy/work	kg * m^2 * s^-2
coulomb	C	charge	A * s
watt	W	power	J/s
volt	V	voltage (electric potential difference)	W/A
ohm	Ω	resistance, impedance	V/A
farad	F	capacitance	C/V
henry	H	inductance	Wb/A
hertz	Hz	frequency	s^-1
siemens	S	conductance	A/V or 1/Ω
weber	Wb	magnetic flux	V * s
tesla	T	magnetic field strength	Wb/(m^2)

EM SPECTRUM CHARTS





	Wavelength	Frequenzy
Red	~ 625 – 740 nm	~ 480 – 405 THz
Orange	~ 590 – 625 nm	~ 510 – 480 THz
Yellow	~ 565 – 590 nm	~ 530 – 510 THz
Green	~ 520 – 565 nm	~ 580 – 530 THz
Blue	~ 445 – 520 nm	~ 675 – 580 THz
Indigo	~ 425 – 445 nm	~ 700 – 675 THz
Violet	~ 380 – 425 nm	~ 790 – 700 THz

Class			Wave-length λ	Freq-uency f	Energy per photon E
Ionizing radiation	γ	Gamma rays	1 pm	300 EHz	1.24 MeV
	HX	Hard X-rays	10 pm	30 EHz	124 keV
	SX	Soft X-rays	100 pm	3 EHz	12.4 keV
			1 nm	300 PHz	1.24 keV
	EUV	Extreme ultraviolet	10 nm	30 PHz	124 eV
			100 nm	3 PHz	12.4 eV
	NUV	Near ultraviolet, visible	1 µm	300 THz	1.24 eV
	NIR	Near infrared	10 µm	30 THz	124 meV
	MIR	Mid infrared	100 µm	3 THz	12.4 meV
	FIR	Far infrared	1 mm	300 GHz	1.24 meV
Micro-waves and radio waves	EHF	Extremely high frequency	1 cm	30 GHz	124 µeV
	SHF	Super high frequency	1 dm	3 GHz	12.4 µeV
	UHF	Ultra high frequency	1 m	300 MHz	1.24 µeV
	VHF	Very high frequency	10 m	30 MHz	124 neV
	HF	High frequency	100 m	3 MHz	12.4 neV
	MF	Medium frequency	1 km	300 kHz	1.24 neV
	LF	Low frequency	10 km	30 kHz	124 peV
	VLF	Very low frequency	100 km	3 kHz	12.4 peV
	ULF	Ultra low frequency	1 Mm	300 Hz	1.24 peV
	SLF	Super low frequency	10 Mm	30 Hz	124 feV
	ELF	Extremely low frequency	100 Mm	3 Hz	12.4 feV

Material	Refractive Index
Vacuum	1
Gases at 0 °C and 1 atm	
Air	1.000293
Carbon Dioxide	1.00045
Helium	1.000036
Hydrogen	1.000132
Liquids at 20 °C	
Arsenic Trisulfide and Sulfur in Methylene Iodide	1.9
Benzene	1.501
Carbon Disulfide	1.628
Carbon Trichloride	1.461
Ethyl Alcohol (Ethanol)	1.361
Silicone Oil	1.336-1.582
Water	1.3330
10% Glucose Solution in Water	1.3477
20% Glucose Solution in Water	1.3635
60% Glucose Solution in Water	1.4394
Solids at Room Temperature	
Titanium Dioxide (Rutile Phase)	2.614
Diamond	2.419
Strontium Titanate	2.41
Amber	1.55
Fused Silica (Fused Quartz)	1.458
Sodium Chloride	1.544
Other	
Liquid Helium	1.025
Water Ice	1.31
Cornea (human)	1.373-1.401
Lens (human)	1.386-1.406
Acetone	1.36
Ethanol	1.36
Glycerol	1.4729
Bromine	1.661
Teflon AF	1.315
Teflon	1.35-1.38
Cytop	1.34
Sylgard 184 (Polydimethylsiloxane)	1.4118
Polylactic acid	1.46
Acrylic glass	1.490 - 1.492
Polycarbonate	1.584 - 1.586
PMMA	1.4893 - 1.4899
PETg	1.57
PET	1.5750
Kerosene	1.39
Crown glass (pure)	1.50 - 1.54
Flint glass (pure)	1.60 - 1.62
Crown glass (impure)	1.485 - 1.755
Flint glass (impure)	1.523 - 1.925
Pyrex (a borosilicate glass)	1.470
Cryolite	1.338
Rock salt	1.516
Sapphire	1.762–1.778
Sugar Solution, 25%	1.3723
Sugar Solution, 50%	1.4200
Cubic zirconia	2.15 - 2.18
Potassium niobate ($KNbO_3$)	2.28
Silicon carbide	2.65 - 2.69
Cinnabar (Mercury sulfide)	3.02
Gallium(III) phosphide	3.5
Gallium(III) arsenide	3.927
Zinc Oxide	2.4
Germanium	4.05 - 4.01
Silicon	3.48 - 3.42

Formulas

BASIC WAVE PROPAGATION

Reference: Speed of Light = ~300,000 km/s (299,792,458 m/s)
All EM waves travel at the speed of light.

Period = wavelength/velocity

Period = 1/frequency

Frequency = velocity/wavelength

Rate = distance/time

Refraction index = speed of light / velocity in medium

ENERGY

A general rule to follow when determining the energy of electromagnetic waves is, the shorter the wavelength, the higher the energy it possesses. The following also refers to the energy of a photon.

$$E = hf$$

E is energy in joules (J)

- *h* is Planck's constant (6.626 x 10^{-34} joule-seconds (Js))
- *f* is frequency in hertz (Hz), which is 1/s

Energy of a Photon

E=hf=ch/λ

Alternatively, E=1.24λ, where λ is in micrometers and E comes out in electron-volts.

ELECTRICITY AND MAGNETISM FORMULAS

$$E = h * f$$

$$f = \frac{1}{2*\pi*\sqrt{L*C}}$$

$$c = \lambda * v$$

$$v = \sqrt{\frac{T}{\mu}}$$

$$f_n = n * f_1$$

$$\lambda_n = \frac{\lambda_1}{n}$$

$\lambda = \frac{v}{f}$

$n = \frac{c}{v}$

$n_1 \sin\theta_1 = n_2 \sin\theta_2$

$\frac{1}{s_i} + \frac{1}{s_o} = \frac{1}{f}$

$|M| = \left|\frac{h_i}{h_o}\right| = \left|\frac{s_i}{s_o}\right|$

$\Delta L = m\lambda$

$d\sin\theta = m\lambda$

d = separation
f = frequency or focal length
h = height
L = distance
M = magnification
m = an integer
n = index of refraction
s = distance
v = speed
λ = wavelength
θ = angle

ELECTRICITY AND MAGNETISM

$|\vec{F}_E| = \frac{1}{4\pi\varepsilon_0}\left|\frac{q_1q_2}{r^2}\right|$

$\vec{E} = \frac{\vec{F}_E}{q}$

$\oint \vec{E}\cdot d\vec{A} = \frac{Q}{\varepsilon_0}$

$E_x = -\frac{dV}{dx}$

$\Delta V = -\int \vec{E}\cdot d\vec{r}$

$V = \frac{1}{4\pi\varepsilon_0}\sum_i \frac{q_i}{r_i}$

$U_E = qV = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r}$

$\Delta V = \frac{Q}{C}$

$C = \frac{\kappa\varepsilon_0 A}{d}$

$C_p = \sum_i C_i$

$\frac{1}{C_s} = \sum_i \frac{1}{C_i}$

$I = \frac{dQ}{dt}$

$U_C = \frac{1}{2}Q\Delta V = \frac{1}{2}C(\Delta V)^2$

$R = \frac{\rho\ell}{A}$

$\vec{E} = \rho\vec{J}$

$I = Nev_d A$

$I = \frac{\Delta V}{R}$

$R_s = \sum_i R_i$

$\frac{1}{R_p} = \sum_i \frac{1}{R_i}$

$P = I\Delta V$

A = area
B = magnetic field
C = capacitance
d = distance
E = electric field
$\mathcal{E}$ = emf
F = force
I = current
J = current density
L = inductance
ℓ = length
n = number of loops of wire per unit length
N = number of charge carriers per unit volume
P = power
Q = charge
q = point charge
R = resistance
r = radius or distance
t = time
U = potential or stored energy
V = electric potential
v = velocity or speed
ρ = resistivity
Φ = flux
κ = dielectric constant

$\vec{F}_M = q\vec{v}\times\vec{B}$

$\oint \vec{B}\cdot d\vec{\ell} = \mu_0 I$

$d\vec{B} = \frac{\mu_0}{4\pi}\frac{I\,d\vec{\ell}\times\hat{r}}{r^2}$

$\vec{F} = \int I\,d\vec{\ell}\times\vec{B}$

$B_s = \mu_0 nI$

$\Phi_B = \int \vec{B}\cdot d\vec{A}$

$\mathcal{E} = \oint \vec{E}\cdot d\vec{\ell} = -\frac{d\Phi_B}{dt}$

$\mathcal{E} = -L\frac{dI}{dt}$

$U_L = \frac{1}{2}LI^2$

Although angular velocity, angular frequency and the unit hertz all have the dimension 1/T, angular velocity and angular frequency are not expressed in hertz, but rather in an appropriate angular unit such as the radian per second. Thus a disc rotating at 60 revolutions per minute (rpm) is said to be rotating at either 2π rad/s *or* 1 Hz, where the former measures the angular velocity and the latter reflects the number of *complete* revolutions per second. The conversion between a frequency *f* measured in hertz and an angular velocity *ω* measured in radians per second is: w=2fπ.

Intensity (of a beam) = power/area

Units: w/m^2

Power and voltage (mW, dBm, volts)

$P_{(dBm)} = 10 \log_{10} P_{(mW)}$

$P_{(mW)} = 10^{(P_{(dBm)}/10)}$

$P_{(mW)} = [V_{RMS\,(V)}]^2 * 10^3/R$

$V_{RMS\,(V)} = \sqrt{(P_{(mW)} \cdot R / 10^3)}$

$V_P = \sqrt{2} * V_{RMS}$, for sinusoid – Fig. a.

$V_P = V_{RMS}$, for square wave – Fig. b.

$V_{P\text{-}P} = 2 * V_P$

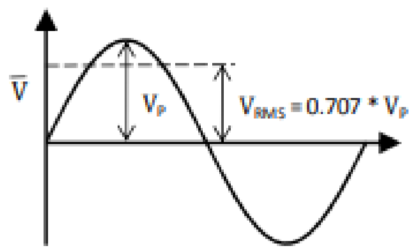


Fig. a. Sinusoidal signal

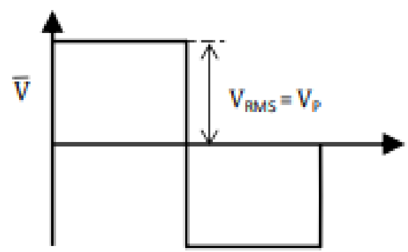


Fig. b. Square wave signal

dB	dBm	dBi
dB stands for Decibels.	dBm stands for Decibel Milliwatts.	dBi stands for Decibel Relative to Isotropic Gain.
It is the measure of loudness.	It is a unit used to express decibels in milliwatts and is often used to measure the strength of the signal in wires and cables.	It draws a comparison between a real antenna and a hypothetical isotropic antenna.
dB gives the ratio.	dBm gives absolute power.	dBi is used to measure the strength of the hypothetical antenna.
Formula $L_p = 10\log10(P/P_0)$ dB	Formula $S(dBm) = 10 \log_{10} P$	Formula $G(dBi) = 10 \log(G)$
dB is used to measure sound intensity	It is used to measure small values and is used in wires.	dBi is used to measure the performance of the antenna

Antenna Formulas:

Gain = directives X antenna efficiency

Amplitude of current = amplitude of voltage / impedance

Current lag behind voltage:

- arctan(reactance/resistance)

Impedance matching

- Keep same resistance, take negative reactance ⇒ put into vector form

The radiation intensity is a far field parameter which can be obtained by simply multiplying the radiation power density by the square distance.

As the source emits electromagnetic radiation of a given wavelength, the far-field electric component of the wave E, the far-field magnetic component H, and power density are related by the equations: E = H × 377 and Pd = E × H.

OR

Calculate the area of a beam using the radius in cm.

Divide the beam's power by that area.

POWER DENSITY

Radio Frequency (RF) propagation is defined as the travel of electromagnetic waves through or along a medium. For RF propagation between approximately 100 MHz and 10 GHz, radio waves travel very much as they do in free space and travel in a direct line of sight. There is a very slight difference in the dielectric constants of space and air. The dielectric constant of space is one. The dielectric constant of air at sea level is 1.000536. In all but the highest precision calculations, the slight difference is neglected.

From chapter 3, Antennas, an isotropic radiator is a theoretical, lossless, omnidirectional (spherical) antenna. That is, it radiates uniformly in all directions. The power of a transmitter that is radiated from an isotropic antenna will have a uniform power density (power per unit area) in all directions. The power density at any distance from an isotropic antenna is simply the transmitter power divided by the surface area of a sphere ($4\pi R^2$) at that distance. The surface area of the sphere increases by the square of the radius, therefore the power density, P_D, (watts/square meter) decreases by the square of the radius.

$$\begin{array}{l}\textit{Power density from}\\ \textit{an isotropic antenna}\end{array} = P_D = \frac{P_t}{4\pi R^2} \qquad \text{where: } \begin{array}{l} P_t = \textit{Transmitter Power} \\ R = \textit{Range From Antenna (i.e. radius of sphere)}\end{array} \qquad [1]$$

P_t is either peak or average power depending on how P_D is to be specified.

Radars use directional antennas to channel most of the radiated power in a particular direction. The Gain (G) of an antenna is the ratio of power radiated in the desired direction as compared to the power radiated from an isotropic antenna, or:

$$G = \frac{\textit{Maximum radiation intensity of actual antenna}}{\textit{Radiation intensity of isotropic antenna with same power input}}$$

The power density at a distant point from a radar with an antenna gain of G_t is the power density from an isotropic antenna multiplied by the radar antenna gain.

Power density from radar, $$P_D = \frac{P_t G_t}{4\pi R^2} \qquad [2]$$

P_t is either peak or average power depending on how P_D is to be specified.

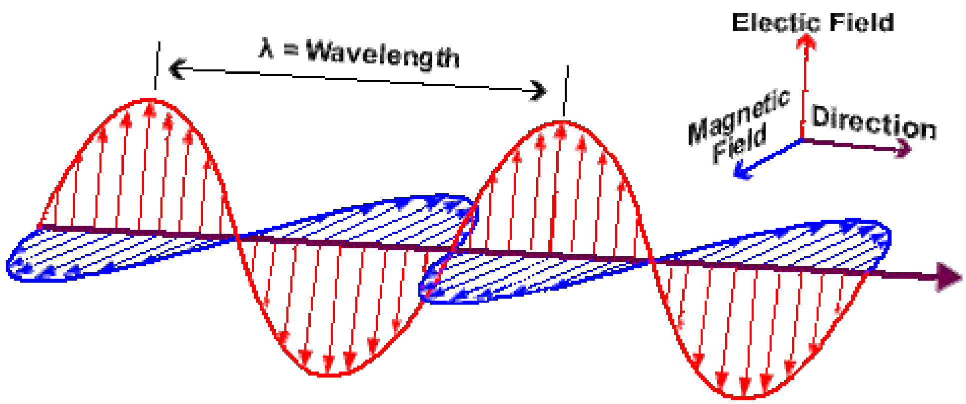
Another commonly used term is effective radiated power (ERP), and is defined as: $\mathbf{ERP = P_t\, G_t}$

A receiving antenna captures a portion of this power determined by it's effective capture Area (A_e). The received power available at the antenna terminals is the power density times the effective capture area (A_e) of the receiving antenna.

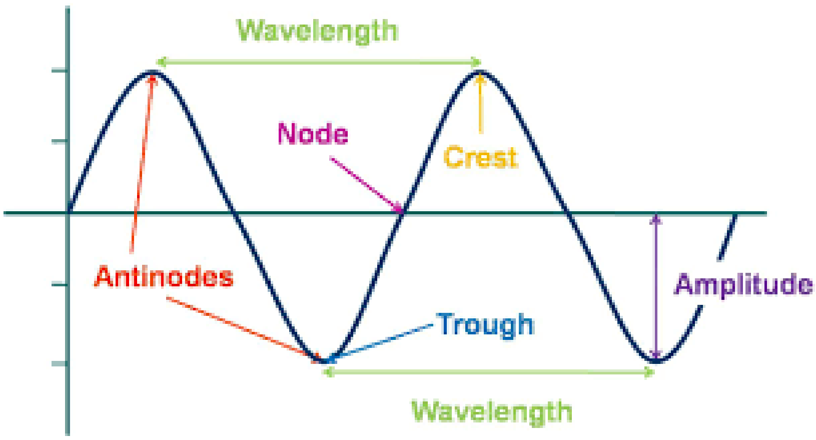
e.g. If the power density at a specified range is one microwatt per square meter and the antenna's effective capture area is one square meter then the power captured by the antenna is one microwatt.

For a given receiver antenna size the capture area is constant no matter how far it is from the transmitter, as illustrated in Figure 1. Also notice from Figure 1 that the received signal power decreases by 1/4 (6 dB) as the distance doubles. This is due to the R^2 term in the denominator of equation [2].

Wave References



Electromagnetic waves are transverse waves; the electric and magnetic fields oscillate in a plane that is perpendicular to the direction of propagation of the wave.



Crest/peak — highest point of wave
Trough — lowest point
Rest position — the position the wave would be in if there were no disturbances along it; aka normal position, equilibrium position
Wavelength — the distance between two crests or troughs, measured by distance units of metric system
Amplitude — distance between a crest or trough and the rest position, measured by metric distance units
Frequency — the number of wavelengths passed per second; measured in Hz
Period — the time it takes a wave to complete a wavelength (two successive crests to pass ; measured in seconds
Direction of motion — direction in which the wave moves
Direction of oscillation — direction in which particles in wave move, perpendicular to direction of motion
Velocity — speed and direction in which the wave is moving, equal to wavelength x frequency

Units:
Hertz – one cycle per second
M/s – velocity measurement
Electron volt -- a unit of energy equal to the work done on an electron in accelerating it through a potential difference of one volt.

- In physics, an **electronvolt** (symbol **eV**, also written **electron-volt** and **electron volt**) is the measure of an amount of kinetic energy gained by a single electron accelerating from rest through an electric potential difference of one volt in vacuum. When used as a unit of energy, the numerical value of 1 eV in joules (symbol J) is equivalent to the numerical value of the charge of an electron in coulombs (symbol C). Under the 2019 redefinition of the SI base units, this sets 1 eV equal to the exact value $1.602176634 \times 10^{-19}$ J.[1]

- Historically, the electronvolt was devised as a standard unit of measure through its usefulness in electrostatic particle accelerator sciences, because a particle with electric charge q gains an energy $E = qV$ after passing through a voltage of V. Since q must be an integer multiple of the elementary charge e for any isolated particle, the gained energy in units of electronvolts conveniently equals that integer times the voltage.

More Wave Info and Behavior

A pulse is a wave consisting of a single disturbance that moves through the medium with a constant amplitude.

Amplitude, Power, and Energy of Waves
Amount of energy in a wave is related to amplitude.

- Sound → higher amplitude = louder sound

A wave is a displacement that is resisted by a restoring force.
F = kx

Energy is related to amplitude because displacement (x) is related to amplitude, and work is related to F*x, which corresponds to the difference in energy.

W is proportional to Fx = kx^2
Energy is directly proportional to Amplitude^2

Modeling a Wave as an Oscillating String
Kinetic energy = potential energy = ¼ (u * A^2 * f^2 * w)
u = linear density
A = amplitude
f = frequency
w = angular frequency

Wave Intensity

In physics, the **intensity** or **flux** of radiant energy is the power transferred per unit area, where the area is measured on the plane perpendicular to the direction of propagation of the energy. In the SI system, it has units watts per square meter (W/m^2), or $kg{\cdot}s^{-3}$ in base units. Intensity is used most frequently with waves such as acoustic waves (sound) or electromagnetic waves such as light or radio waves, in which case the ***average*** power transfer over one period of the wave is used. *Intensity* can be applied to other circumstances where energy is transferred. For example, one could calculate the intensity of the kinetic energy carried by drops of water from a garden sprinkler.

The word "intensity" as used here is not synonymous with "strength", "amplitude", "magnitude", or "level", as it sometimes is in colloquial speech.

Intensity can be found by taking the energy density (energy per unit volume) at a point in space and multiplying it by the velocity at which the energy is moving. The resulting vector has the units of power divided by area (i.e., surface power density).

If a point source is radiating energy in all directions (producing a spherical wave), and no energy is absorbed or scattered by the medium, then the intensity decreases in proportion to the distance from the object squared. This is an example of the inverse-square law.

Applying the law of conservation of energy, if the net power emanating is constant,

$$P = \int \mathbf{I} \cdot d\mathbf{A},$$

where P is the net power radiated, **I** is the intensity vector as a function of position, the magnitude $|I|$ is the intensity as a function of position, and $d\mathbf{A}$ is a differential element of a closed surface that contains the source.

If one integrates a uniform intensity, $|I| = \text{constant}$, over a surface that is perpendicular to the intensity vector, for instance over a sphere centered around the point source, the equation becomes

$$P = |I| \cdot A_{\mathrm{surf}} = |I| \cdot 4\pi r^2 \ ,$$

where $|I|$ is the intensity at the surface of the sphere, r is the radius of the sphere.

Solving for $|I|$ gives

$$|I| = \frac{P}{A_{\mathrm{surf}}} = \frac{P}{4\pi r^2}.$$

If the medium is damped, then the intensity drops off more quickly than the above equation suggests.

Anything that can transmit energy can have an intensity associated with it. For a monochromatic propagating electromagnetic wave, such as a plane wave or a Gaussian beam, if E is the complex amplitude of the electric field, then the time-averaged energy density of the wave, traveling in a non-magnetic material, is given by:

$$\langle U \rangle = \frac{n^2 \varepsilon_0}{2} |E|^2,$$

and the local intensity is obtained by multiplying this expression by the wave velocity, c/n:

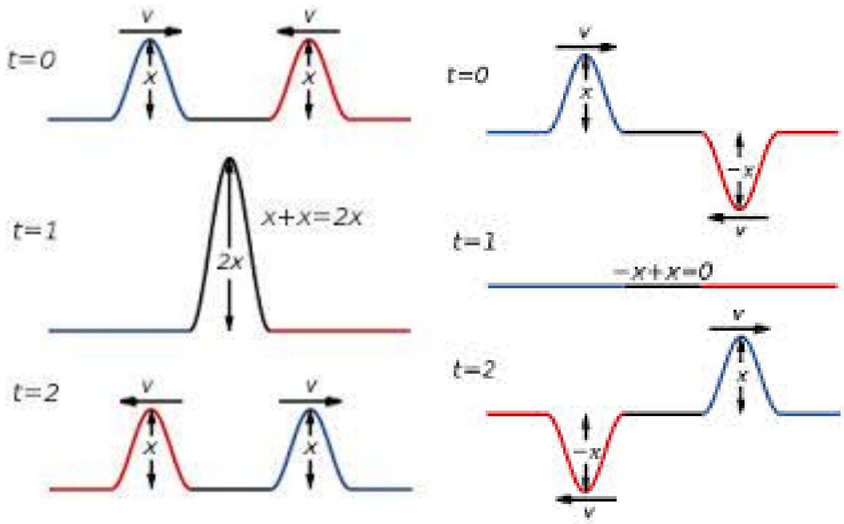
$$I = \frac{\mathrm{c} n \varepsilon_0}{2} |E|^2,$$

where n is the refractive index, c is the speed of light in vacuum and (funny looking E) is the vacuum permittivity.

For non-monochromatic waves, the intensity contributions of different spectral components can simply be added. The treatment above does not hold for arbitrary electromagnetic fields. For example, an evanescent wave may have a finite electrical amplitude while not transferring any power. The intensity should then be defined as the magnitude of the Poynting vector.[1]

Interference

- Two waves strike each other



Constructive Interference

- Two waves reinforce each otherl; meet crest to crest, creating a larger wave

Destructive Interference

- Two waves cancel out each other; meet trough to crest and cancel each other out

<u>Doppler Effect:</u>

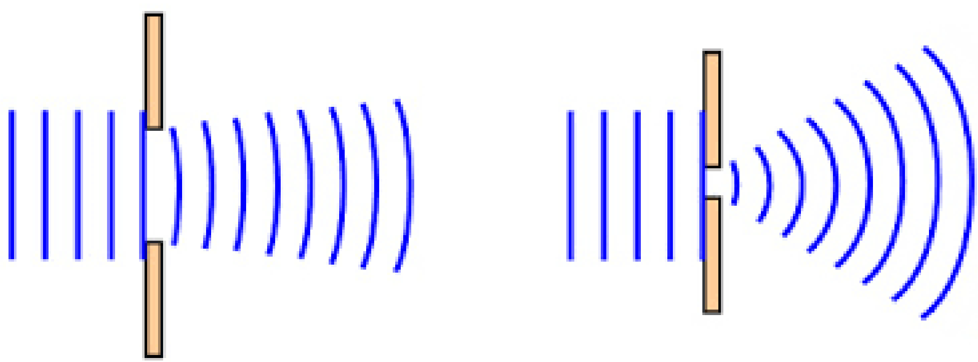
- Difference in frequency of wave caused by source moving relative to observer; crests of wave will bunch up in front of object and spread out behind, causing higher frequency when source moves towards observer and vice versa
- Equation:

f = (c + v1)/(c + v2) x f0

f is observed frequency; f0 is emitted frequency; c is wave's velocity in medium; v1 is velocity of observer relative to medium (positive or negative possibilities); v2 is velocity of source relative to medium

<u>Diffraction</u>

- Diffraction is when a wave spreads out when encountering a corner or hole that is comparable to its wavelength.



$$d \sin \theta = n\lambda$$

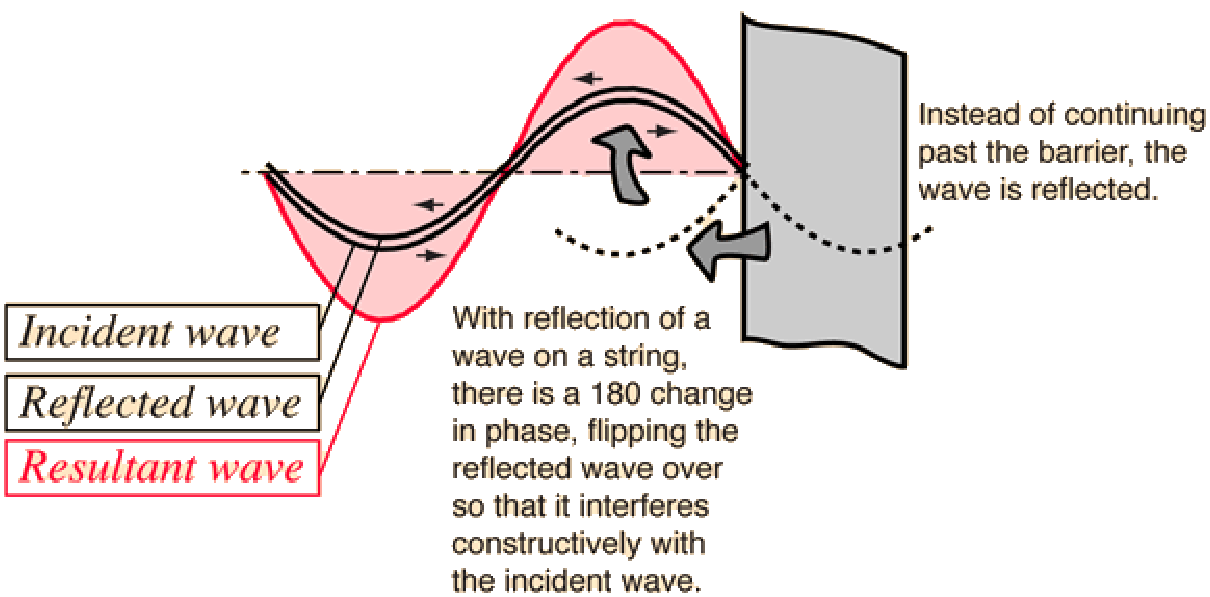
d = distance between slits

θ = diffraction angle

n = order number for the maximum

λ = wavelength

<u>Standing Waves</u>
Standing (stationary) waves are a combination of two waves moving in opposite directions, each having the same amplitude and frequency — when waves are superimposed, their energies are either added together or canceled out (interference).
Standing waves occur when a wave does not appear to be made up of moving waves. This is from a combination of reflection and interference. Nodes are points of maximum destructive interference while anti-nodes are points of maximum constructive interference.
The following image shows how a standing wave can be simulated by attaching a string to a barrier, like a wall, and then moving it up and down. As the string is moved up and down, it forms a wave, but the wave stops at the barrier instead of going past it. When the wave stops, it is reflected back towards where the string is being moved, which causes a 180-degree shift in phase. This causes the interference in the wave necessary for a standing wave. This experiment can be tried at home with simple materials and by attaching the string to a rigid object, such as a hook or a doorknob of a closed door.



<u>Specular Reflection</u>
If the reflection interface is very smooth, specular reflection will occur. Specular reflection is mirror-like (forms images).

Laws of reflection:

The normal, incident ray, and reflected ray all lie on the same plane.

The incident ray is the same angle from the normal as the reflected ray:
$\theta i = \theta r$

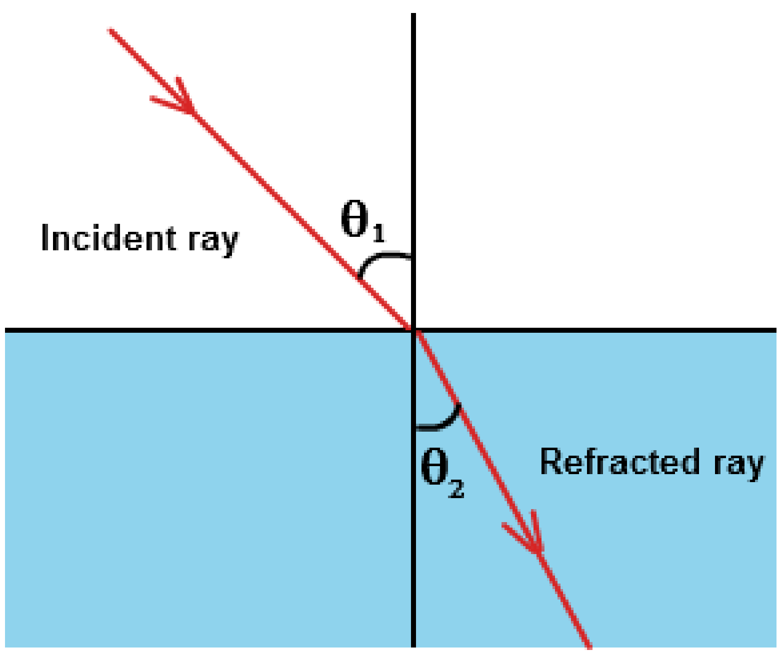
The incident ray and reflected ray are on opposite sides of the normal.

An image in a glass mirror is 1) virtual, 2) reversed, 3) the right side up, 4) the same size of the object, and 5) the same distance behind the mirror as the object is in front of the mirror.

Diffuse
If the reflection interface is rough (non-metallic), diffuse reflection will occur. Diffuse reflection is where an incident ray is reflected at many different angles as opposed to specular reflection with only one angle of reflection. The visibility of objects is primarily due to diffuse reflection. Diffuse interreflection occurs when light reflected off a nearby object reflects off surrounding objects, illuminating them.

Refraction
Refraction is the change in direction of a wave caused by a change in its medium. Refraction is responsible for rainbows and mirages.

Snell's Law



$(\sin(\theta 1)/\sin(\theta 2)) = v1/v2 = n1/n2$

$\theta 1$ is the angle between the incident ray and the normal,
$\theta 2$ is the angle between the refracted ray and the normal,
v1 is the velocity of light in the first medium (white),
v2 is the velocity of light in the second medium (blue),
n1 is the refractive index of the first medium (white),
n2 is the refractive index of the second medium (blue).

Rayleigh Criterion

- The Rayleigh Criterion estimates the angular resolution of an optical system, specifying the minimum separation between two light sources that can be resolved into distinct objects.
- Through a circular aperture, the equation is: $\theta = 1.220\frac{\lambda}{D}$
  - θ is the angular resolution (in radians), λ is the wavelength of the light, and D is the diameter of the lens' aperture.

Young's Equation

- Young's Equation finds the wavelength of a light source relative to certain distances associated with a two-point light interference pattern.
- $\lambda = y * \frac{d}{m * L}$
  - λ is the wavelength, y is the perpendicular distance from a point P on a nodal or antinodal line to a point on the central antinodal line, d is the distance between the slits or sources of light, m is the order value of the line P is on, L is the distance from point P to the sources of light.

Gratings

- A diffraction grating splits and diffracts light into many beams traveling in different directions and results in a characteristic rainbow-ish coloration. A grating typically has ridges on its surface. The grating equation relates the grating spacing and the angles of incident and diffracted light beams.
- $m\lambda = d(\sin\theta_i + \sin\theta_r)$
  - m is the diffraction order, λ is the wavelength, d is the spacing of the grooves or slits, θ_i is the angle of incidence, θ_2 is the angle of diffraction.

Harmonics and Resonant Frequency

- $f_n = (n+1) * f_0$
  - f is the nth harmonic frequency, n is the harmonic number, f_0 is the fundamental frequency.

Polarization - Malus' Law

- Malus' Law finds the intensity of light after passing through a linear polarizer.
- $I = I_0 \cos^2\theta_i$
  - I is the intensity, I_0 is the initial intensity of the light, θ_i is the angle between the light's initial polarization direction and the polarizer's axis.

Brewster's Angle

- Brewster's Angle is the angle of incidence where light with a certain polarization is transmitted through a transparent surface with no reflection.
- $\theta_i = \arctan \frac{n_2}{n_1}$
  - θ_i is the angle of incidence, n_1 is the first (incident) medium, n_2 is the second medium.

Energy of a Photon

- $E = hf = \frac{ch}{\lambda}$
  - E is the energy of a photon, h is Planck's constant (approximately $6.626 * 10^{-34} joule * s$, c is the speed of light (approximately $2.998 * 10^8 \frac{m}{s}$, λ is the wavelength
- Alternatively, $E = \frac{1.24}{\lambda}$, where λ is in micrometers and E comes out in electron-volts.

The Wave Equation

$$\underbrace{\hat{H}}_{\text{Hamiltonian Operator (Energy operator)}} \Psi = \underbrace{E}_{\text{Energy eigenvalue}} \Psi$$

The wave equation is a second-order linear partial differential equation for the description of waves — as they occur in classical physics.

Maxwell's Equations

$$\begin{aligned} \nabla \cdot \mathbf{D} &= \rho \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{H} &= \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \end{aligned}$$

In the differential equations,

- the nabla symbol, ∇, denotes the three-dimensional gradient operator, del,

- the $\nabla\cdot$ symbol (pronounced "del dot") denotes the divergence operator,
- the $\nabla\times$ symbol (pronounced "del cross") denotes the curl operator.

Maxwell's equations are a set of coupled partial differential equations that, together with the Lorentz force law, form the foundation of classical electromagnetism, classical optics, and electric circuits. The equations provide a mathematical model for electric, optical, and radio technologies, such as power generation, electric motors, wireless communication, lenses, radar etc. They describe how electric and magnetic fields are generated by charges, currents, and changes of the fields. The equations are named after the physicist and mathematician James Clerk Maxwell, who, in 1861 and 1862, published an early form of the equations that included the Lorentz force law. Maxwell first used the equations to propose that light is an electromagnetic phenomenon. The modern form of the equations in their most common formulation is credited to Oliver Heaviside.

Maxwell's equations may be combined to demonstrate how fluctuations in electromagnetic fields (waves) propagate at a constant speed, c (299792458 m/s in vacuum). Known as electromagnetic radiation, these waves occur at various wavelengths to produce a spectrum of radiation from radio waves to gamma rays.

The equations have two major variants. The *microscopic* equations have universal applicability but are unwieldy for common calculations. They relate the electric and magnetic fields to total charge and total current, including the complicated charges and currents in materials at the atomic scale. The *macroscopic* equations define two new auxiliary fields that describe the large-scale behavior of matter without having to consider atomic scale charges and quantum phenomena like spins. However, their use requires experimentally determined parameters for a phenomenological description of the electromagnetic response of materials. The term "Maxwell's equations" is often also used for equivalent alternative formulations. Versions of Maxwell's equations based on the electric and magnetic scalar potentials are preferred for explicitly solving the equations as a boundary value problem, analytical mechanics, or for use in quantum mechanics. The covariant formulation (on spacetime rather than space and time separately) makes the compatibility of Maxwell's equations with special relativity manifest. Maxwell's equations in curved spacetime, commonly used in high energy and gravitational physics, are compatible with general relativity. In fact, Albert Einstein developed special and general relativity to accommodate the invariant speed of light, a consequence of Maxwell's equations, with the principle that only relative movement has physical consequences.

The publication of the equations marked the unification of a theory for previously separately described phenomena: magnetism, electricity, light, and associated radiation. Since the mid-20th century, it has been understood that Maxwell's equations do not give an exact description of electromagnetic phenomena, but are instead a classical limit of the more precise theory of quantum electrodynamics.

Types of Waves

A wave transmits information or energy from one point to another in the form of signals, but no material object makes this journey.

A wave is a flow or transfer of energy in the form of oscillation through a medium – space or mass.

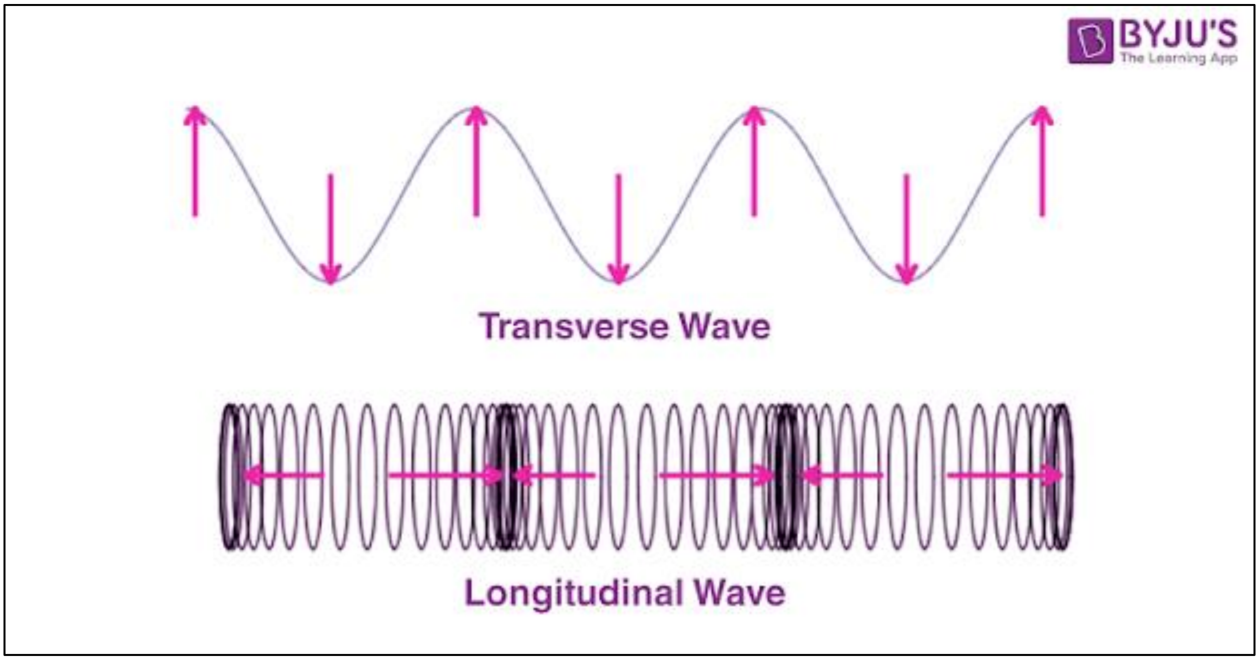
Different types of waves have different sets of characteristics. Based on the orientation of particle motion and direction of energy, there are three categories:

- Mechanical waves
- Electromagnetic waves
- Matter waves
- A mechanical wave is a wave that is an oscillation of matter and is responsible for the transfer of energy through a medium.
- The distance of the wave's propagation is limited by the medium of transmission. In this case, the oscillating material moves about a fixed point, and there is very little translational motion. **One intriguing property of**

mechanical waves is the way they are measured, which is given by displacement divided by the wavelength. When this dimensionless factor is 1, it generates harmonic effects; for example, waves break on the beach when this factor exceeds 1, resulting in turbulence.

There are two types of mechanical waves:

- **Longitudinal waves –** In this type of wave, the movement of the particles is parallel to the motion of the energy, i.e. the displacement of the medium is in the same direction in which the wave is moving. Example – Sound Waves, Pressure Waves.
- **Transverse waves –** When the movement of the particles is at right angles or perpendicular to the motion of the energy, then this type of wave is known as a transverse wave. Light is an example of a transverse wave.



Water waves are an example of a combination of both longitudinal and transverse motions.

- **Surface waves –** In this type, the particles travel in a circular motion. These waves usually occur at interfaces. Waves in the ocean and ripples in a cup of water are examples of such waves.
- Electromagnetic waves are created by a fusion of electric and magnetic fields.
- One interesting property here is that unlike mechanical waves, electromagnetic waves do not need a medium to travel.

Following are the different types of electromagnetic waves:

- Microwaves
- X-ray
- Radio waves
- Ultraviolet waves

Difference Between Mechanical Wave and Non-Mechanical Wave

Mechanical Waves vs Non-Mechanical Waves	
Mechanical Wave	**Non-Mechanical Wave**
Mechanical waves are waves that need a medium for propagation.	Non-mechanical waves are waves that do not need any medium for propagation.
Sound waves, water waves and seismic waves are some examples of mechanical waves.	The electromagnetic wave is the only non-mechanical wave.
Mechanical waves cannot travel through vacuum	Non-mechanical waves can travel through vacuum

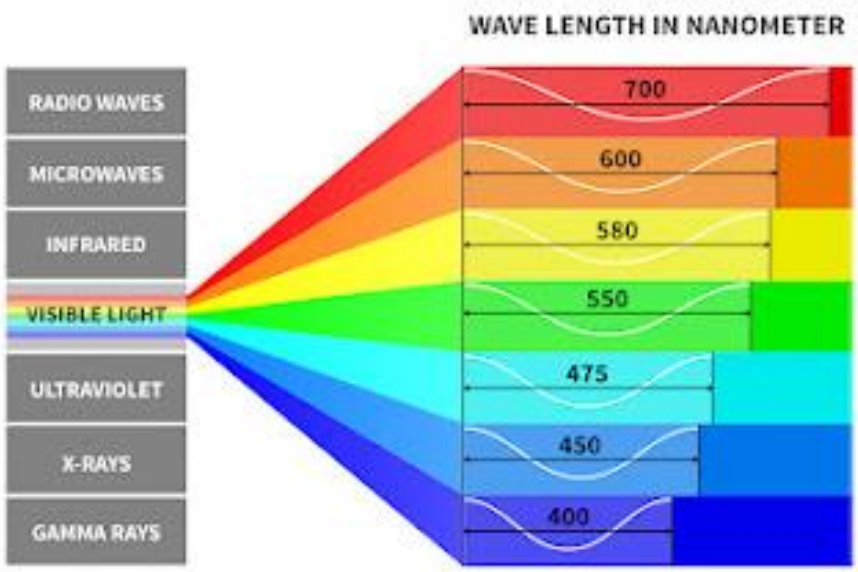
Matter Wave

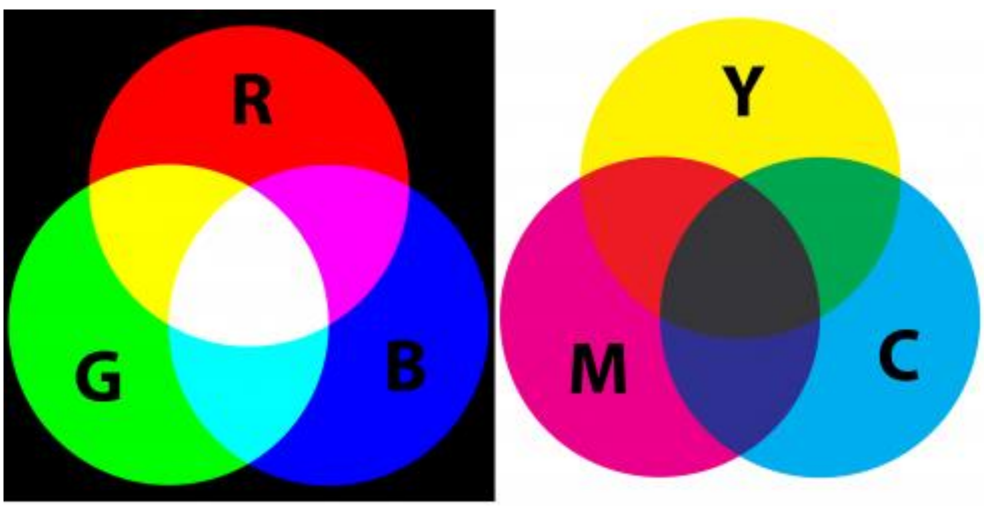
- This concept is a little complicated to understand. The dual nature of matter; its ability to exist both as a particle and a wave was first brought to light by the founders of the field of Quantum Physics.
- For example, a beam of electrons can be diffracted just like any other beam of electromagnetic radiation or water wave. This property of matter was brought forward by Louis de Broglie’s Hypothesis.

No, mechanical waves cannot travel through vacuum. Waves that do not need any medium for propagation are known as non-mechanical waves.

Types of mechanical waves are: Longitudinal waves, transverse waves

Overview on Visible Light





Left: light mixing; Right: pigment mixing

Filters

Filters: absorptive and dichroic/interference/thin film/reflective

Absorptive filters are usually made of glass with several compounds added which absorb specific wavelengths of light. They can also be made of plastic, which the compounds are added to, to produce gel filters.

Dichroic filters have little reflective cavities which resonate with specific wavelengths. Using destructive interference, the wavelengths are canceled out, leaving the rest of the wavelengths to pass through. They are used for precise scientific work since their exact color range can be controlled. Interference filters are more expensive and more delicate.

Long-Pass Filter: Transmits waves with wavelengths longer than a specific range, Attenuates waves with shorter wavelengths

Short-Pass Filter: Transmits waves with wavelengths shorter than a specific range, Attenuates waves with longer wavelengths

Bandpass-Filter: Combination of long-pass and short-pass filters, transmits waves with a wavelength in a specific interval

Monochromatic Filter: Only a small range (usually one color) of wavelengths is allowed to pass.

Infrared Filter: The term can refer to infrared-passing or infrared cut-off filters, infrared photography (passing), projectors (cut-off),

Ultraviolet Filter: Block ultraviolet rays but transmit visible light rays, ultraviolet pass and ultraviolet bandpass filters are much less common, used in cameras

Neutral Density Filter: Attenuate all wavelengths of visible light, optical density is the common logarithm of the transmission coefficient, which is

Amplitude initial : amplitude incident OR intensity initial : intensity incident, make photographic exposures longer

Polarizer Filter: Blocks light depending on its polarization, usually made of Polaroid, sunglasses and photography, darker color

Spectra

Spectra are an application of the visible light spectrum to specific materials. Since certain materials have a unique absorption spectrum and emission spectrum associated with them, spectra can be used to identify unknown materials. They can also be used to learn more about materials at a microscopic level, including things such as molecular structure, crystal structure, and purity.

Big organizations >:(~regulatory bodies*

https://www.fcc.gov/engineering-technology/policy-and-rules-division/general/radio-spectrum-allocation

IEEE: Institute of Electrical and Electronics Engineers
FCC: Federal Communications Commission
NTIA: National Telecommunications and Information Administration
CORF: The National Academy of Sciences' Committee on Radio Frequencies
ARRL: The American Radio Relay League
ITU: International Telecommunication Union
ITU-R: ITU Radiocommunication Sector
CEPT: European Conference of Postal and Telecommunications Administrations

A Written History of Antenna-Related Stuff

1830s — Michael Faraday — Did the first experiments that coupled electricity and magnetism and showed a definitive relationship. He slid a magnet around the coils of a wire attached to a galvanometer. In moving the magnet, he was in effect creating a time-varying magnetic field, which as a result (from Maxwell's Equations), must have had a time-varying electric field. The coil acted as a loop antenna and received the electromagnetic radiation, which was received (detected) by the galvanometer - the work of an antenna. The concept of electromagnetic waves had not even been thought up at this point.

1842 — Joseph Henry-Princeton — inventor of wire telegraphy, upper room to cellar 30 feet below magnetize needles. By “throwing a spark” to a circuit of wire in an upper room, Henry found that the current received in a parallel circuit in a cellar 30 ft below could magnetize needles. Later experiments extended the range, possibly up to half a mile.

In the 1860s (1865), James Clerk Maxwell united electricity and magnetism into electromagnetism, he described light as—and proved it to be—an electromagnetic phenomenon. He predicted the existence of electromagnetic waves at radio frequencies, that is at much lower frequencies than light. In 1886, Maxwell was proven right by Heinrich Rudolf Hertz who—without realizing it himself —created the first ever radio system, consisting of a transmitter and a receiver (induction coil and leyden jar).

1875 — Thomas Edison — discovered telegraphy key-clicks radiated at a distance; used vertical, top-loaded, grounded antenna (wire antenna)

Heinrich Hertz developed a wireless communication system in which he forced an electrical spark to occur in the gap of a dipole antenna. He used a loop antenna as a receiver, and observed a similar disturbance. This was 1886. He verified Maxwell’s theory of the dipole antenna and did research in the loop antenna, grating of wires, and fundamentals of polarization. He also experimented with microwave antennas — cylindrical parabolic antenna, 1888.

By 1901, Marconi was sending information across the atlantic. For a transmit antenna, he used several vertical wires attached to the ground. Across the Atlantic Ocean, the receive antenna was a 200 meter wire held up by a kite.

In 1906, Columbia University had an Experimental Wireless Station where they used a transmitting aerial cage. This was a cage made up of wires and suspended in the air, resembling a cage.

1917 – Marconi station N.J. (22 KHz) – 5000 ft by 600 ft on top of 13 masts, each 400 ft high

1919 – aircraft and dirigible antennas communicate over trans-Atlantic

1923 – H.H. Beverage – wave tilt antenna

1922 – Taylor and Young (Navy Research) detected moving objects by radio

1928 – Yagi Uda in Japan – endfire array with parasitic elements

1931 – Microwave link between France and England

Yagi-Uda Antenna, 1920s (1926)
Invented by Shintaro Uda of Tohoku Imperial University with a small role played by Hidetsugu Yagi. Uda established the concept through experiment, but Yagi filed a patent first and transferred it to the Marconi Company, later transferred the patent to RCA Corporation.

Were first used widely during World War II in radar systems by Japan, Germany, Britain, and the US. Later became popular for television antennas.

VHF Radar, 1935

FM Broadcast at 2.5 m, 1935

TV Broadcast at 45 MHz, 1936

Horn antennas, 1938/9.
Early antenna literature discussed waveguides (1936) as "hollow metal pipes". The inventor of both was Wilmer Lanier Barrow, while it was invented independently also by G.C. Southworth.

1939 – Slot antenna (resonant) – A.D. Blumlein

Antenna Arrays, 1940s
Credited to Ferdinand Braun, Nobel Prize winner, who placed three monopoles in a triangle.

Parabolic Reflectors, late 1940s, early 1950s

Equiangular Spiral, 1955 Dyson

Conical Spiral, 1959 Dyson

Dish Antennas, 1960s

1965 – Synchronous satellites, log periodic dipole arrays (Dwight Isbell)

Microstrip/Patch Antennas, 1970s

Planar Inverted-F Antennas, 1980s

Wifi protocol comparison

2.4 GHz	5 GHz
11 channels, 20 MHz wide 9 non-overlapping channels Transmits farther	The 5 GHz Wi-Fi band covers a 150 MHz range from 5.725 GHz to 5.875 GHz!!! 24 non-overlapping channels Widest channels

Bluetooth

Bluetooth is a short-range wireless technology standard that is used for exchanging data between fixed and mobile devices over short distances and building personal area networks (PANs). In the most widely used mode, transmission power is limited to 2.5 milliwatts, giving it a very short range of up to 10 metres (33 ft). It employs UHF radio waves in the ISM bands, from 2.402 GHz to 2.48 GHz.[3] It is mainly used as an alternative to wire connections, to exchange files between nearby portable devices and connect cell phones and music players with wireless headphones.

Bluetooth is managed by the Bluetooth Special Interest Group (SIG), which has more than 35,000 member companies in the areas of telecommunication, computing, networking, and consumer electronics. The IEEE standardized Bluetooth as IEEE 802.15.1, but no longer maintains the standard. The Bluetooth SIG oversees development of the specification, manages the qualification program, and protects the trademarks.[4] A manufacturer must meet Bluetooth SIG standards to market it as a Bluetooth device.[5] A network of patents apply to the technology, which are licensed to individual qualifying devices. As of 2009, Bluetooth integrated circuit chips ship approximately 920 million units annually.[6] By 2017, there were 3.6 billion Bluetooth devices being shipped annually and the shipments were expected to continue increasing at about 12% a year.[7] In 2021, shipments reached 4.7 billion units, with 9% growth forecast. [8]

HISTORY OF WIFI PROTOCOLS

- In 1971, ALOHAnet connected the Hawaiian Islands with a UHF wireless packet network. ALOHAnet and the ALOHA protocol were early forerunners to Ethernet, and later the IEEE 802.11 protocols, respectively.
- Vic Hayes is often regarded as the “father of Wi-Fi.” He started such work in 1974 when he joined NCR Corp., now part of semiconductor components maker Agere Systems.
- A 1985 ruling by the U.S. Federal Communications Commission released the ISM band for unlicensed use – these are frequencies in the 2.4GHz band. These frequency bands are the same ones used by equipment such as microwave ovens and are subject to interference.
- In 1991, NCR Corporation with AT&T Corporation invented the precursor to 802.11, intended for use in cashier systems. The first wireless products were under the name WaveLAN. They are the ones credited with inventing Wi-Fi.
- The Australian radio-astronomer John O’Sullivan with his colleagues Terence Percival, Graham Daniels, Diet Ostry, John Deane developed a key patent used in Wi-Fi as a by-product of a Commonwealth Scientific and Industrial Research Organization (CSIRO) research project, “a failed experiment to detect exploding mini black holes the size of an atomic particle”.
- In 1992 and 1996, CSIRO obtained patents for a method later used in Wi-Fi to “unsmear” the signal.
- The first version of the 802.11 protocol was released in 1997, and provided up to 2 Mbit/s link speeds. This was updated in 1999 with 802.11b to permit 11 Mbit/s link speeds, and this proved to be popular.

802.11-1997 (802.11 legacy)
The original version of the standard IEEE 802.11 was released in 1997 and clarified in 1999, but is now obsolete. It specified two net bit rates of 1 or 2 megabits per second (Mbit/s), plus forward error correction code. Some earlier WLAN technologies used lower frequencies, such as the U.S. 900 MHz ISM band.

802.11b (1999)
The 802.11b standard has a maximum raw data rate of 11 Mbit/s, and uses the same media access method defined in the original standard. 802.11b products appeared on the market in early 2000, since 802.11b is a direct extension of the modulation technique defined in the original standard. The dramatic increase in throughput of 802.11b (compared to the original standard) along with simultaneous substantial price reductions led to the rapid acceptance of 802.11b as the definitive wireless LAN technology. Devices using 802.11b experience interference from other products operating in the 2.4 GHz band. Devices operating in the 2.4 GHz range include microwave ovens, Bluetooth devices, baby monitors, cordless telephones, and some amateur radio equipment.

802.11a (2012, OFDM waveform)

The 802.11a standard uses the same data link layer protocol and frame format as the original standard, but an OFDM based air interface (physical layer). It operates in the 5 GHz band with a maximum net data rate of 54 Mbit/s, plus error correction code, which yields realistic net achievable throughput in the mid-20 Mbit/s.
Since the 2.4 GHz band is heavily used to the point of being crowded, using the relatively unused 5 GHz band gives 802.11a a significant advantage. However, this high carrier frequency also brings a disadvantage: the effective overall range of 802.11a is less than that of 802.11b/g. In theory, 802.11a signals are absorbed more readily by walls and other solid objects in their path due to their smaller wavelength, and, as a result, cannot penetrate as far as those of 802.11b. In practice, 802.11b typically has a higher range at low speeds (802.11b will reduce speed to 5.5 Mbit/s or even 1 Mbit/s at low signal strengths). 802.11a also suffers from interference, but locally there may be fewer signals to interfere with, resulting in less interference and better throughput.

802.11g (2003)
In June 2003, a third modulation standard was ratified: 802.11g. This works in the 2.4 GHz band (like 802.11b), but uses the same OFDM based transmission scheme as 802.11a. It operates at a maximum physical layer bit rate of 54 Mbit/s exclusive of forward error correction codes, or about 22 Mbit/s average throughput. Like 802.11b, 802.11g devices suffer interference from other products operating in the 2.4 GHz band, for example wireless keyboards.

802.11 (2007)
In 2003, task group TGma was authorized to “roll up” many of the amendments to the 1999 version of the 802.11 standard. REVma or 802.11ma, as it was called, created a single document that merged 8 amendments (802.11a, b, d, e, g, h, i, j) with the base standard. Upon approval on March 8, 2007, 802.11REVma was renamed to the then-current base standard IEEE 802.11-2007.

802.11n (2009)
802.11n is an amendment that improves upon the previous 802.11 standards by adding multiple-input multiple-output antennas (MIMO). 802.11n operates on both the 2.4 GHz and the 5 GHz bands. Support for 5 GHz bands is optional. It operates at a maximum net data rate from 54 Mbit/s to 600 Mbit/s. The IEEE has approved the amendment, and it was published in October 2009.

802.11 (2012)
In May 2007, task group TGmb was authorized to “roll up” many of the amendments to the 2007 version of the 802.11 standard. REVmb or 802.11mb, as it was called, created a single document that merged ten amendments (802.11k, r, y, n, w, p, z, v, u, s) with the 2007 base standard. In addition much cleanup was done, including a reordering of many of the clauses. Upon publication on March 29, 2012, the new standard was referred to as IEEE 802.11-2012.

802.11ac (2013)
IEEE 802.11ac-2013 is an amendment to IEEE 802.11, published in December 2013, that builds on 802.11n. Changes compared to 802.11n include wider channels (80 or 160 MHz versus 40 MHz) in the 5 GHz band, more spatial streams (up to eight versus four), higher-order modulation (up to 256-QAM vs. 64-QAM), and the addition of Multi-user MIMO (MU-MIMO). As of October 2013, high-end implementations support 80 MHz channels, three spatial streams, and 256-QAM, yielding a data rate of up to 433.3 Mbit/s per spatial stream, 1300 Mbit/s total, in 80 MHz channels in the 5 GHz band.

802.11ad (2010)
IEEE 802.11ad is an amendment that defines a new physical layer for 802.11 networks to operate in the 60 GHz millimeter wave spectrum. This frequency band has significantly different propagation characteristics than the 2.4 GHz and 5 GHz bands where Wi-Fi networks operate. Products implementing the 802.11ad standard are being brought to market under the WiGig brand name. The certification program is now being developed by the Wi-Fi Alliance instead of the now defunct WiGig Alliance. The peak transmission rate of 802.11ad is 7 Gbit/s.

802.11af (2014)

IEEE 802.11af, also referred to as "White-Fi" and "Super Wi-Fi" is an amendment, approved in February 2014, that allows WLAN operation in TV white space spectrum in the VHF and UHF bands between 54 and 790 MHz. It uses cognitive radio technology to transmit on unused TV channels, with the standard taking measures to limit interference for primary users, such as analog TV, digital TV, and wireless microphones.

801.11 Wifi Protocols and Data Rates

Protocol	**Frequency**	**Channel Width**	MIMO	**Maximum data rate (theoretical)**	**Date Released**
802.11ax	2.4 or 5GHz	20, 40, 80, 160MHz	Multi User (MU-MIMO)	2.4 Gbps1	
802.11ac wave2	5 GHz	20, 40, 80, 160MHz	Multi User (MU-MIMO)	1.73 Gbps2	June 2016
802.11ac wave1	5 GHz	20, 40, 80MHz	Single User (SU-MIMO)	866.7 Mbps2	January 2014
802.11n	2.4 or 5 GHz	20, 40MHz	Single User (SU-MIMO)	450 Mbps3	
802.11g	2.4 GHz	20 MHz	N/A	54 Mbps	2003
802.11a	5 GHz	20 MHz	N/A	54 Mbps	1999
802.11b	2.4 GHz	20 MHz	N/A	11 Mbps	1999
Legacy 802.11	2.4 GHz	20 MHz	N/A	2 Mbps	1997

1 2 Spatial streams with 1024-QAM modulation.
2 2 Spatial streams with 256-QAM modulation.
3 3 Spatial streams with 64-QAM modulation.

802.11ax (Wi-Fi 6)

- Supports both 2.4 & 5 GHz

Mode	**Maximum rate**	**Antenna transmit / receive arrangements**
1x1 20 MHz	143 Mbps	1 TX (Transmit, Upload), 1 RX (Receive, Download)
2x2 20 MHz	287 Mbps	2 TX, 2 RX
1x1 40 MHz	287 Mbps	1 TX, 1 RX
2x2 40 MHz	574 Mbps	2 TX, 2 RX

1x1 80 MHz	601 Mbps	1 TX, 1 RX
2x2 80 MHz	1.2 Gbps	2 TX, 2 RX
1x1 160 MHz	1.2 Gbps	1 TX, 1 RX
2x2 160 MHz	2.4 Gbps	2 TX, 2 RX

802.11ac wave2

- Released in June 2016.
- Key New Features for Wi-Fi clients:
    - Multi-User MIMO
    - 160 MHz channels

Mode	Maximum rate	Antenna transmit / receive arrangements
1x1 40 MHz	200 Mbps	1 TX, 1 RX
2x2 40 MHz	400 Mbps	2 TX, 2 RX
1x1 80 MHz	433 Mbps	1 TX, 1 RX
2x2 80 MHz	866 Mbps	2 TX, 2 RX
1x1 160 MHz	866 Mbps	1 TX, 1 RX
2x2 160 MHz	1.73 Gbps	2 TX, 2 RX

802.11ac wave1

- Released in January 2014.
- Data rates varying modulation types and number of spatial streams; 200 Mbps, 400 Mbps, 433 Mbps, 600 Mbps, 867 Mbps. See table below.
- 24 non-overlapping unlicensed national information infrastructure (UNII) channels in 5 GHz frequency band.

Mode	Maximum rate	Antenna transmit / receive arrangements
1x1 40 MHz	200 Mbps	1 TX, 1 RX
2x2 40 MHz	400 Mbps	2 TX, 2 RX
1x1 80 MHz	433 Mbps	1 TX, 1 RX
2x2 80 MHz	866 Mbps	2 TX, 2 RX

802.11n

- Data rates with varying modulation types: 1, 2, 5.5, 6, 9, 11, 12, 18, 24, 36, 48, 54 Mbps (see table below)
- Orthogonal frequency-division multiplexing (OFDM) using multiple-input/multiple-output (MIMO) and channel bonding (CB)
- Three non-overlapping channels in industrial, scientific, medical (ISM) frequency band at 2.4 GHz
- 12 non-overlapping unlicensed national information infrastructure (UNII) channels in 5 GHz

frequency band with and without CB

Note	We recommend channel bonding for the 5 GHz because there are a limited number of non-overlapping channels available in the 2.4 GHz band.

Mode	Maximum rate	Antenna transmit / receive arrangements
1x1 20 MHz	72.2 Mbps	1 TX, 1 RX
1x1 40 Mhz	150 Mbps	1 TX, 1 RX
2x2 20 MHz	144.4 Mbps	2 TX, 2 RX
2x2 40 MHz	300 Mbps	2 TX, 2 RX
3x3 20 MHz	216.7 Mbps	3 TX ,3 RX
3x3 40 MHz	450 Mbps	3 TX, 3 RX

802.11g

- Released in 2003.
- Data rates with varying modulation types: 6, 9, 12, 18, 24, 36, 48 and 54 Mbps; can revert to 1, 2, 5.5, and 11 Mbps using DSSS and CCK.
- Orthogonal frequency-division multiplexing (OFDM) with 52 subcarrier channels; backwards compatible with 802.11b using DSSS and CCK.
- Three non-overlapping channels in industrial, scientific, medical (ISM) frequency band at 2.4 GHz.

802.11a

- Released in 1999.
- Data rates with varying modulation types: 6, 9, 12, 18, 24, 36, 48 and 54 Mbps.
- Orthogonal frequency-division multiplexing (OFDM) with 52 subcarrier channels.
- 12 non-overlapping unlicensed national information infrastructure (UNII) channels in 5 GHz frequency band.

802.11b

- Released in 1999.
- Data rates with varying modulation types: 1, 2, 5.5 and 11 Mbps.
- High-rate direct-sequence spread spectrum (HR-DSSS).
- Three non-overlapping channels in industrial, scientific, medical (ISM) frequency band at 2.4 GHz.

Legacy 802.11

- Released in 1997.

- Two raw data rates of 1 and 2 Mbps.
- Frequency hopping spread spectrum (FHSS) or direct-sequence spread spectrum (DSSS).
- Three non-overlapping channels in industrial, scientific, medical (ISM) frequency band at 2.4 GHz.
- Originally defined carrier sense multiple access with collision avoidance (CSMA-CA).

HISTORY OF WIFI PROTECTION PROTOCOLS

	WEP	WPA	WPA2	WPA3
Release Year	1999	2003	2004	2018
Encryption Method	Rivest Clipher 4 (RC4)	Temporal Key Integrity Protocol(TKIP) with RC4	CCMP and Advanced Encryption Standard	Advanced Encryption Standard(AES)
Session Key Size	40-bit	128-bit	128-bit	128-bit(WPA3-Personal) 192-bit(WPA3-Enterprise)
Clipher Type	Stream	Stream	Block	Block
Data Integrity	CRC-32	Message Integrity Code	CBC-MAC	Secure Hash Algorithm
Key Management	Not provided	4-way handshaking mechanism	4-way handshaking mechanism	Simultaneous Authentication of Equals handshark
Authentication	WPE-Open WPE-Shared	Pre-Shared Key(PSK)& 802.1x with EAP variant	Pre-Shared Key(PSK)& 802.1x with EAP variant	Simultaneous Authentication of Equals(SAE)&802.1x with EAP variant

WEP—The first Wi-Fi Security Protocol

WEP stands for Wired Equivalent Privacy, and it was the first Wi-Fi security protocol approved in September 1999. It was initially expected to deliver the same security level as wired networks. A secondary function of WEP is said to prevent unauthorized access to a wireless network. However, it has been found that WEP is not as secure as desired. WEP is used at the two lowest layers of the OSI model – the data link and physical layers; it therefore does not offer end-to-end security. Nevertheless, at that time, cryptographic technology was restricted and the Wi-Fi devices were limited to 64-bit encryption. Even though the limitation was broken through and increased to 128-bit, there were also many security issues in WEP that made the keys easy to crack. Therefore, WEP, as a highly vulnerable wireless security protocol that can not bear its responsibility for protecting security, was finally replaced by WPA.

WPA—Temporary Enhancement for WEP

In 2003, as WEP gradually performed its weakness, WPA was adopted by the Wi-Fi Alliance as an alternative for WEP. 256-bit encryption technology was introduced to WPA, which is an obvious increase compared with the 64-bit and 128-bit encryption in the WEP system. In the WPA standard, there is a diversity between the two modes: WPA-Enterprise and WPA-Personal, which use different encryption methods. WPA-Personal is a common method to secure wireless networks, and it is suitable for most home networks. WPA-Enterprise provides the security needed for wireless networks in business environments where a RADIUS server is deployed.

WPA2—Improvement Based on WPA

WPA2 was ratified as the new Wi-Fi security standard in 2004. The most significant improvement in the WPA2 security standard is the implementation of the Advanced Encryption Standard (AES), which provides higher security and performance. There is still a vulnerability that brings security problems because a hacker can get access to a secured WPA2 network and get access to certain keys to attack other devices on the same network. It is a security issue that matters for enterprise networks, instead of home network users.

WPA3—The Next-Generation Wi-Fi Security

With the aim to “simplify Wi-Fi security, enable more robust authentication and deliver increased cryptographic strength for highly sensitive data markets”, WPA3 was proposed by the Wi-Fi Alliance in June 2018. The advent of WPA3 remedies the protection against the flaws in WPA2 such as dictionary attacks. For public networks such as coffee shops or hotels, WPA3 has really good security because it will automatically encrypt the connection without any need for credentials.

WPA-Personal

Also referred to as *WPA-PSK* (pre-shared key) mode, this is designed for home and small office networks and does not require an authentication server. Each wireless network device encrypts the network traffic by deriving its 128-bit encryption key from a 256-bit shared key. This key may be entered either as a string of 64 hexadecimal digits, or as a passphrase of 8 to 63 printable ASCII characters. This pass-phrase-to-PSK mapping is nevertheless not binding, as Annex J is informative in the latest 802.11 standard. If ASCII characters are used, the 256-bit key is calculated by applying the PBKDF2 key derivation function to the passphrase, using the SSID as the salt and 4096 iterations of HMAC-SHA1. WPA-Personal mode is available on all three WPA versions.

WPA-Enterprise

Also referred to as *WPA-802.1X mode*, and sometimes just *WPA* (as opposed to WPA-PSK), this is designed for enterprise networks and requires a RADIUS authentication server. This requires a more complicated setup, but provides additional security (e.g. protection against dictionary attacks on short passwords). Various kinds of the Extensible Authentication Protocol (EAP) are used for authentication. WPA-Enterprise mode is available on all three WPA versions.

Wi-Fi Protected Setup (WPS)

This is an alternative authentication key distribution method intended to simplify and strengthen the process, but which, as widely implemented, creates a major security hole via WPS PIN recovery.

Encryption protocol

TKIP (Temporal Key Integrity Protocol)

The RC4 stream cipher is used with a 128-bit per-packet key, meaning that it dynamically generates a new key for each packet. This is used by WPA.

CCMP (CTR mode with CBC-MAC Protocol)

The protocol used by WPA2, based on the Advanced Encryption Standard (AES) cipher along with strong message authenticity and integrity checking, is significantly stronger in protection for both privacy and integrity than the RC4-based TKIP that is used by WPA. Among informal names are *AES* and *AES-CCMP*. According to the 802.11n specification, this encryption protocol must be used to achieve fast 802.11n high bitrate schemes, though not all implementations enforce this.Otherwise, the data rate will not exceed 54 Mbit/s.

Security issues

Weak password

Pre-shared keys WPA and WPA2 remain vulnerable to password cracking attacks if users rely on a weak password or passphrase. WPA passphrase hashes are seeded from the SSID name and its length; rainbow tables exist for the top 1,000 network SSIDs and a multitude of common passwords, requiring only a quick lookup to speed up cracking WPA-PSK. Brute forcing of simple passwords can be attempted using the Aircrack Suite starting from the four-way authentication handshake exchanged during association or periodic re-authentication. WPA3 replaces cryptographic protocols susceptible to off-line analysis with protocols that require interaction with the infrastructure for each guessed password, supposedly placing temporal limits on the number of guesses. However, design flaws in WPA3 enable attackers to plausibly launch brute-force attacks (see Dragonblood attack).

Lack of forward secrecy

WPA and WPA2 do not provide forward secrecy, meaning that once an adverse person discovers the pre-shared key, they can potentially decrypt all packets encrypted using that PSK transmitted in the future and even past, which could be passively and silently collected by the attacker. This also means an attacker can silently capture and decrypt others' packets if a WPA-protected access point is provided free of charge at a public place, because its password is usually shared to anyone in that place. In other words, WPA only protects from attackers who do not have access to the password. Because of that, it's safer to use Transport Layer Security (TLS) or similar on top of that for the transfer of any sensitive data. However starting from WPA3, this issue has been addressed.

WPA packet spoofing and decryption

Mathy Vanhoef and Frank Piessens significantly improved upon the WPA-TKIP attacks of Erik Tews and Martin Beck. They demonstrated how to inject an arbitrary number of packets, with each packet containing at most 112 bytes of payload. This was demonstrated by implementing a port scanner, which can be executed against any client using WPA-TKIP. Additionally, they showed how to decrypt arbitrary packets sent to a client. They mentioned this can be used to hijack a TCP connection, allowing an attacker to inject malicious JavaScript when the victim visits a website. In contrast, the Beck-Tews attack could only decrypt short packets with mostly known content, such as ARP messages, and only allowed injection of 3 to 7 packets of at most 28 bytes. The Beck-Tews attack also requires quality of service (as defined in 802.11e) to be enabled, while the Vanhoef-Piessens attack does not. Neither attack leads to recovery of the shared session key between the client and Access Point. The authors say using a short rekeying interval can prevent some attacks but not all, and strongly recommend switching from TKIP to AES-based CCMP.

Halvorsen and others show how to modify the Beck-Tews attack to allow injection of 3 to 7 packets having a size of at most 596 bytes. The downside is that their attack requires substantially more time to execute: approximately 18 minutes and 25 seconds. In other work Vanhoef and Piessens showed that, when WPA is used to encrypt broadcast packets, their original attack can also be executed. This is an important extension, as substantially more networks use WPA to protect broadcast packets, than to protect unicast packets. The execution time of this attack is on average around 7 minutes, compared to the 14 minutes of the original Vanhoef-Piessens and Beck-Tews attack.

The vulnerabilities of TKIP are significant because WPA-TKIP had been held before to be an extremely safe combination; indeed, WPA-TKIP is still a configuration option upon a wide variety of wireless routing devices provided by many hardware vendors. A survey in 2013 showed that 71% still allow usage of TKIP, and 19% exclusively support TKIP.

WPS PIN recovery

A more serious security flaw was revealed in December 2011 by Stefan Viehböck that affects wireless routers with the Wi-Fi Protected Setup (WPS) feature, regardless of which encryption method they use. Most recent models have this feature and enable it by default. Many consumer Wi-Fi device manufacturers had taken steps to eliminate the potential of weak passphrase choices by promoting alternative methods of automatically generating and distributing strong keys when users add a new wireless adapter or appliance to a network. These methods include pushing buttons on the devices or entering an 8-digit PIN.

The Wi-Fi Alliance standardized these methods as Wi-Fi Protected Setup; however, the PIN feature as widely implemented introduced a major new security flaw. The flaw allows a remote attacker to recover the WPS PIN and, with it, the router's WPA/WPA2 password in a few hours. Users have been urged to turn off the WPS feature, although this may not be possible on some router models. Also, the PIN is written on a label on most Wi-Fi routers with WPS, and cannot be changed if compromised.

WPA3 introduces a new alternative for the configuration of devices that lack sufficient user interface capabilities by allowing nearby devices to serve as an adequate UI for network provisioning purposes, thus mitigating the need for WPS.

MS-CHAPv2 and lack of AAA server CN validation

Several weaknesses have been found in MS-CHAPv2, some of which severely reduce the complexity of brute-force attacks, making them feasible with modern hardware. In 2012 the complexity of breaking MS-CHAPv2 was reduced to that of breaking a single DES key (work by Moxie Marlinspike and Marsh Ray). Moxie advised: "Enterprises who are depending on the mutual authentication properties of MS-CHAPv2 for connection to their WPA2 Radius servers should immediately start migrating to something else."

Tunneled EAP methods using TTLS or PEAP which encrypt the MSCHAPv2 exchange are widely deployed to protect against exploitation of this vulnerability. However, prevalent WPA2 client implementations during the early 2000s were prone to misconfiguration by end users, or in some cases (e.g. Android), lacked any user-accessible way to properly configure validation of AAA server certificate CNs. This extended the relevance of the original weakness in MSCHAPv2 within MiTM attack scenarios. Under stricter WPA2 compliance tests announced alongside WPA3, certified client software will be required to conform to certain behaviors surrounding AAA certificate validation.

Hole196

Hole196 is a vulnerability in the WPA2 protocol that abuses the shared Group Temporal Key (GTK). It can be used to conduct man-in-the-middle and denial-of-service attacks. However, it assumes that the attacker is already authenticated against Access Point and thus in possession of the GTK.

Predictable Group Temporal Key (GTK)

In 2016 it was shown that the WPA and WPA2 standards contain an insecure expository random number generator (RNG). Researchers showed that, if vendors implement the proposed RNG, an attacker is able to predict the group key (GTK) that is supposed to be randomly generated by the access point (AP). Additionally, they showed that possession of the GTK enables the attacker to inject any traffic into the network, and allowed the attacker to decrypt unicast internet traffic transmitted over the wireless network. They demonstrated their attack against an Asus RT-AC51U router that uses the MediaTek out-of-tree drivers, which generate the GTK themselves, and showed the GTK can be recovered within two minutes or less. Similarly, they demonstrated the keys generated by Broadcom access daemons running on VxWorks 5 and later can be recovered in four minutes or less, which affects, for example, certain versions of Linksys WRT54G and certain Apple AirPort Extreme models. Vendors can defend against this attack by using a secure RNG. By doing so, Hostapd running on Linux kernels is not vulnerable against this attack and thus routers running typical OpenWrt or LEDE installations do not exhibit this issue.

KRACK attack

In October 2017, details of the KRACK (Key Reinstallation Attack) attack on WPA2 were published. The KRACK attack is believed to affect all variants of WPA and WPA2; however, the security implications vary between implementations, depending upon how individual developers interpreted a poorly specified part of the standard. Software patches can resolve the vulnerability but are not available for all devices.

Dragonblood attack

In April 2019, serious design flaws in WPA3 were found which allow attackers to perform downgrade attacks and side-channel attacks, enabling brute-forcing the passphrase, as well as launching denial-of-service attacks on Wi-Fi base stations.

Electromagnetic Waves

The electromagnetic spectrum is the range of frequencies of electromagnetic radiation. The frequencies of these waves are measured in hertz (Hz). The frequency range is divided into separate bands, with the waves within these bands having different names. From the largest wavelength to the shortest, these bands are radio waves, microwaves, infrared and visible light, ultraviolet, x-rays, and gamma rays.

X-rays and gamma rays are known as ionizing radiation and can be dangerous if an organism is exposed to them for too long. X-rays are defined as electronic transitions; gamma rays are generated from nuclear processes such as decay. Both gamma and X-rays have uses in medicine, and gamma rays may be used in the sterilization of food and seeds. UV rays are not ionizing, but can still break chemical bonds, causing sunburn and potentially skin cancer, but most damaging UV rays emitted by the sun are absorbed by the atmosphere (blocked by the ozone layer or absorbed by oxygen or nitrogen in the air).

Visible light occupies a small portion of the electromagnetic spectrum, with different visible colors the result of differing electromagnetic wavelengths – red having the longest and purple the shortest. Electromagnetic radiation between 400-790 terahertz (THz) is visible to the human eye, but sometimes infrared and ultraviolet rays can be referred to as light. Infrared rays are useful in thermal imaging and occasionally in data transmission. Television remotes transmit signals using infrared light (which is why if the front of the remote is blocked the signal won't be received). Some infrared light can be detected by photographic film.

Microwave and radio waves have the lowest frequency of the electromagnetic spectrum, and are known for their use in microwave ovens. They can also be used in industrial heating and radar systems, as well as transmitting information. However, at that intensity microwaves do not have the same heating effects.

Non-radio Wave Uses

Microwave: High frequency microwaves have frequencies which are easily absorbed by molecules in food. The internal energy of the molecules increases when they absorb microwaves, which causes heating. Microwaves pass easily through the atmosphere, so they can pass between stations on Earth and satellites in orbit.

Infrared: Infrared light is used by electrical heaters, cookers for cooking food, and by infrared cameras which detect people in the dark. Security lights and remote controls for TV use infrared waves.

Visible: Visible light is the light we can see. It is used in fiber optic communications, where coded pulses of light travel through glass fibers from a source to a receiver.

UV: We cannot see ultraviolet (UV) light but it can have hazardous effects on the human body. Ultraviolet light in sunlight can cause the skin to tan or burn and can also damage eyes. Fluorescent substances are used in energy-efficient lamps – they absorb ultraviolet light produced inside the lamp, and re-emit the energy as visible light. UV light is also used for banknote security and disinfecting water.

Ionizing radiation: Changes in atoms and their nuclei can cause electromagnetic waves to be generated or absorbed. Gamma rays are produced by changes in the nucleus of an atom. They are a form of nuclear radiation. High energy waves such as X-rays and gamma rays are transmitted through body tissues with very little absorption. This makes them ideal for internal imaging. X-rays are absorbed by dense structures like bones, which is why X-ray photos are used to help identify broken bones. They can add or remove electrons from molecules, producing electrically charged ions.

Radio Waves

WiFi is transmitted over radio waves. Radio waves are transmitted and received by antennas and are widely used to transmit information. They are also used for GPS systems and locating distant objects with radars. To generate radio waves, a transmitter generates an AC current which is applied to the antenna and generates and electric and magnetic field.

Radio waves travel at the speed of light (299,775 km/s)

Wifi is often transmitted over the 2.4 GHz and 5.8 GHz bands which are divided into multiple channels. These channels can be shared by multiple networks, making WiFi more vulnerable to attack than wired connections, but security protocols have been created so that WiFI access is as secure as possible, including the WEP and WPA protocols.

- Radio waves are used for communication such as television and radio. **Radio waves are transmitted easily through air. They do not cause damage if absorbed by the human body, and they can be reflected to change their direction.** These properties make them ideal for communications.
- Radio waves can be produced by oscillations in electrical circuits. Also, when radio waves are absorbed by a conductor, they create an alternating current. This electrical current has the same frequency as the radio waves. Information is coded into the wave before transmission, which can then be decoded when the wave is received. Television and radio systems use this principle to broadcast information.
- Jamming: radio frequency signals coming from sources outside of a radar that transmit in the same frequency as the radar, masking potential targets of interest

EM Wave Propagation

Electromagnetic waves are different from mechanical waves in that they don't require a medium to propagate – they can travel not only through air and solid materials, but also through the vacuum of space. (Mechanical waves are caused by a disturbance or vibration in matter, whether solid, gas, liquid or plasma, and the matter that waves travel through is called a medium. They travel through the medium by causing molecules to bump into each other, like falling dominoes transferring energy).

Electromagnetic waves are created by a charge moving through a magnetic field. Vibration (accelerating) of an electric charge → wave (with electric and magnetic component); process of the oscillating electric field producing and oscillating magnetic field is known as electromagnetic induction

Electricity can be static, as well as magnetism. A changing magnetic field will induce a changing electric field and vice-versa (the two are linked). The changing fields form electromagnetic waves.

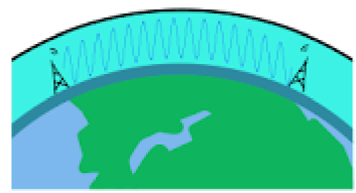
In the 1860's and 1870's, the Scottish scientist James Clerk Maxwell developed a scientific theory to explain electromagnetic waves. He noticed that electrical fields and magnetic fields can couple together to form electromagnetic waves, summing this relationship between electricity and magnetism into what are now referred to as "Maxwell's Equations." Heinrich Hertz (a German physicist) applied Maxwell's theories to the production and reception of radio waves; the unit of frequency of a radio wave – one cycle per second – is named the hertz. His experiment solved two things: 1. He demonstrated that the velocity of radio waves was equal to that of light (proving that radio waves was equal to the velocity of light) and 2. He figured out how to make the electric and magnetic fields detach from wires and go free as electromagnetic waves.

Light is made of packets of energy called photons, which carry momentum, have no mass, and travel and the speed of light; all light has particle-like and wave-like properties. An instrument's design influences the properties of light that are observed.

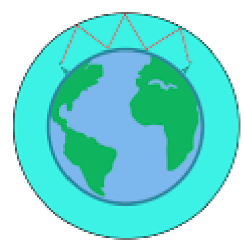
Radio Wave Propagation

BASIC INFO

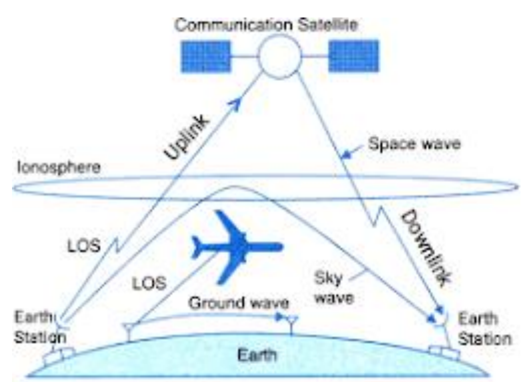
1. Line-of-sight propagation
    a. Travel directly in a line from transmitting antenna to receiving antenna; can pass through obstructions at lower frequencies
        i. Distance from transmitter to receiver is minimized
    b. Most common propagation mode at VHF and above, and the only possible mode at microwave frequencies and above
    c. Limited to ~40 miles on surface of the Earth- used by cell phones, cordless phones, walkie-talkies, wireless networks (wifi), FM, TV broadcasting, radar
    d. Longer line-of-sight paths are used for satellite communication
2. Ground propagation
    a. Travel as surface waves following the contour of the Earth
        i. Propagates by interacting with the conductive surface of the Earth- "clings" to the surface and can travel over mountains
        ii. Propagate in vertical polarization -> monopoles are required



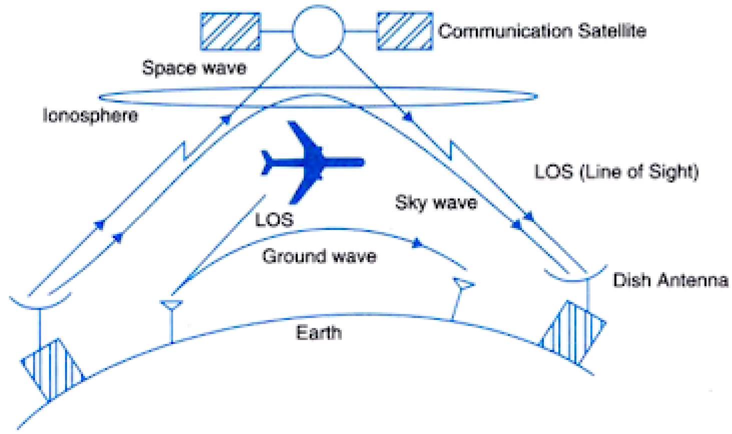
    b. Seen in lower frequency (30-3000 kHz or LF/MF band) vertically polarized radio waves
        i. Ground is not a perfect electrical conductor- waves are attenuated as they follow the Earth's surface (proportional to frequency)
        ii. At even lower frequencies (VLF - ELF), Earth-ionosphere waveguide mechanism -> longer range transmission (secure military coms)
    c. Used for relatively local communication coverage
3. Sky-wave propagation
    a. Rely on reflection and refraction from the ionosphere
        i. Ionosphere: region of atmosphere (60-500 km; above the mesosphere) containing layers of ions which can refract a radio wave back toward Earth
        ii. Radio wave directed at an angle into the sky can be reflected back to Earth -> long distance communication (radio transmission)



4. Space wave propagation
    a. Radio waves that occur within 20km of the atmosphere
    b. $Dm = (2RHt)^{-\frac{1}{2}} + (2RHr)^{-\frac{1}{2}}$
        i. Dm: distance between the two antennas
        ii. R: radius of the earth
        iii. Ht: height of transmission antenna
        iv. Hr: height of receiver antenna
    c. Used in communication systems
        i. Line of sight and satellite communication
        ii. Radar communication
        iii. Microwave linking



There are three main ways in which radio waves may be sent from a transmitter to a receiver, which are LOS, ground wave, and sky wave, but there are others too.



LOS:
The simplest is line-of-sight or LOS propagation, which occurs when the signal is sent straight from the transmitter to the receiver through the shortest possible straight line path. This is used for shorter distances because the signal can be affected by obstacles and can only be used when the transmitter and receiver are in view of each other.

- Limited to about 40 miles/64 km
- Used for cell phones, cordless phones, walkie-talkies, wireless networks, FM and television broadcasting and radar. Satellite communication uses longer LOS paths.

Low-powered microwave transmitters can be foiled by tree branches, or even heavy rain or snow. The presence of objects not in the direct line-of-sight can cause diffraction effects that disrupt radio transmissions. For the best propagation, a volume known as the first Fresnel zone should be free of obstructions.

Reflected radiation from the surface of the surrounding ground or salt water can also either cancel out or enhance the direct signal. This effect can be reduced by raising either or both antennas further from the ground: the reduction in loss achieved is known as *height gain*.

It is important to take into account the curvature of the Earth for calculation of line-of-sight paths from maps, when a direct visual fix cannot be made. Designs for microwave formerly used ⅘ earth radius to compute clearances along the path.

The *radio horizon* is the locus of points at which direct rays from an antenna are tangential to the surface of the Earth. If the Earth were a perfect sphere without an atmosphere, the radio horizon would be a circle.

The radio horizon of the transmitting and receiving antennas can be added together to increase the effective communication range.

Radio wave propagation is affected by atmospheric conditions, ionospheric absorption, and the presence of obstructions, for example mountains or trees. Simple formulas that include the effect of the atmosphere give the range as:

$$\mathrm{horizon}_{\mathrm{mi}} \approx 1.23 \cdot \sqrt{\mathrm{height}_{\mathrm{feet}}}$$

$$\mathrm{horizon}_{\mathrm{km}} \approx 3.57 \cdot \sqrt{\mathrm{height}_{\mathrm{metres}}}$$

Earth bulge refers to the effect of earth's curvature on radio propagation. It is a consequence of a circular segment of earth profile that blocks off long distance communications. Since the vacuum line of sight passes at varying heights over the Earth, the propagating radio wave encounters slightly different propagation conditions over the path.

Ground Wave:
Another method is ground wave propagation (slightly better than LOS), where the signal travels in a curved path around the Earth, allowing it to go farther. The radio wave propagates by interacting with the conductive surface of Earth, “clinging” to the surface; vertically polarized radio waves can travel as surface waves following the contour of Earth, which is called ground wave propagation.

- Used for lower frequencies (MF, LF, VLF bands), between 30-3000 kHz.

- Vertical antennas (monopoles) are required to make the waves vertically polarized
- Used for radio broadcasting stations, time signals, radio navigation

Ground wave refers to the propagation of radio waves parallel to and adjacent to the surface of the Earth, following the curvature of the Earth. This radiative ground wave is known as the Norton surface wave, or more properly the Norton ground wave, because ground waves in radio propagation are not confined to the surface. Another type of surface wave is the non-radiative, bound-mode Zenneck surface wave or Zenneck–Sommerfeld surface wave. The earth has one refractive index and the atmosphere has another, thus constituting an interface that supports the guided Zenneck wave's transmission. Other types of surface wave are the trapped surface wave, the gliding wave and Dyakonov surface waves (DSW) propagating at the interface of transparent materials with different symmetry. Apart from these, various types of surface waves have been studied for optical wavelengths.
Lower frequency radio waves, below 3 MHz, travel efficiently as ground waves. In ITU nomenclature, this includes (in order): medium frequency (MF), low frequency (LF), very low frequency (VLF), ultra low frequency (ULF), super low frequency (SLF), extremely low frequency (ELF) waves.

Ground propagation works because lower-frequency waves are more strongly diffracted around obstacles due to their long wavelengths, allowing them to follow the Earth's curvature. Ground waves propagate in vertical polarization, with their magnetic field horizontal and electric field (close to) vertical.

Conductivity of the surface affects the propagation of ground waves, with more conductive surfaces such as sea water providing better propagation. Increasing the conductivity in a surface results in less dissipation.The refractive indices are subject to spatial and temporal changes. Since the ground is not a perfect electrical conductor, ground waves are attenuated as they follow the earth's surface. The wavefronts initially are vertical, but the ground, acting as a lossy dielectric, causes the wave to tilt forward as it travels. This directs some of the energy into the earth where it is dissipated, so that the signal decreases exponentially.

Most long-distance LF "longwave" radio communication (between 30 kHz and 300 kHz) is a result of groundwave propagation. Mediumwave radio transmissions (frequencies between 300 kHz and 3000 kHz), including AM broadcast band, travel both as groundwaves and, for longer distances at night, as skywaves. Ground losses become lower at lower frequencies, greatly increasing the coverage of AM stations using the lower end of the band. The VLF and LF frequencies are mostly used for military communications, especially with ships and submarines. The lower the frequency the better the waves penetrate sea water. ELF waves (below 3 kHz) have even been used to communicate with deeply submerged submarines.

Ground waves have been used in over-the-horizon radar, which operates mainly at frequencies between 2–20 MHz over the sea, which has a sufficiently high conductivity to convey them to and from a reasonable distance (up to 100 km or more; over-horizon radar also uses skywave propagation at much greater distances).

Sky Wave:
Sky wave propagation utilizes a layer of the atmosphere (ionosphere) to bounce the signal to the receiver. The signal is sent up to the ionosphere, is reflected, hits the ground, and continues the cycle until reaching the destination.

- The ionosphere is located about 60-500 km or 37-311 miles above ground level
- Used for amateur radio operators, commercial marine and aircraft communications, and shortwave broadcasters
- This is more difficult and can only be used in the frequency range from 2-30 MHz.
- Potential effects include diffraction, absorption, and scattering in the atmosphere

Low Angle Skywaves

The ionosphere is a region of the upper atmosphere, from about 80 km to 1000 km in altitude, where neutral air is ionized by solar photons and cosmic rays. When high-frequency signals enter the ionosphere at a low angle they are bent back towards the earth by the ionized layer. If the peak ionization is strong enough for the chosen frequency, a wave will exit the bottom of the layer earthwards – as if obliquely reflected from a mirror. Earth's surface (ground or water) then reflects the descending wave back up again towards the ionosphere.

When operating at frequencies just below the maximum useable frequency, losses can be quite small, so the radio signal may effectively "bounce" or "skip" between the earth and ionosphere two or more times (multi-hop propagation), even following the curvature of the earth. Consequently, even signals of only a few Watts can sometimes be received many thousands of miles away. This is what enables shortwave broadcasts to travel all over the world. If the ionization is not great enough, the wave only curves slightly downwards, and subsequently upwards as the ionization peak is passed so that it exits the top of the layer only slightly displaced. The wave is then lost in space. To prevent this, a lower frequency must be chosen. With a single "hop", path distances up to 3500 km may be reached. Longer transmissions can occur with two or more hops.

Near-Vertical Skywaves

Skywaves directed almost vertically are referred to as *near-vertical-incidence skywaves* (*NVIS*). At some frequencies, generally in the lower shortwave region, the high angle skywaves will be reflected directly back towards the ground. When the wave returns to ground it is spread out over a wide area, allowing communications within several hundred miles of the transmitting antenna. NVIS enables local plus regional communications, even from low-lying valleys, to a large area, for example, an entire state or small country. Coverage of a similar area via a line-of-sight VHF transmitter would require a very high mountaintop location. NVIS is thus useful for statewide networks, such as those needed for emergency communications. In short wave broadcasting, NVIS is very useful for regional broadcasts that are targeted to an area that extends out from the transmitter location to a few hundred miles, such as would be the case in a country or language group to be reached from within the borders of that country. This will be much more economical than using multiple FM (VHF) or AM broadcast transmitters. Suitable antennas are designed to produce a strong lobe at high angles. When short range skywave is undesirable, as when an AM broadcaster wishes to avoid interference between the ground wave and sky wave, anti-fading antennas are used to suppress the waves being propagated at the higher angles.

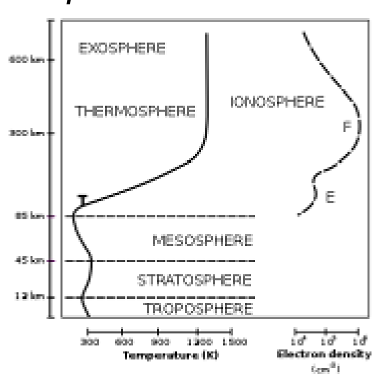
Intermediate Distance Coverage

For every distance, from local to maximum distance transmission, (DX), there is an optimum "take off" angle for the antenna, as shown here. For example, using the F layer during the night, to best reach a receiver 500 miles away, an antenna should be chosen that has a strong lobe at 40 degrees elevation. One can also see that for the longest distances, a lobe at low angles (below 10 degrees) is best. For NVIS, angles above 45 degrees are optimum. Suitable antennas for long distance would be a high Yagi or a rhombic; for NVIS, a dipole or array of dipoles about .2 wavelengths above ground; and for intermediate distances, a dipole or Yagi at about .5 wavelengths above ground. Vertical patterns for each type of antenna are used to select the proper antenna.

Fading

At any distance sky waves will fade. The layer of ionospheric plasma with sufficient ionization (the reflective surface) is not fixed, but undulates like the surface of the ocean. Varying reflection efficiency from this changing surface can cause the reflected signal strength to change, causing "*fading*" in shortwave broadcasts. Even more serious fading can occur when signals arrive via two or more paths, for example when both single-hop and double-hop waves interfere with each other, or when a skywave signal and a ground-wave signal arrive at about the same strength. This is the most common source of fading with nighttime AM broadcast signals. Fading is always present with sky wave signals, and except for digital signals such as DRM seriously limit the fidelity of shortwave broadcasts.

Ionosphere



The ionosphere is a shell of electrons and electrically charged atoms and molecules that surrounds the Earth, stretching from a height of about 50 km (30 mi) to more than 1,000 km (600 mi). It exists primarily due to ultraviolet radiation from the Sun.

At heights of above 80 km (50 mi), in the thermosphere, the atmosphere is so thin that free electrons can exist for short periods of time before they are captured by a nearby positive ion. The number of these free electrons is sufficient to affect radio propagation. This portion of the atmosphere is partially *ionized* and contains a plasma which is referred to as the ionosphere.

Ultraviolet (UV), X-ray and shorter wavelengths of solar radiation are *ionizing,* since photons at these frequencies contain sufficient energy to dislodge an electron from a neutral gas atom or molecule upon absorption. The reverse process to ionization is recombination, in which a free electron is "captured" by a positive ion. The balance between these two processes determines the quantity of ionization present.

Ionization depends primarily on the Sun and its activity. The amount of ionization in the ionosphere varies greatly with the amount of radiation received from the Sun. Thus there is a diurnal (time of day) effect and a seasonal effect. The local winter hemisphere is tipped away from the Sun, thus there is less received solar radiation. The activity of the Sun modulates following the solar cycle, with more radiation occurring with more sunspots, with a periodicity of around 11 years. Radiation received also varies with geographical location (polar, auroral zones, mid-latitudes, and equatorial regions). There are also mechanisms that disturb the ionosphere and decrease the ionization, such as solar flares.

At night the F layer is the only layer of significant ionization present, while the ionization in the E and D layers is extremely low. During the day, the D and E layers become much more heavily ionized, as does the F layer, which develops an additional, weaker region of ionization known as the F_1 layer. The F_2 layer persists by day and night and is the main region responsible for the refraction and reflection of radio waves.

D Layer

The D layer is the innermost layer, 48 km (30 mi) to 90 km (56 mi) above the surface of the Earth. Ionization here is due to Lyman series-alpha hydrogen radiation at a wavelength of 121.6 nanometre (nm) ionizing nitric oxide (NO). In addition, high solar activity can generate hard X-rays (wavelength < 1 nm) that ionize N_2 and O_2. Recombination rates are high in the D layer, so there are many more neutral air molecules than ions.

Medium frequency (MF) and lower high frequency (HF) radio waves are significantly attenuated within the D layer, as the passing radio waves cause electrons to move, which then collide with the neutral molecules, giving up their energy. Lower frequencies experience greater absorption because they move the electrons farther, leading to greater chance of collisions. This is the main reason for absorption of HF radio waves, particularly at 10 MHz and below, with progressively less absorption at higher frequencies. This effect peaks around noon and is reduced at night due to a decrease in the D layer's thickness; only a small part remains due to cosmic rays. A common example of the D layer in action is the disappearance of distant AM broadcast band stations in the daytime.

During solar proton events, ionization can reach unusually high levels in the D-region over high and polar latitudes. Such very rare events are known as Polar Cap Absorption (or PCA) events, because the increased ionization significantly enhances the absorption of radio signals passing through the region.[14] In fact, absorption levels can increase by many tens of dB during intense events, which is enough to absorb most (if not all) transpolar HF radio signal transmissions. Such events typically last less than 24 to 48 hours.

E layer

The E layer is the middle layer, 90 km (60 mi) to 150 km (90 mi) above the surface of the Earth. Ionization is due to soft X-ray (1–10 nm) and far ultraviolet (UV) solar radiation ionization of molecular oxygen (O_2). Normally, at oblique incidence, this layer can only reflect radio waves having frequencies lower than about 10 MHz and may contribute a bit to absorption on frequencies above. However, during intense sporadic E events, the E_s layer can reflect frequencies up to 50 MHz and higher. The vertical structure of the E layer is primarily determined by the competing effects of ionization and recombination. At night the E layer weakens because the primary source of ionization is no longer present. After sunset an increase in the height of the E layer maximum increases the range to which radio waves can travel by reflection from the layer.

This region is also known as the Kennelly–Heaviside layer or simply the Heaviside layer.

Sporadic E-layer

The E_s layer (sporadic E-layer) is characterized by small, thin clouds of intense ionization, which can support reflection of radio waves, frequently up to 50 MHz and rarely up to 450 MHz. Sporadic-E events may last for just a few minutes to many hours. Sporadic E propagation makes VHF-operating by radio amateurs very exciting when long distance propagation paths that are generally unreachable "open up" to two-way communication. There are multiple causes of sporadic-E that are still being pursued by researchers. This propagation occurs every day during June and

July in northern hemisphere mid-latitudes when high signal levels are often reached. The skip distances are generally around 1,640 km (1,020 mi). Distances for one hop propagation can be anywhere from 900 km (560 mi) to 2,500 km (1,600 mi). Multi-hop propagation over 3,500 km (2,200 mi) is also common, sometimes to distances of 15,000 km (9,300 mi) or more.

F Layer

The F layer or region, also known as the Appleton–Barnett layer, extends from about 150 km (90 mi) to more than 500 km (300 mi) above the surface of Earth. It is the layer with the highest electron density, which implies signals penetrating this layer will escape into space. Electron production is dominated by extreme ultraviolet (UV, 10–100 nm) radiation ionizing atomic oxygen. The F layer consists of one layer (F_2) at night, but during the day, a secondary peak (labeled F_1) often forms in the electron density profile. Because the F_2 layer remains by day and night, it is responsible for most skywave propagation of radio waves and long distance high frequency (HF, or shortwave) radio communications.

Above the F layer, the number of oxygen ions decreases and lighter ions such as hydrogen and helium become dominant. This region above the F layer peak and below the plasmasphere is called the topside ionosphere.

Space wave propagation:

A radio wave that travels directly from a high transmitting antenna to the receiving station/antenna. The radio waves there can propagate either directly or after reflection from the ground or in the atmosphere.

Tropospheric Scatter:

Tropospheric scatter, also known as troposcatter, is a method of communicating with microwave radio signals over considerable distances – often up to 500 kilometers (310 mi) and further depending on frequency of operation, equipment type, terrain, and climate factors. This method of propagation uses the tropospheric scatter phenomenon, where radio waves at UHF and SHF frequencies are randomly scattered as they pass through the upper layers of the troposphere. Radio signals are transmitted in a narrow beam aimed just above the horizon in the direction of the receiver station. As the signals pass through the troposphere, some of the energy is scattered back toward the Earth, allowing the receiver station to pick up the signal.[1]

It was developed in the 1950s and used for military communications until communications satellites largely replaced it in the 1970s.

Because the troposphere is turbulent and has a high proportion of moisture, the tropospheric scatter radio signals are refracted and consequently only a tiny proportion of the transmitted radio energy is collected by the receiving antennas. Frequencies of transmission around 2 GHz are best suited for tropospheric scatter systems as at this frequency the wavelength of the signal interacts well with the moist, turbulent areas of the troposphere, improving signal to noise ratios.

Bands of Radio waves

Radio waves can be grouped into frequencies called bands (interval in frequency domain, characterized by lower frequency and upper)

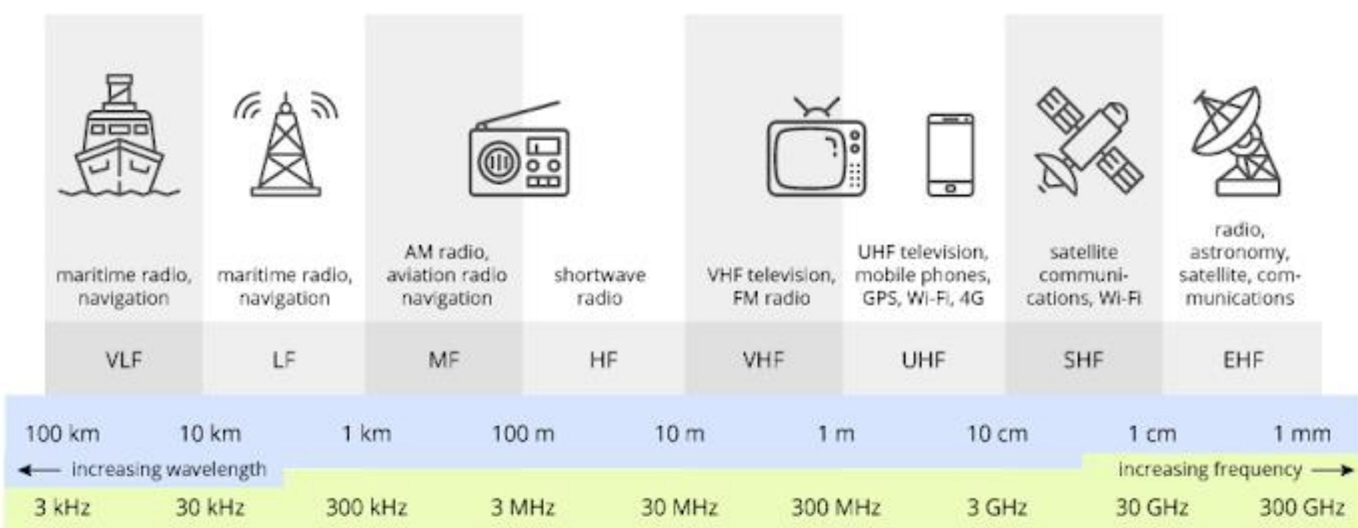
1. Bandwidth: the portion of the spectrum that a given telecommunications system can use (ex. System operating on frequencies from 150-200 MHz has a bandwidth of 50 MHz)
2. Narrowband vs broadband
    a. Narrowband signals have smaller bandwidth (kHz)- used for limited services such as paging and low-speed data transmission
    b. Broadband signals have a large bandwidth (MHz)- support many advanced telecommunications systems such as high-speed data and video transmission
3. Guard bands are implemented to alleviate the effects of interference between different transmissions as a result of overlapping channels; that's why standardized radio frequency channels don't use the entire range of radio frequencies.

ITU Radio Bands:

Band	Frequency range	Wavelength range	Uses
Extremely Low Frequency (ELF)	<3 kHz	>100 km	Underwater communication
Very Low Frequency (VLF)	3 to 30 kHz	10 to 100 km	Penetrates dirt and rock and seawater for some distance, measures conductivity near earth, submarine coms near surface, navigation beacons, time radio station (syncs clocks)
Low Frequency (LF)	30 to 300 kHz	1 m to 10 km	AM radio, navigational radio beacons, ship to shore coms, transoceanic air traffic control
Medium Frequency (MF)	300 kHz to 3 MHz	100 m to 1 km	Mostly AM radio- similar to LF
High Frequency (HF) aka short-wave	3 to 30 MHz	10 to 100 m	Shortwave radio, air to ground coms (aviation), dipole antennas. NAVTEX uses this (navigational telex)
Very High Frequency (VHF)	30 to 300 MHz	1 to 10 m	Similar applications to HF- and FM radio
Ultra High Frequency (UHF)	300 MHz to 3 GHz	10 cm to 1 m	Satellite TV, mobile phones, wifi, walkie talkies, gps, military, bluetooth, GSM, CDMA, LTE mobile transmission
Super High Frequency (SHF) *(sometimes considered microwave)*	3 to 30 GHz	1 dm to 1 cm	Point to point coms, satellite systems, direct TV broadcasting (Ku band), wifi, microwave ovens, mobile networks
Extremely High Frequency (EHF) *(sometimes considered microwave)*	30 to 300 GHz	1 mm to 1 c	Radio astronomy, remote sensing, suggested for high speed internet

Chart of RF (radio frequency) bands

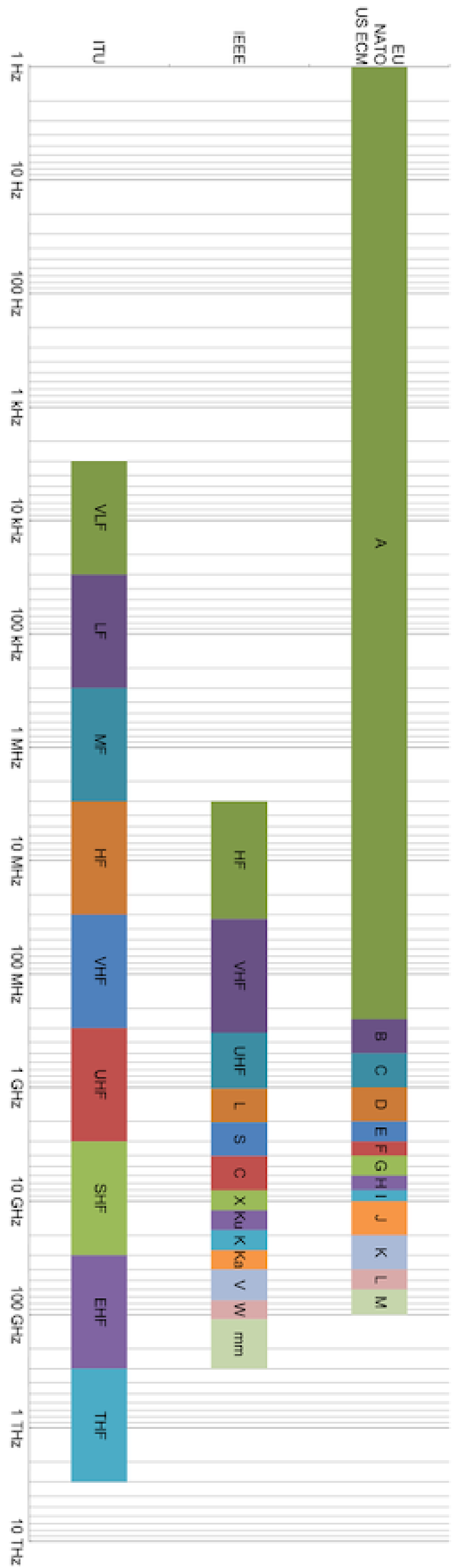
Band	ITU Band Number	Frequency	Wavelength Range	Uses
Extremely Low Frequency (ELF)	1	3-30 Hz	100,000-10,000 km	Communications with submarines
Super Low Frequency (SLF)	2	30-300 Hz	10,000-1,000 km	Communication with submarines
Ultra Low Frequency (ULF)	3	300-3,000 Hz	1,000-100 km	Submarine communication, Communication within mines
Very Low Frequency (VLF)	4	3-30 kHz	100-10 km	Maritime radio, navigation
Low Frequency (LF)	5	30-300 kHz	10-1 km	Maritime radio, navigation
Medium Frequency (MF)	6	300-3,000 kHz	1,000-100 m	AM radio, aviation radio navigation
High Frequency (HF)	7	3-30 MHz	100-10 m	Shortwave radio, aka decameter band
Very High Frequency (VHF)	8	30-300 MHz	10-1 m	VFH television, FM radio
Ultra High Frequency (UHF)	9	300-3,000 MHz	1-0.1 m	UHF television, mobile phones, GPS, Wi-fi, 4G
Super High Frequency (SHF)	10	3-30 GHz	100-10 mm	Satellite communications, Wi-Fi
Extremely High Frequency (EHF)	11	30-300 GHz	10-1 mm	Radio astronomy, satellite, communications
Terahertz or Tremendously high frequency (THz or THF)	12	300-3,000 GHz	1-0.1 mm	Remote sensing, terahertz computing/communications, experimental medical imaging to replace X-rays aka submillimeter band



Microwave Bands (IEEE) (?):

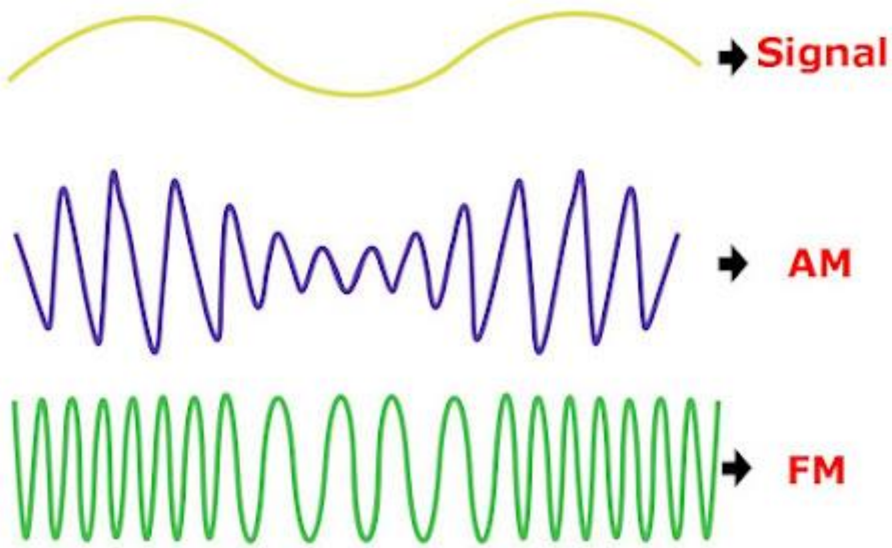
VHF band (very high frequency)	30 to 300 MHz		• FM radio • Television broadcasts
UHF band (ultra high frequency)	300 to 3000 MHz		• Television broadcasts • Microwave oven • Microwave devices • Communications • Radio astronomy • Mobile phones • Wireless LAN • Bluetooth
L band (long)	1-2 GHz	30 to 15 cm	• Military telemetry • GPS • Air traffic control (ATC) radar
S band (short)	2-4 GHz	15 to 5 cm	• Weather radar • Surface ship radar • Microwave ovens • Microwave devices • Communications
C band (compromise (between s and x))	4-8 GHz	5 to 3.75 cm	• Long-distance radio telecommunications
X band (X for “crosshair” (used in WW2 for fire control radar))	8-12 GHz	3.75 to 2.5 cm	• Satellite communications • Radar • Terrestrial broadband • Space communications
Ku band (Kurtz under)	12-18 GHz	2.5 to 1.6 cm	• Satellite communications Less susceptible to rain fade
K band (Kurtz (German for short))	18-26 GHz	1.6 to 1.2 cm	• Radar • Satellite communications • Astronomical observations • Automotive radar Suitable for harsh weather conditions
Ka band (Kurtz over)	26-40 GHz	1.6 cm to 750 mm	• Satellite communications
V band	40-75 GHz	750 mm to 40 mm	high capacity line of sight communications Used in point to point radio solution market Usable in congested cities without interference Issues with absorption of signals due to oxygen
W band	75-111 GHz	40 mm to 28 mm	automotive radars, satellite communication, astronomy, defense, and security applications. Overlaps with anti designated M band
mm or G band	>111 GHz	“millimeter wave?”	

IEEE (Institute of Electrical and Electronics Engineers) Band Number	Band Explanation	Frequency	Wavelength Range
MF	Medium Frequency	300KHz - 3 MHz	1 km - 100 m
HF	High Frequency	3 - 30 MHz	100 m - 10 m
VHF	Very High Freq	30 - 300 MHz	10 m - 1 m
UHF	Ultra High Freq	300 MHz - 3 GHz	1 m - 10 cm
L	Long wave	1 - 2 GHz	30 cm - 15 cm
S	Short wave	2 - 4 GHz	15 cm - 5 cm
C	Compromise between S, X	4 - 8 GHz	5 cm - 3.75 cm
X	Used in WWII for fire control, X for crosshair	8 - 12 GHz	3.75 cm - 2.5 cm
K_u	Kurz-under	12 - 18 GHz	2.5 cm - 1.6 cm
K	Kurz (German: short)	18 - 26 GHz	1.6 cm - 1.2 cm
K_a	Kurz-above	26 - 40 GHz	1.6 cm - 750 mm
V		40 - 75 GHz	750 mm - 40 mm
W	W follows V	75 - 111 GHz	40 mm - 28 mm
mm or G	Millimeter	Above 111 GHz	“Millimeter wave”


ITU
IEEE
EU
NATO
US ECM
1 Hz
10 Hz
100 Hz
1 kHz
10 kHz
100 kHz
1 MHz
10 MHz
100 MHz
1 GHz
10 GHz
100 GHz
1 THz
10 THz
VLF
LF
MF
HF
VHF
UHF
SHF
EHF
THF
HF
VHF
UHF
L
S
C
X
Ku
K
Ka
V
W
mm
A
B
C
D
E
F
G
H
I
J
K
L
M

<table>
<tr><th colspan="4">NATO LETTER BAND DESIGNATION[15][14][16]</th><th rowspan="3">BROADCASTING BAND DESIGNATION</th></tr>
<tr><th colspan="2">NEW NOMENCLATURE</th><th colspan="2">OLD NOMENCLATURE</th></tr>
<tr><th>BAND</th><th>FREQUENCY (MHz)</th><th>BAND</th><th>FREQUENCY (MHz)</th></tr>
<tr><td rowspan="3">A</td><td rowspan="3">0 – 250</td><td rowspan="2">I</td><td rowspan="2">100 – 150</td><td>Band I
47 – 68 MHz (TV)</td></tr>
<tr><td>Band II
87.5 – 108 MHz (FM)</td></tr>
<tr><td>G</td><td>150 – 225</td><td>Band III
174 – 230 MHz (TV)</td></tr>
<tr><td>B</td><td>250 – 500</td><td>P</td><td>225 – 390</td><td></td></tr>
<tr><td rowspan="2">C</td><td rowspan="2">500 – 1 000</td><td rowspan="2">L</td><td rowspan="2">390 – 1 550</td><td>Band IV
470 – 582 MHz (TV)</td></tr>
<tr><td>Band V
582 – 862 MHz (TV)</td></tr>
<tr><td>D</td><td>1 000 – 2 000</td><td rowspan="3">S</td><td rowspan="3">1 550 – 3 900</td><td rowspan="3"></td></tr>
<tr><td>E</td><td>2 000 – 3 000</td></tr>
<tr><td>F</td><td>3 000 – 4 000</td></tr>
<tr><td>G</td><td>4 000 – 6 000</td><td>C</td><td>3 900 – 6 200</td><td></td></tr>
<tr><td>H</td><td>6 000 – 8 000</td><td rowspan="2">X</td><td rowspan="2">6 200 – 10 900</td><td rowspan="2"></td></tr>
<tr><td>I</td><td>8 000 – 10 000</td></tr>
<tr><td>J</td><td>10 000 – 20 000</td><td>Ku</td><td>10 900 – 20 000</td><td rowspan="2"></td></tr>
<tr><td>K</td><td>20 000 – 40 000</td><td>Ka</td><td>20 000 – 36 000</td></tr>
<tr><td rowspan="2">L</td><td rowspan="2">40 000 – 60 000</td><td>Q</td><td>36 000 – 46 000</td><td rowspan="2"></td></tr>
<tr><td>V</td><td>46 000 – 56 000</td></tr>
<tr><td>M</td><td>60 000 – 100 000</td><td>W</td><td>56 000 – 100 000</td><td></td></tr>
<tr><td colspan="4">US- MILITARY / SACLANT</td><td></td></tr>
<tr><td>N</td><td colspan="3">100 000 – 200 000</td><td></td></tr>
<tr><td>O</td><td colspan="3">100 000 – 200 000</td><td></td></tr>
</table>

AM vs FM Radio

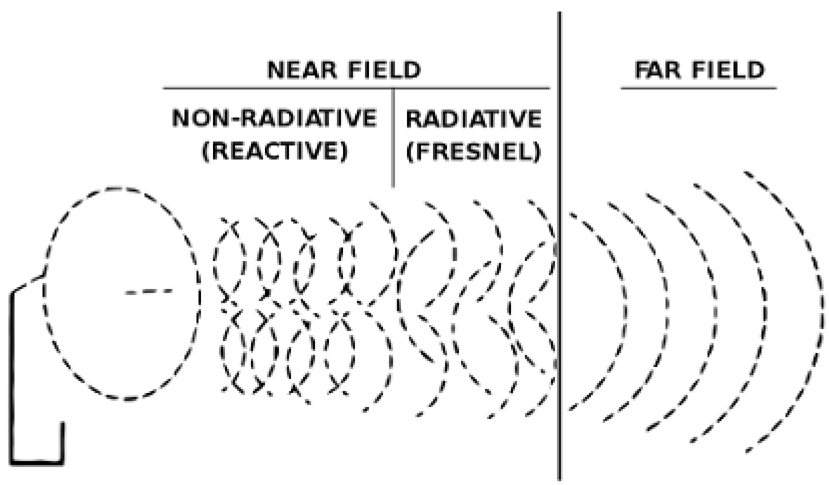


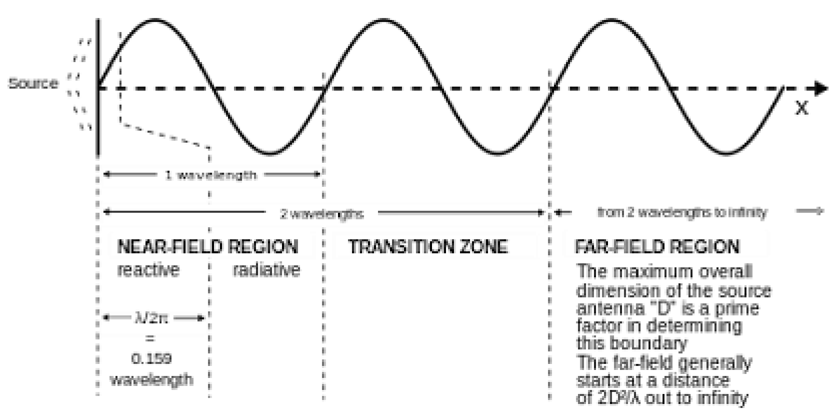
North American FM Radio Range: 88-108 MHz
North American AM Radio Range: 535-1605 KHz

Stands for	Amplitude Modulation	Frequency Modulation
Origin	AM method of audio transmission was first successfully carried out in the mid 1870s.	FM radio was developed in the United states in the 1930s, mainly by Edwin Armstrong.
Modulating differences	In AM, a radio wave known as the "carrier" or "carrier wave" is modulated in amplitude by the signal that is to be transmitted. The frequency and phase remain the same. Vertically polarized	In FM, a radio wave known as the "carrier" or "carrier wave" is modulated in frequency by the signal that is to be transmitted. The amplitude and phase remain the same.
Pros and cons	AM has poorer sound quality compared with FM, but is cheaper and can be transmitted over long distances. It has a lower bandwidth so it can have more stations available in any frequency range.	FM is less prone to interference than AM. However, FM signals are impacted by physical barriers. FM has better sound quality due to higher bandwidth.
Frequency Range	AM radio ranges from 535 to 1705 KHz (OR) Up to 1200 bits per second.	FM radio ranges in a higher spectrum from 88 to 108 MHz. (OR) 1200 to 2400 bits per second.
Bandwidth Requirements	Twice the highest modulating frequency. In AM radio broadcasting, the modulating signal has bandwidth of 15kHz, and hence the bandwidth of an amplitude-modulated signal is 30kHz.	Twice the sum of the modulating signal frequency and the frequency deviation. If the frequency deviation is 75kHz and the modulating signal frequency is 15kHz, the bandwidth required is 180kHz.

Zero crossing in modulated signal	Equidistant	Not equidistant
Complexity	Transmitter and receiver are simple but synchronization is needed in case of SSBSC AM carrier.	Transmitter and receiver are more complex as variation of modulating signal has to be converted and detected from corresponding variation in frequencies (i.e. voltage to frequency and frequency to voltage conversion has to be done).
Noise	AM is more susceptible to noise because noise affects amplitude, which is where information is "stored" in an AM signal.	FM is less susceptible to noise because information in an FM signal is transmitted through varying the frequency, and not the amplitude.

Fields





The near field and far field are regions of the electromagnetic field (EM) around an object, such as a transmitting antenna, or the result of radiation scattering off an object. Non-radiative *near-field* behaviors dominate close to the antenna or scattering object, while electromagnetic radiation *far-field* behaviors dominate at greater distances.

Far-field E (electric) and B (magnetic) field strength decreases as the distance from the source increases, resulting in an inverse-square law for the radiated *power* intensity of electromagnetic radiation. By contrast, near-field E and B strength decrease more rapidly with distance: the radiative field decreases by the inverse-distance squared, the reactive field by an inverse-cube law, resulting in a diminished power in the parts of the electric field by an inverse fourth-power and sixth-power, respectively. The rapid drop in power contained in the near-field ensures that effects due to the near-field essentially vanish a few wavelengths away from the radiating part of the antenna.

The separation of the electric and magnetic fields into components is mathematical, rather than clearly physical, and is based on the relative rates at which the amplitude of different terms of the electric and magnetic field equations diminish as distance from the radiating element increases. The amplitudes of the far-field components fall off as 1/r, the *radiative* near-field amplitudes fall off as 1/(r^2), and the *reactive* near-field amplitudes fall off as 1/(r^3). Definitions of the *regions* attempt to characterize locations where the activity of the associated field *components* are the strongest. Mathematically, the distinction between *field components* is very clear, but the demarcation of the spatial *field regions* is subjective. All of the field components overlap everywhere, so for example, there are always substantial far-field and radiative near-field components in the closest-in near-field reactive region.

The regions defined below categorize field behaviors that are variable, even within the region of interest. Thus, the boundaries for these regions are approximate rules of thumb, as there are no precise cutoffs between them: All behavioral changes with distance are smooth changes. Even when precise boundaries can be defined in some cases, based primarily on antenna type and antenna size, experts may differ in their use of nomenclature to describe the regions. Because of these nuances, special care must be taken when interpreting technical literature that discusses far-field and near-field regions.

The term *near-field region* (also known as the *near field* or *near zone*) has the following meanings with respect to different telecommunications technologies:

- The close-in region of an antenna where the angular field distribution is dependent upon the distance from the antenna.
- In the study of diffraction and antenna design, the near field is that part of the radiated field that is below distances shorter than the Fraunhofer distance,[1] which is given by $d_F = \frac{2D^2}{\lambda}$ from the source of the diffracting edge or antenna of longitude or diameter D.
- In optical fiber communications, the region near a source or aperture that is closer than the Rayleigh length. (Presuming a Gaussian beam, which is appropriate for fiber optics.)

Reactive Near Field Zone

In the immediate vicinity of the antenna, we have the reactive near field. In this region, the fields are predominately reactive fields, which means the E- and H- fields are out of phase by 90 degrees to each other (recall that for propagating or radiating fields, the fields are orthogonal (perpendicular) but are in phase). The boundary of this region is commonly given as:

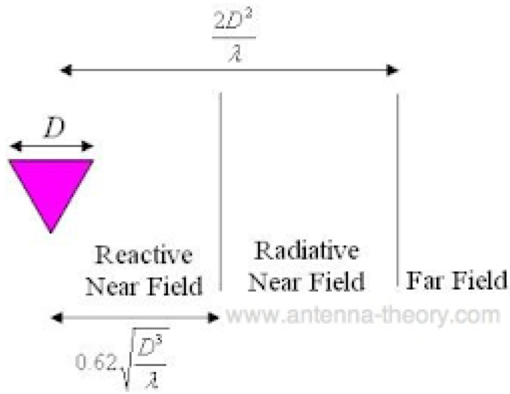
$$R < 0.62\sqrt{\frac{D^3}{\lambda}}$$

Fresnel Zone (near radiating)

One of a series of confocal prolate ellipsoidal regions of space between and around a transmitter and a receiver. The primary wave will travel in a relative straight line from the transmitter to the receiver. Aberrant transmitted radio, sound, or light waves which are transmitted at the same time can follow slightly different paths before reaching a receiver, especially if there are obstructions or deflecting objects between the two. The two waves can arrive at the receiver at slightly different times and the aberrant wave may arrive out of phase with the primary wave due to the different path lengths. Depending on the magnitude of the phase difference between the two waves, the waves can interfere constructively or destructively. The size of the calculated Fresnel zone at any particular distance from the transmitter and receiver can help to predict whether obstructions or discontinuities along the path will cause significant interference.

Fraunhofer Zone (far)

In this region, the radiation pattern does not change shape with distance (R). Although the E- and H- fields still die off as 1/R, the power density dies off as 1/R^2. The far field is dominated by radiated fields, with the E- and H-fields orthogonal to each other and the direction of propagation, as with plane waves.



The far field is the region far from the antenna, as you might suspect. In this region, the radiation pattern does not change shape with distance (R). Although the E- and H- fields still die off as 1/R, the power density dies off as 1/R^2. The far field is dominated by radiated fields, with the E- and H-fields orthogonal to each other and the direction of propagation, as with plane waves.

If the maximum linear dimension of an antenna is D and the wavelength is , then the following 3 conditions must all be satisfied to be in the far field region:

far field distance for an antenna

$$R > \frac{2D^2}{\lambda}$$

[Equation 1]

far field distance for an antenna

$$R >> D$$

[Equation 2]

far field distance for an antenna

$$R >> \lambda$$

[Equation 3]

The first and second equation above ensure that the power radiated in a given direction from distinct parts of the antenna are approximately parallel (see Figure 1). This helps ensure the fields in the far-field region behave like plane waves. Note that >> means "much much greater than" and is typically assumed satisfied if the left side is 10 times larger than the right side.

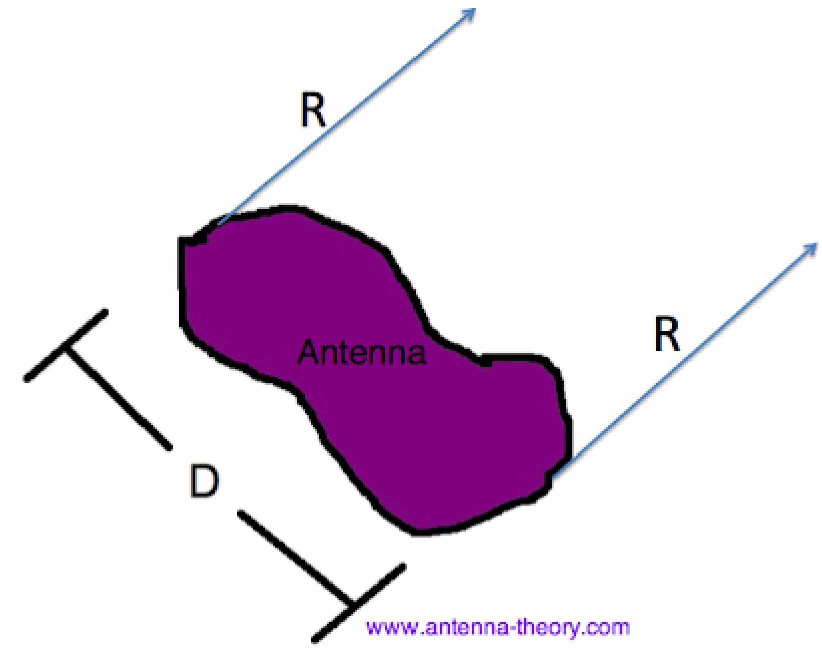


Figure 1. The Rays from any Point on the Antenna are Approximately Parallel in the Far Field.

Finally, where does the third far-field equation come from? Near a radiating antenna, there are reactive fields (see reactive near field region, below), that typically have the E-fields and H-fields die off with distance as 1/r^2 and 1/r^3. The third equation above ensures that these near fields are gone, and we are left with the radiating fields, which fall off with distance as 1/r.

The far-field region is sometimes referred to as the Fraunhofer region, a carryover term from optics.

Poynting Vector

In physics, the **Poynting vector** (or **Umov-Poynting vector**) represents the directional energy flux (the energy transfer per unit area per unit time) or *power flow* of an electromagnetic field. The SI unit of the Poynting vector is the watt per square meter (W/m^2); kg/s^3 in base SI units. It is named after its discoverer John Henry Poynting who first derived it in 1884. Nikolay Umov is also credited with formulating the concept. Oliver Heaviside also discovered it independently in the more general form that recognises the freedom of adding the curl of an arbitrary vector field to the definition. The Poynting vector is used throughout electromagnetics in conjunction with Poynting's theorem, the continuity equation expressing conservation of electromagnetic energy, to calculate the power flow in electromagnetic fields.

In Poynting's original paper and in most textbooks, the Poynting vector S is defined as the cross product

S = E x H
where bold letters represent vectors and

- **E** is the electric field vector;
- **H** is the magnetic field's auxiliary field vector or *magnetizing field*.

This expression is often called the *Abraham form* and is the most widely used.[7] The Poynting vector is usually denoted by **S** or **N**.

Parts of an Antenna

Antenna basics

- A transmitting antenna converts electrical signals into EM waves
- A receiving antenna converts EM waves into electric signals
- The radiation pattern of the antenna is the same whether transmitting or receiving signals

SMA connectors

- Stands for SubMiniature A
- Developed in the 1960s
- Impedance of 50 ohms
- 
- 

    - Female have outer threads
    - Male have inner threads
    - Inner pin thing is male but RPSMA reverses that and puts the inner pin in the female one
    - RPSMA can fit physically but not electronically into an sma connector
- Used in: TV/CCTV cables, surveillance, mobile telephone antennas (basically connects cables-- there are many in my house)

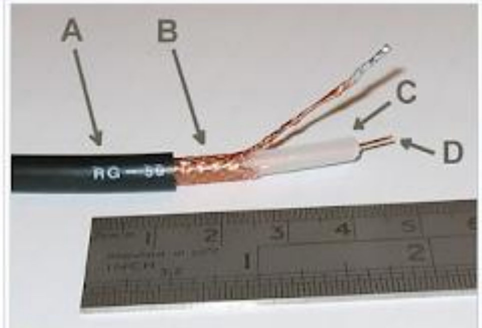
<u>BNC Connector:</u> short for Bayonet Neill-Concelman

- miniature quick connect/disconnect radio frequency connector used for coaxial cable. It is designed to maintain the same characteristic impedance of the cable, with 50 ohm and 75 ohm types being made. It is usually applied for video and radio frequency connections up to about 2 GHz and up to 500 volts. The connector has a twist to lock design with two lugs in the female portion of the connector engaging a slot in the shell of the male portion. The type was introduced on military radio equipment in the 1940s and has since become widely applied in radio systems, and is a common type of video connector. Similar radio-frequency connectors differ in dimensions and attachment features, and may allow for higher voltages, higher frequencies, or three-wire connections.
- A patent was granted for it in 1951

Feed lines

- Coaxial cable

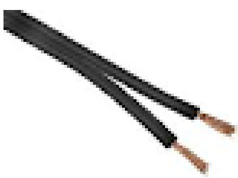
- Coaxial cable, or coax is a type of electrical cable consisting of an inner conductor surrounded by a concentric conducting shield, with the two separated by a dielectric (insulating material); many coaxial cables also have a protective outer sheath or jacket. The term coaxial refers to the inner conductor and the outer shield sharing a geometric axis.
- Coaxial cable is a type of transmission line, used to carry high-frequency electrical signals with low losses. It is used in such applications as telephone trunk lines, broadband internet networking cables, high-speed computer data busses, cable television signals, and connecting radio transmitters and receivers to their antennas. It differs from other shielded cables because the dimensions of the cable and connectors are controlled to give a precise, constant conductor spacing, which is needed for it to function efficiently as a transmission line.
- Coaxial cable was used in the first (1858) and following transatlantic cable installations, but its theory was not described until 1880 by English physicist, engineer, and mathematician Oliver Heaviside, who patented the design in that year (British patent No. 1,407).



RG-59 **flexible coaxial cable** composed of:

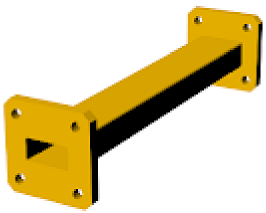
A. Outer plastic sheath
B. Woven copper shield
C. Inner dielectric insulator
D. Copper core

* Twin-lead
    - Twin-lead cable is a two-conductor flat cable used as a balanced transmission line to carry radio frequency (RF) signals. It is constructed of two stranded or solid copper or copper-clad steel wires, held a precise distance apart by a plastic (usually polyethylene) ribbon. The uniform spacing of the wires is the key to the cable's function as a transmission line; any abrupt changes in spacing would reflect some of the signal back toward the source. The plastic also covers and insulates the wires. It is available with several different values of characteristic impedance, the most common type is 300 ohm.
    - Twin lead is mainly used as an antenna feedline at shortwave and VHF frequencies, to connect radio receivers and transmitters to their antennas. It can have significantly lower signal loss than miniature flexible coaxial cable, the main alternative type of feedline at these frequencies; for example, type RG-58 coaxial cable loses 6.6 dB per 100 m at 30 MHz, while 300 ohm twin-lead loses only 0.55 dB.[1] 300 ohm twin lead is widely used to connect FM radios to their antennas, and was previously used to connect television antennas to televisions until it was replaced by coaxial cable. However, it is more vulnerable to interference; proximity to metal objects will inject



signals into twin-leads that would be blocked out by coaxial cable. It therefore requires spacing around rain gutters, and standoff insulators along metal support masts.

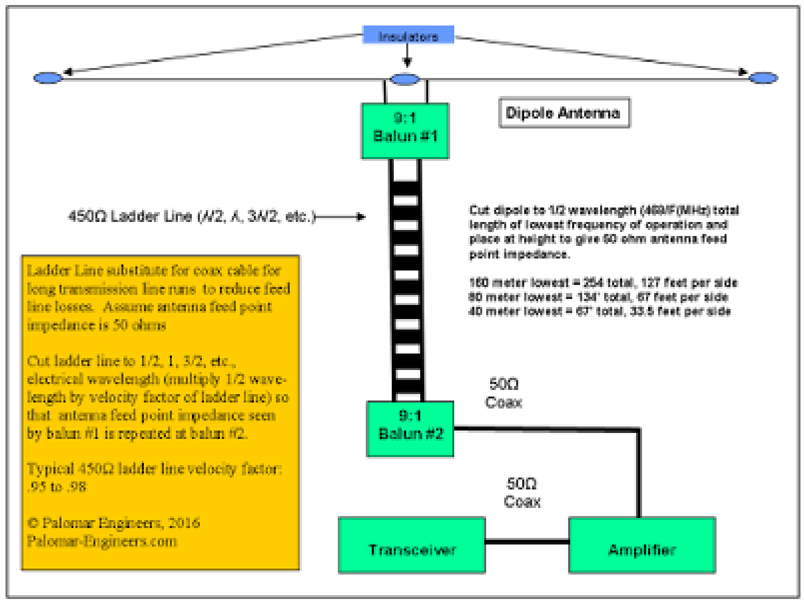
- Ladder line
    - The advantage of ladder line over coaxial cable is its relative lack of loss. As you increase in frequency, say on the HF band (10m) or at VHF, ladder line will not experience as much power loss as coax. (quora)
    - Variation on coaxial cable
- Waveguide
    - A waveguide is a special form of transmission line consisting of a hollow, metal tube. The tube wall provides distributed inductance, while the empty space between the tube walls provides distributed capacitance. Wave guides conduct microwave energy at lower loss than coaxial cables.



Counterpoise - network of suspended horizontal or vertical wires used as a substitute for an earth connection

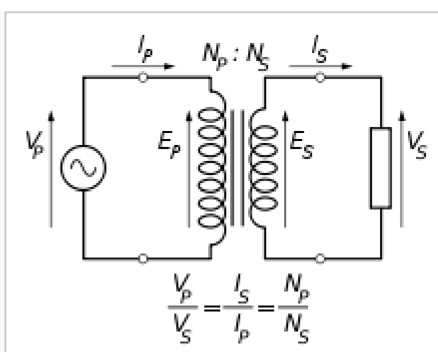
Balun – an electrical device that allows balanced and unbalanced lines to be interfaced without disturbing the impedance arrangement of either line; used to balance unbalanced systems, messes with current such as making a chokepoint to be 0

Infinite Balun – uses currents flowing outside coaxial cable, helps cable to direct where you want the current to flow



Baluns (i think… this section feels unnecessary)

Classical transformer type[edit]



Isolation transformer

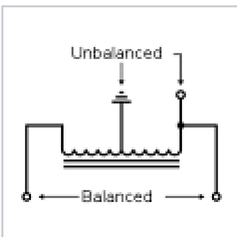
In classical transformers, there are two electrically separate windings of wire coils around the transformer's core. The advantage of transformer-type over other types of balun is that the electrically separate windings for input and output allow these baluns to connect circuits whose ground-level voltages are subject to ground loops or are otherwise electrically incompatible; for that reason they are often called *isolation transformers*.

This type is sometimes called a *voltage balun*. The *primary* winding receives the input signal, and the *secondary* winding puts out the converted signal. The core that they are wound on may either be empty (air core) or, equivalently, a magnetically neutral material like a porcelain support, or it may be a material which is good magnetic conductor like ferrite in modern high-frequency (HF) baluns, or soft iron as in the early days of telegraphy.

The electrical signal in the primary coil is converted into a magnetic field in the transformer's core. When the electrical current through the primary reverses, it causes the established magnetic field to collapse. The collapsing magnetic field then induces an electric field in the secondary winding.

The ratio of loops in each winding and the efficiency of the coils' magnetic coupling determines the ratio of electrical potential (voltage) to electrical current and the total power of the output. For idealized transformers, although the ratio of voltage to current will change in exact proportion to the square of the winding ratio, the power (measured in watts) remains identical. In real transformers, some energy is lost inside to heating of the metallic core of the transformer, and lost outside to the surrounding environment because of imperfect magnetic coupling between the two coils.

Autotransformer type[edit]



Circuit diagram of a 4:1 autotransformer balun using three taps on a single winding on a ferrite rod.

Generally a balun consists of two wires (primary and secondary) and a toroid core: the current in the primary wire generates a magnetic field in the core, which in turn induces an electric field in the secondary wire. An autotransformer balun has only one coil, or is made of two or more coils that have an electrical connection. The coil is typically wound on a ferrite rod or doughnut-shaped toroid. One can also make an autotransformer from an ordinary transformer by cross-wiring the primary and secondary windings. Baluns made with autotransformer windings are also called *voltage baluns*, since they produce balanced output voltage, but not necessarily balanced current.

Picture a 4:1 balun of the same design, wound on ferrite toroid. Notice that the black and red winding wires are joined at the threaded connector.

In all autotransformers, the single winding must have at least one extra electrical connection – called a *tap* or *tap point* – between the two ends of the winding. The current sent into the balun through one pair of connections acts as if it were a primary coil, and magnetizes the entire core. When the electric current in the input segment of the coil changes, the induced magnetic field collapses and the collapse of the magnetic field in the core induces an electric current in the entire coil. Electrical connections to parts of the coil different from the input connections have higher or lower voltages depending on the length of the coil that the output is tapped from.

As with a two-winding transformer balun, the ratio of voltage to current changes in proportion to the square of number of windings between the two input wires divided by the number of windings between the two output wires.

Unlike transformer-type baluns, an autotransformer balun provides a path for DC current to ground from every terminal. Since outdoor antennas are prone to build-up of static electric charge, the path for the static to drain to ground through an autotransformer balun can be a distinct advantage.

Transmission-line transformer type[edit]

Transmission line or *choke* baluns can be considered as simple forms of transmission line transformers. This type is sometimes called a *current balun*, since it ensures equal current on both sides of its output, but not necessarily equal voltage. These are normally called ununs, because they go from unbalanced to unbalanced or un-un. Baluns are balanced to unbalanced or bal-un.

Homemade 1:1 balun using a toroidal core and coaxial cable. This simple RF choke works as a balun by preventing signals passing along the outside of the braid. Such a device can be used to cure television interference by acting as a braid-breaker.

A more subtle type results when the transformer type (magnetic coupling) is combined with the transmission line type (electro-magnetic coupling). Most typically the same kind of transmission line wires are used for the windings as carry the signal from the radio to the antenna, although these baluns can be made using any type of wire. The resulting devices have very wideband operation.[3] *Transmission line transformers* commonly use small ferrite cores in toroidal rings or two-hole, binocular, shapes. Something as simple as 10 turns of coaxial cable coiled up on a diameter about the size of a dinner plate makes an effective choke balun for frequencies from about 10 MHz to beyond 30 MHz. The magnetic material may be air, but it is a transmission line transformer.

The Guanella transmission line transformer (Guanella 1944) is often combined with a balun to act as an impedance matching transformer. Putting balancing aside a 1:4 transformer of this type consists of a 75 Ω transmission line divided in parallel into two 150 Ω cables, which are then combined in series for 300 Ω. It is implemented as a specific wiring around the ferrite core of the balun.

Delay-line type[edit]

A large class of baluns uses connected transmission lines of specific lengths, with no obvious "transformer" part. These are usually built for (narrow) frequency ranges where the lengths involved are some multiple of a quarter wavelength of the intended frequency in the transmission line medium. A common application is in making a coaxial connection to a balanced antenna, and designs include many types involving coaxial loops and variously connected "stubs".

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

Another narrow band design is to use a λ/4 length of metal pipe. The coaxial cable is placed inside the pipe; at one end the braid is wired to the pipe while at the other end no connection is made to the pipe. The balanced end of this balun is at the end where no connection is made to the pipe. The λ/4 conductor acts as a transformer, converting the zero impedance at the short to the braid into an infinite impedance at the open end. This infinite impedance at the open end of the pipe prevents current flowing into the outer coax formed by the outside of the inner coax shield and the pipe, forcing the current to remain in the inside coax. This balun design is impractical for low frequencies because of the long length of pipe that will be needed. An easy way to make such a balun is to paint the outside of the coax with conductive paint, then to connect this paint to the braid through a break in the outer insulation 1/4 wave from the end. For both forms (pipe or paint), the length is dependent on the velocity factor for the outer transmission line.

Although baluns are designed as magnetic devices – each winding in a balun is an inductor – all transformers made of real materials also have a small capacitance between the primary and secondary windings, as well as between individual loops in any single winding, forming unwanted *self-capacitance*.

The electrical connection of capacitance and inductance leads to a frequency where the electrical reactance of the self-inductance and self-capacitance in the balun are equal in magnitude but opposite in sign: resonance. A balun of any design operates poorly at frequencies at or above its resonance, and some of the design considerations for baluns are for the purpose of making the resonant frequency as far above the operating frequency as possible.

An RF choke can be used in place of a balun. If a coil is made using coaxial cable near to the feed point of a balanced antenna, then the RF current that flows on the outer surface of the coaxial cable can be attenuated. One way of doing this would be to pass the cable through a ferrite toroid. The end result is exactly the same as a 1:1 current balun (or Guanella-type balun). (Straw 2005, 25-26)

A balun's function is generally to achieve compatibility between systems, and as such, finds extensive application in modern communications, particularly in realizing frequency conversion mixers to make cellular phone and data transmission networks possible. They are also used to send an E1 carrier signal from coaxial cable (BNC connector, 1.0/2.3 connector, 1.6/5.6 connector, Type 43 connectors) to UTP CAT-5 cable or IDC connector.

Radio and television[edit]

A 75-to-300-Ω balun built into the antenna plug.

In television, amateur radio, and other antenna installations and connections, baluns convert between impedances and symmetry of feedlines and antennas.[4]

For example, transformation of 300-Ω twin-lead or 450-Ω ladder line (balanced) to 75-Ω coaxial cable (unbalanced), or to directly connect a balanced antenna to unbalanced coaxial cable. To avoid feed line radiation, baluns are typically used as a form of common mode choke attached at the antenna feed point to prevent the coaxial cable from acting as an antenna and radiating power. This typically is needed when a balanced antenna (for instance, a dipole) is fed with coax; without a balun, the shield of the coax could couple with one side of the dipole, inducing common mode current, and becoming part of the antenna and unintentionally radiating.[5]

When it comes to transmitting antennas the choice of the toroid core is crucial. A rule of thumb is: the more power the bigger the core.[6]

In measuring the impedance or radiation pattern of a balanced antenna using a coaxial cable, it is important to place a balun between the cable and the antenna feed. Unbalanced currents that may otherwise flow on the cable will make the measured antenna impedance sensitive to the configuration of the feed cable, and the radiation pattern of small antennas may be distorted by radiation from the cable.

Baluns are present in radars, transmitters, satellites, in every telephone network, and probably in most wireless network modem/routers used in homes. It can be combined with transimpedance amplifiers to compose high-voltage amplifiers out of low-voltage components.

Baseband video uses frequencies up to several megahertz. A balun can be used to couple video signals to twisted-pair cables instead of using coaxial cable. Many security cameras now have both a balanced unshielded twisted pair (UTP) output and an unbalanced coaxial one via an internal balun. A balun is also used on the video recorder end to convert back from the 100 Ω balanced to 75 Ω unbalanced. A balun of this type has a BNC connector with two screw terminals. VGA/DVI baluns are baluns with electronic circuitry used to connect VGA/DVI sources (laptop, DVD, etc.) to VGA/DVI display devices over long runs of CAT-5/CAT-6 cable. Runs over 130 m (400 ft) may lose quality because of attenuation and variations in the arrival time of each signal. A skew control and special low skew or skew free cable is used for runs over 130 m (400 ft).[*citation needed*]

Three audio transformers; two of them baluns.

In audio applications, baluns serve multiple purposes: they can convert between high-impedance unbalanced and low impedance balanced lines. Another application is decoupling of devices (avoidance of earth loops).

A third application of baluns in audio systems is in the provision of balanced mains power to the equipment. The common-mode rejection of interference characteristic of balanced mains power, eliminates a wide range of noise coming from the wall plug, e.g. mains-borne interference from air conditioner/furnace/refrigerator motors, switching noise produced by fluorescent lighting and dimmer switches, digital noise from personal computers, and radio frequency signals picked up by the power lines/cords acting as antennae. This noise infiltrates the audio/video system through the power supplies and raises the noise floor of the entire system.[7]

Except for the connections, the three devices in the image are electrically identical, but only the leftmost two can be used as baluns. The device on the left would normally be used to connect a high impedance source, such as a guitar, into a balanced microphone input, serving as a passive DI unit. The one in the center is for connecting a low impedance balanced source, such as a microphone, into a guitar amplifier. The one at the right is not a balun, as it provides only impedance matching.

Other applications[edit]

- In power line communications, baluns are used in coupling signals onto a power line.
- In electronic communications, baluns convert Twinax cables to Cat 5 cables, and back.

Ground Plane

In electrical engineering, a **ground plane** is an electrically conductive surface, usually connected to electrical ground. The term has two different meanings in separate areas of electrical engineering. In antenna theory, a ground plane is a conducting surface large in comparison to the wavelength, such as the Earth, which is connected to the transmitter's ground wire and serves as a reflecting surface for radio waves. In printed circuit boards, a ground plane is a large area of copper foil on the board which is connected to the power supply ground terminal and serves as a return path for current from different components on the board.

SMA Connector

Figure 1. Standard male SMA connector: male body (inside threads) with male inner pin

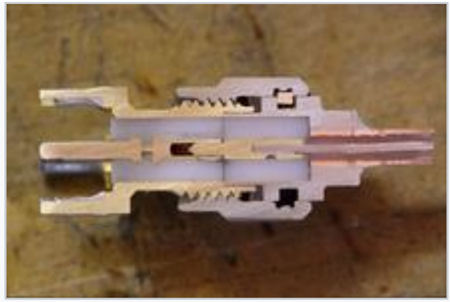
Type	RF coaxial connector
General specifications	
Diameter	Male: 0.312 in (7.9 mm) HEX
Cable	Coaxial
Passband	Typically 0–18 GHz, some up to 26.5 GHz

SMA (*SubMiniature version A*) connectors are semi-precision coaxial RF connectors developed in the 1960s as a minimal connector interface for coaxial cable with a screw-type coupling mechanism. The connector has a 50 Ω impedance. SMA was originally designed for use from DC (0 Hz) to 12 GHz, however this has been extended over time and variants are available to 18 GHz and 26.5 GHz.[1] There are also mechanically compatible connectors such as the K-connector which operate up to 40 GHz.[2] The SMA connector is most commonly used in microwave systems, hand-held radio and mobile telephone antennas and, more recently, with WiFi antenna systems and USB software-defined radio dongles.[3] It is also commonly used in radio astronomy, particularly at higher frequencies (5 GHz+).

Connector design[edit]

The interface dimensions for SMA connectors are listed in MIL-STD-348.[4] The SMA connector employs a 1⁄4 inch diameter, 36-thread-per-inch threaded barrel. The male is equipped with a hex nut measuring 5⁄16 inch (0.3125 inch / 7.9 mm) across opposite flats, thus taking the same wrench as a #6 SAE hex nut.

A *standard-polarity* SMA male connector has a 0.9mm diameter center pin surrounded by barrel with inside threads, and the standard SMA female connector has a center sleeve surrounded by a barrel with outside threads. The center pin is the same diameter as the center of RG402 Coax so that connections can be made with no discontinuity, forming the pin from the coax itself. As with most other connectors, the gender assignment corresponds to the innermost electrical component. There are also *reverse-polarity* ("RP") SMA connectors in which the pin and sleeve are swapped so that the "male" RP-SMA has a center sleeve surrounded by an inside-threaded barrel, and the "female" RP-SMA has a center pin and an outside-threaded barrel. See below for a fuller description.[5]



Cross section of an SMA mated pair

The SMA connector uses a polytetrafluoroethylene (PTFE) dielectric that contacts along the mating plane. Variability in the construction and the mating of the connectors limits the repeatability of the connector impedance. For that reason and that they are just rated for a limited number of connection cycles, an SMA connector is not usually a good choice for metrological applications.[6]

SMA connectors are rated for up to 500 mating cycles,[7] but to achieve this it is necessary to properly torque the connector when making the connection. A 5⁄16 inch torque wrench is required for this, set to 3–5 in·lbf (0.3 to 0.6 N·m) for brass, and 7–10 in·lbf (0.8 to 1.1 N·m) for stainless steel connectors. Flats are sometimes also provided on the cable side of the connector assembly so that a second wrench can be used to prevent it from rotating and damaging the joint to the cable. It is also advisable to inspect and clean out loose debris from the internal surfaces with compressed air or a gas duster can before mating.[8][9]

SMA connectors must not be confused with the standard household 75-ohm type F coax connector (diameters: male 7⁄16 inch (11 mm) circular or hex; female 3⁄8 inch (9.5 mm) external threads), as there is only about a 2 mm difference overall in the specifications. Type F cannot be mated with SMA connectors without the use of an adapter.

Variations[edit]

Picture of SMA (left), 3.5 mm (center) and 2.92 mm (right) coaxial connectors. Top: male versions, bottom: female versions. The air-dielectric is clearly visible in the 3.5 mm and 2.92 mm versions

The SMA connector is typically rated for mode-free operation from DC to 18 GHz, though some proprietary versions are rated to 26.5 GHz.[10] For performance above this, other SMA-like connectors are used. These include the 3.5 mm connector, rated to 34 GHz, and the 2.92 mm (also known as 2.9 mm, K type, or SMK),[11] good up to 46 GHz. These connectors keep the same outside thread as the SMA, so they can potentially be cross-mated, but the precision connector can be easily damaged when mating with low-grade SMA connectors.[12] The precision versions use an air dielectric with appropriately scaled center conductors.

Beyond 46 GHz, the 2.4 mm, 1.85 mm (also known as V type) and 1.0 mm (also known as W type) connectors exist. These are similar to the SMA connector, but with the geometries incompatibly scaled, and a metric thread to prevent accidental intermating. (But 2.4 mm and 1.85 mm connectors are compatible with each other.) These offer mode-free operation to 50, 65, and 110 GHz respectively.

Reverse polarity[edit]

Figure 2. Female RP-SMA connector: female connector body (outside threads) with a male inner pin contact. A male RP-SMA connector is the opposite in both respects – male connector body (inside threads) with a female inner sleeve contact

Reverse-polarity SMA (RP-SMA or RSMA) is a variation of the SMA connector specification that reverses the gender of the interface, as shown in Figures 1 and 2. The term "reverse polarity" here refers only to the gender of the connector's contact pin, not in any way to the signal polarity.

The female RP-SMA connector has the same external housing as a standard or conventional female SMA connector, which consists of an outer shell with the threads on the outside; however, the center receptacle is replaced by a male pin.

Similarly, the RP-SMA male has threads on the inside like a conventional male, but has a center receptacle instead of the male pin in the middle.[13][14] Normal SMA connectors are incompatible with RP-SMA connectors.

SMA male connector, SMA female connector, RP-SMA female connector, RP-SMA male connector

Occasionally, the opposite convention is used to designate the gender of an RP connector: In this situation the female connector has a socket (or sleeve) contact and threads on the outside.[15] Users should take care to check drawings and specifications carefully.

	Center pin	Center receptacle

Internal thread	SMA male/plug	RP-SMA male/plug
External thread	RP-SMA female/jack[16]	SMA female/jack

Wi-Fi equipment manufacturers have widely used RP-SMA connectors to comply with specific national regulations, such as those from the FCC,[17] which are designed to prevent consumers from connecting antennas that provide additional gain and therefore breach Part 15 compliance. However, by 2000, the FCC regarded the connectors as readily available,[18] though delaying its ruling indefinitely.[19] As of 2018, leading manufacturers such as Netgear and Linksys are still using RP-SMA connectors on their Wi-Fi equipment.[20]

What Makes an Antenna Good for (Insert Purpose)?

Cell Phones:

- Low directivity → the signal can come from any direction
- GSM antenna (Global System for Mobile Communications) – describes any antenna that is good/suitable for a cell phone
    - Wideband 690-2700 MHz Log Periodic Antenna - 8-10dB Gain
        - A wideband log periodic antenna offers exceptional performance on all the major wireless carriers' frequencies as well as GPS, Wi-Fi, and WiMax frequencies. Typically they have a low standing wave ratio (SWR) of less than 1.5:1 across the entire specified frequency range. Low SWR equates to maximum power being conducted from the antenna providing maximum signal range.
    - Wideband 800-2500 MHz Log Periodic Antenna - 10dB Gain
        - Designed for easy outside installation on a mast/pole, a wideband directional antenna is ideal for use outside homes, offices, and commercial buildings in areas of low cellular signal strength. This kind of antenna offers excellent signal pulling power for fixed installations where previously few solutions existed.
    - Multi-Band 698-1000 and 1700-2700 MHz Panel Antenna - 7-10dB Gain
        - Multi wideband antennas offer higher performance on all the major wireless carriers' frequencies as well as Wi-Fi and WiMax frequencies.
    - Yagi 700 MHz 4G LTE Antenna - 6dB Gain
        - A quality Yagi antenna for the 700 MHz bands has applications that include 4G LTE, SMH bands, point to multipoint, and public safety. Some features include a wider beamwidth, 6dB gain, and a rugged powder coated finish to provide outstanding corrosion resistance and longevity in the harshest environments. Maximum performance and distance is achieved with a voltage standing wave ratio (VSWR) of less than 1.5:1 across the entire frequency band (650-830 MHz).
    - Wideband Yagi 880-960 MHz Antenna - 14dB Gain
        - A wideband Yagi similar to its LTE counterpart has a wide frequency range, higher gain, and a rugged powder coated finish. Applications include GSM 900, ISM, CMTS, and DSRR. This antenna has an excellent front to back ratio to block unwanted signals.
    - Other: helix, planar inverted-F, whip, patch
- Polarization:
    - Older (1990s era) GSM started w/ mostly vertical polarization
    - As capacity requirements increased, cross (X) - polarized antennas became popular (45 & -45 degrees)

Satellite Dish Antennas:

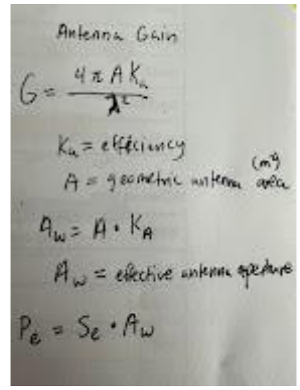
- High directivity → signal is received from a certain direction (e.g. that of the TV station)
- Polarization:
    - Determined by feed antenna's radiation

Submarines

- HF and Multi-Function Antenna Systems
    - Current products include a fast tuning HF antenna system (1.8-30 MHz) and multi-function submarine antenna system (30-3000 MHz). The antennas are enclosed inside ruggedised radomes designed for the desired depth requirements and specific mechanical mast integration.
- High gain and directivity
- Typically uses phased arrays and directors

Antenna Properties

BASIC INFO



Gain = directivity * efficiency of antenna

- Gain: combines directivity and efficiency of antenna; describes how much power is transmitted in the direction of peak radiation (takes losses that occur into account)
    - If converted to decibels: G = 10 * $\log_{10}$ (gain)
    - Gain (dBd) = Gain (dBi) - 2.15
        - dBi: decibels relative to an isotropic antenna (same as dB- gain of isotropic antenna is 0 dB; 1 dB = 1 dBi)
        - dBd: decibels relative to a dipole antenna
    - Gain (dB) = Gain (dBm) - 300
        - dBm: decibel milliwatts

Logarithmic units and decibels [edit]

Power gain [edit]

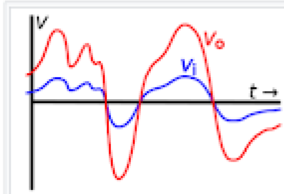
Power gain, in decibels (dB), is defined as follows:

$$\text{gain-db} = 10\log_{10}\left(\frac{P_{\text{out}}}{P_{\text{in}}}\right)\ \text{dB},$$

where P_{in} is the power applied to the input, P_{out} is the power from the output.

A similar calculation can be done using a natural logarithm instead of a decimal logarithm, resulting in nepers instead of decibels:

$$\text{gain-np} = \frac{1}{2}\ln\left(\frac{P_{\text{out}}}{P_{\text{in}}}\right)\ \text{Np}.$$



Graph of the input $v_i(t)$ (blue) and output voltage $v_o(t)$ (red) of an ideal linear amplifier with a voltage gain of 3 with an arbitrary input signal. At any instant the output voltage is three times the input voltage.

Directivity: concentration of antenna's radiation pattern in a particular direction

- Radiation intensity from a given direction divided by intensity averaged over all directions
- Determined by radiation pattern of antenna

Efficiency: amount of input power actually radiated

- For percentage: Efficiency = radiated power / input power
- Decibel conversion: dB = 10 * $\log_{10}$ (percentage)
- Note (if you need to calculate radiated power): P = IV (power = current * voltage)

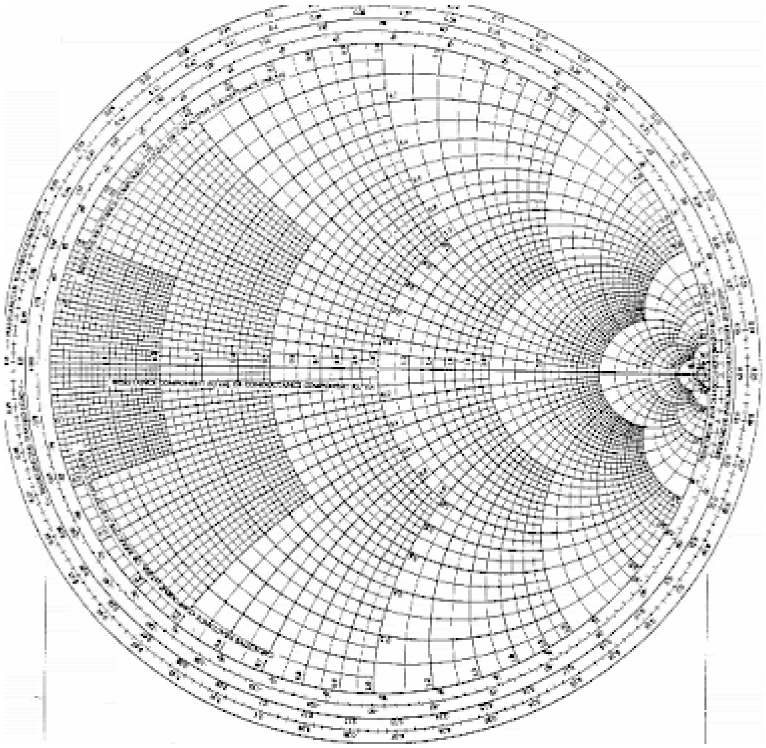
- What causes an antenna to not have an efficiency of 100% (or 0 dB)? Antenna efficiency losses are typically due to:
    - conduction losses (due to finite conductivity of the metal that forms the antenna)
    - dielectric losses (due to conductivity of a dielectric material near an antenna)
    - impedance mismatch loss
    - Examples of dielectrics include glass, plastics, teflon, and rubber. The strong Electric Fields near an antenna lose energy to heat due to the conductivity of the dielectric. If the electrical conductivity is zero, the dielectric loss within a material is zero. However, many materials (such as silicone and glass) have conductivity that is low but still enough to significantly decrease the antenna efficiency.
- Efficiency is one of the most important antenna parameters. It can be very close to 100% (or 0 dB) for dish antennas, horn antennas, or half-wavelength dipoles with no lossy materials around them. Mobile phone antennas, or wifi antennas in consumer electronics products, typically have efficiencies from 20%-70% (-7 to -1.5 dB). Car radio antennas can have an antenna efficiency of -20 dB (1% efficiency) at the AM radio

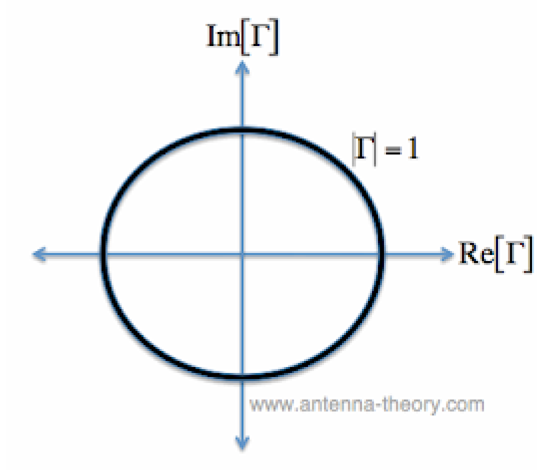
frequencies; this is because the antennas are much smaller than a half-wavelength at the operational frequency, which greatly lowers antenna efficiency. The radio link is maintained because the AM Broadcast tower uses a very high transmit power.

- Improving impedance mismatch loss is discussed in the Smith Charts and impedance matching section. Impedance matching can greatly improve the efficiency of an antenna.
- Finally, a note on dB vs. percentage. It is very common in industry to quote antenna efficiency in percent. However, there are two strong reasons why antenna efficiency should be measured in decibels (dB):
- {1} everything associated with the RF (radio frequency) world is measured in dB: transmit power is dB, isolation is in dB, desense is in dB, radio sensitivity is in dB. Hence, antenna efficiency should be in dB.
- {2} If a change to an antenna is made, and someone says "how much did the efficiency change" and the response is "5%", that is ambiguous. An increase from 1% to 6% is a huge change (7.8 dB), whereas an increase from 85% to 90% is small (0.24 dB).Efficiency is one of the most important antenna parameters. It can be very close to 100% (or 0 dB) for dish antennas, horn antennas, or half-wavelength dipoles with no lossy materials around them. Mobile phone antennas, or wifi antennas in consumer electronics products, typically have efficiencies from 20%-70% (-7 to -1.5 dB). Car radio antennas can have an antenna efficiency of -20 dB (1% efficiency) at the AM radio frequencies; this is because the antennas are much smaller than a half-wavelength at the operational frequency, which greatly lowers antenna efficiency. The radio link is maintained because the AM Broadcast tower uses a very high transmit power.
- Improving impedance mismatch loss is discussed in the Smith Charts and impedance matching section. Impedance matching can greatly improve the efficiency of an antenna.
- Finally, a note on dB vs. percentage. It is very common in industry to quote antenna efficiency in percent. However, there are two strong reasons why antenna efficiency should be measured in decibels (dB):
  - {1} everything associated with the RF (radio frequency) world is measured in dB: transmit power is dB, isolation is in dB, desense is in dB, radio sensitivity is in dB. Hence, antenna efficiency should be in dB.
  - {2} If a change to an antenna is made, and someone says "how much did the efficiency change" and the response is "5%", that is ambiguous. An increase from 1% to 6% is a huge change (7.8 dB), whereas an increase from 85% to 90% is small (0.24 dB).

Smith Charts

- The Smith Chart is a fantastic tool for visualizing the impedance of a transmission line and antenna system as a function of frequency. Smith Charts can be used to increase understanding of transmission lines and how they behave from an impedance viewpoint. Smith Charts are also extremely helpful for impedance matching, as we will see. The Smith Chart is used to display an actual (physical) antenna's impedance when measured on a Vector Network Analyzer (VNA).
- Smith Charts were originally developed around 1940 by Phillip Smith as a useful tool for making the equations involved in transmission lines easier to manipulate. See, for instance, the input impedance equation for a load attached to a transmission line of length L and characteristic impedance Z0. With modern computers, the Smith Chart is no longer used to simplify the calculation of transmission line equations; however, their value in visualizing the impedance of an antenna or a transmission line has not decreased.

- 
- The Smith Chart displays the complex reflection coefficient [Equation 1, below], in polar form, for an arbitrary impedance (we'll call the impedance ZL or the load impedance). The reflection coefficient is completely determined by the impedance ZL and the "reference" impedance Z0. Note that Z0 can be viewed as the impedance of the transmitter, or what is trying to deliver power to the antenna. Hence, the Smith Chart is a graphical method of displaying the impedance of an antenna, which can be a single point or a range of points to display the impedance as a function of frequency. For a primer on complex math, click here.
  - Recall that the complex reflection coefficient () for an impedance ZL attached to a transmission line with characteristic impedance Z0 is given by: equation for reflection coefficient
    - $$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$ [Equation 1]
- For this Smith Chart tutorial, we will assume Z0 is 50 Ohms, which is often, but not always the case. Note that the Smith Chart can be used with any value of Z0.
- The complex reflection coefficient, Γ, or reflection coefficient, must have a magnitude between 0 and 1. As such, the set of all possible values for Γ must lie within the unit circle:

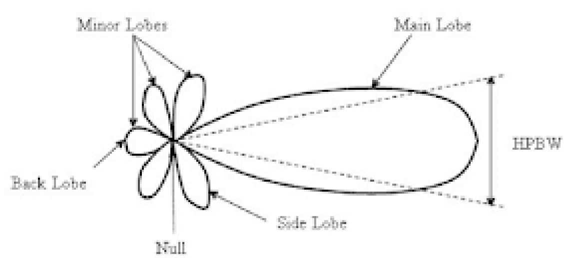


- In Figure 2, we are plotting the set of all values for the complex reflection coefficient, along the real and imaginary axis. The center of the Smith Chart is the point where the reflection coefficient is zero. That is, this is the only point on the Smith Chart where no power is reflected by the load impedance.
    - The outer ring of the Smith Chart is where the magnitude of   is equal to 1. This is the black circle in Figure 1. Along this curve, all of the power is reflected by the load impedance.

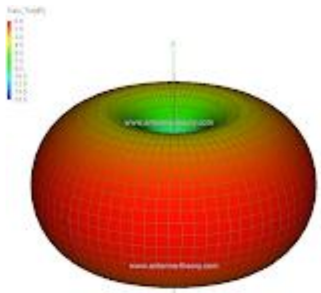
Beamwidth

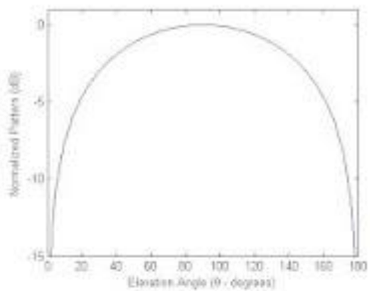
- the angle between two points on the same plane where the radiation falls to 'half power
  G = Antenna Gain
  λ = Wavelength (m)
  $A_e = \frac{G\lambda^2}{4\pi}$ Antenna Effective Area
  $G = \frac{\pi^2 k^2}{\theta\phi}$ θ, ϕ are H and V beamwidths (radians), k antenna factor
  $G = \frac{\pi^2}{\theta^2}$ For circular antennas, θ beamwidth (radians)
- Power radiated from the antenna as a function of the direction away

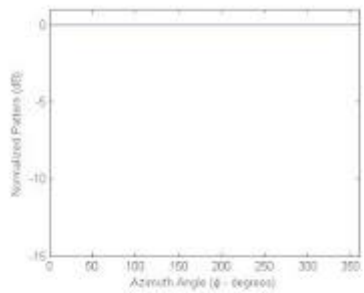
Radiation lobes

- 

- 3D radiation band

- 

- 2D graph
    - 



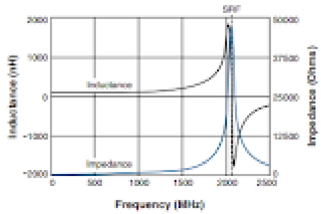
- Isotopic - same in all directions (basically a sphere)
- Omnidirectional - same in one direction (circle)- uniform horizontal radiation pattern and non-uniform vertical radiation pattern
    - Radio broadcasting antennas
    - Ex. Whip antennas (tv and radio)
- Directional - same in no direction
- Reciprocity - property of transmitting and receiving at same pattern

THE WAVE EQUATION (calculus)

- wave in the form $y(x,t)=A\cos(\omega t+\beta x+\varphi)$y(x,t) propagates along negative x direction and $y(x,t)=A\cos(\omega t-\beta x+\varphi)$y(x,t) propagates along positive x
- The wave equation for a plane wave traveling in the x direction is
- $$\frac{\partial^2 y}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 y}{\partial t^2}$$
- where v is the phase velocity of the wave and y represents the variable which is changing as the wave passes. This is the form of the wave equation which applies to a stretched string or a plane electromagnetic wave. The mathematical description of a wave makes use of partial derivatives.

IMPEDANCE (WE NEED MORE CALCULATION INFO HERE)

- Opposition to an antenna's transmission
- relates voltage to current at input of antenna
- Is resonant if impedance is entirely real
- Self Resonance - the frequencies at which the coil begins to absorb energy and resonate on its own rather than allow that energy to pass through it on up to the antenna. Impedance peaks really high when antennas are self resonant



    - Ex.
- Measured in ohms (symbol is omega in greek)
- Standard impedance at 50 Ohms
- Impedance of free space: 377 ohms
- voltage/impedance = current
- Capacitive - imaginary part of impedance of negative
- Inductive - imaginary part of impedance if positive
- $$Z = \sqrt{R^2 + (X_L - X_C)^2}$$
    - Z = impedance
    - R = resistance
    - XL = inductive impedance
    - XC = capacitive impedance
- Z = R + Xi
    - R = resistance
    - X = reactance

BANDWIDTH

1. Bandwidth: range of frequencies that an antenna can operate (radiate/receive energy)
    a. Highest frequency - lowest frequency
    b. Bands with the same width carry the same amount of information (doesn't matter where on the EM spectrum)
2. Bandwidth of antennas (list and order common types of antennas):
    a. FILL IT IN UNLESS IT'S ON THE COMMON TYPES OF ANTENNAS PAGE
3. Edholm's law - bandwidth and data rates double every 18 months
4. Measured in bps (bits per second)
5. percentage bandwidth
    a. %BW = (BW/fC) * 100
    b. Where, BW= bandwidth, Center frequency (fC) = (fH+fL)/2 or what it says the center frequency is

NOISE

1. Undesirable variations in voltage/current that interfere with signals, can often be heard in radios with a faint buzzing
2. Caused by thermal, cosmic background radiation, man made signals such as car motors or fluorescent lights
3. Antenna temperature is a measurement of how much noise an antenna creates
4. Pn = kTnB
    a. Pn = noise power
    b. *k* = Bolzmann's constant = 1.38 × 10−23 J/K
    c. Tn = noise temperature (K)
    d. B = Bandwidth (Hz)
5. N0 = kTn
6. Wien's Law
    a. Peak wavelength of black body radiation

b. $\lambda_{\text{peak}} = \dfrac{b}{T}$

i. B = 2.897 x 10^-3 = Wien's displacement constant

ii. T = absolute temperature

INFORMATION (information theory and entropy were the only things i could find on practice tests- there was like one question on this in all of them combined lol)

1. In abstract information theory, entropy is the measure of information.
2. Less information = less uncertainty/surprise ??
3. Entropy - average amount of information needed to represent probability distribution for a random variable

RADAR EQUATION/ RADAR RANGE EQUATION

- The radar range equation represents the physical dependences of the transmit power, which is the wave propagation up to the receiving of the echo signals

$$R_{max} = \sqrt[4]{\frac{P_t\, G^2\, \lambda^2\, \sigma}{(4\pi)^3\, P_{min}}} = \sqrt[4]{\frac{P_t\, G^2\, c^2\, \sigma}{f_o^2\,(4\pi)^3\, P_{min}}}$$

P_t = **Transmit power** (power dimensions)
P_{min} = **minimum detectable signal** (power)
λ = **transmit wavelength** (length)
σ = **Target radar cross section** (area)
f_o = **Frequency** (Hz)
G = **Antenna Gain** (ratio)
c = **speed of light**

-

Coverage of antenna = 4.4 x sqrt of height

Radar Equation → represents physical dependences of transmit power (wave propogation up to receiving of the echo signals)

→ Gives power P_e returning to receiving antenna, depending on transmitted power P_s, start range R, & reflecting characteristics of the aim (radar cross section σ)

→ Determines the theoretically maximum range

Non-directional Power Density (S_u)

$$S_u = \frac{P_s}{4\pi R_1^2}$$

P_s = transmitted power [W]
S_u = nondirectional power intensity
R_1 = range from transmitter antenna to the aim [m]

Directional Power Density

$$S_g = S_u \cdot G = \frac{P_s G}{4\pi R_1^2}$$

G = antenna

Radar Equation

$$R = \sqrt[4]{\frac{P_s G^2 \lambda^2 \sigma}{P_e (4\pi)^3}}$$

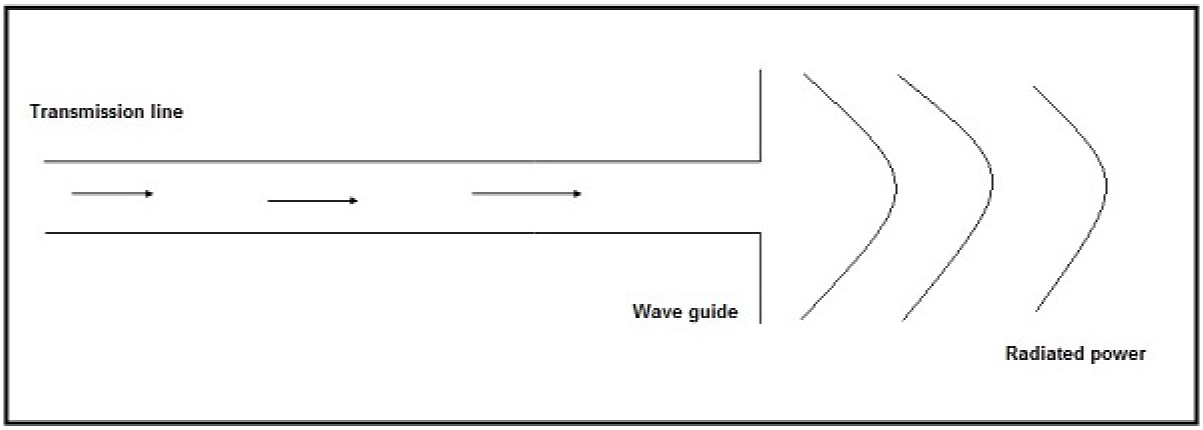
P_e = power returning to receiving antenna
P_s = transmitted power

LAURA STUFF

The sole functionality of an antenna is power radiation or reception. Antenna (whether it transmits or receives or does both) can be connected to the circuitry at the station through a transmission line. The functioning of an antenna depends upon the radiation mechanism of a transmission line.
A conductor, which is designed to carry current over large distances with minimum losses, is termed as a transmission line. For example, a wire, which is connected to an antenna. A transmission line conducting current with uniform velocity, and the line being a straight one with infinite extent, radiates no power.
For a transmission line to become a waveguide or radiate power, it has to be processed as such.

- If the power has to be radiated, though the current conduction is with uniform velocity, the wire or transmission line should be bent, truncated or terminated.
- If this transmission line has current, which accelerates or decelerates with a time varying constant, then it radiates the power even though the wire is straight.
- The device or tube, if bent or terminated to radiate energy, then it is called a waveguide. These are especially used for the microwave transmission or reception.

This can be well understood by observing the following diagram −



The above diagram represents a waveguide, which acts as an antenna. The power from the transmission line travels through the waveguide which has an aperture, to radiate the energy.

Reciprocity

An antenna can be used as both transmitting antenna and receiving antenna. While using so, we may come across a question whether the properties of the antenna might change as its operating mode is changed. Fortunately, we need not worry about that. The properties of an antenna being unchangeable is called the property of reciprocity.

Properties under Reciprocity

The properties of transmitting and receiving antenna that exhibit the reciprocity are −

Equality of Directional patterns

The radiation pattern of transmitting antenna1, which transmits to the receiving antenna2 is equal to the radiation pattern of antenna2, if it transmits and antenna1 receives the signal.

Equality of Directivities

Directivity is same for both transmitting and receiving antennas, if the value of directivity is same for both the cases i.e. the directivities are same whether calculated from transmitting antenna’s power or receiving antenna’s power.

Equality of Effective lengths

The value of maximum effective aperture is the same for both transmitting and receiving antennas. Equality in the lengths of both transmitting and receiving antennas is maintained according to the value of the wavelength.

Equality in Antenna Impedances

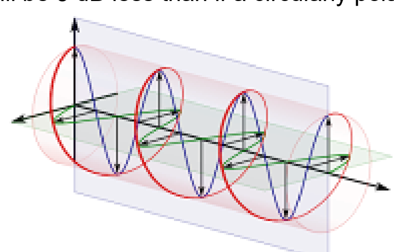
The output impedance of a transmitting antenna and the input impedance of a receiving antenna are equal in an effective communication.

As a transmitting antenna, the transmission line is connected to a source/generator at one end. Along the uniform part of the line, energy is guided as a Plane TEM wave with little loss; the spacing between the line is a small fraction of the wavelength. As the line is opened out and the separation between the two lines becomes comparable to the wavelength, it acts like an antenna and launches a free space wave. From the circuit's POV the antenna appears to have a resistance of Rr, which is called Radiation Resistance.

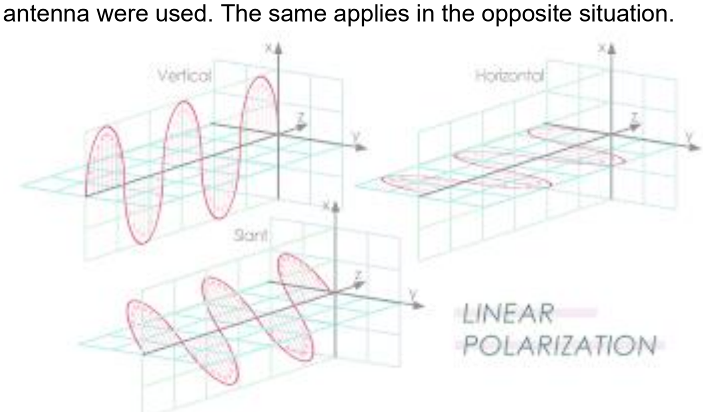
Polarization

Polarization of an EM wave refers to the orientation of the E field component of the wave. For a linearly polarized wave, the orientation stays the same as the wave moves through space. If we choose the axis system such that the electric field is vertical, we say that the wave is vertically polarized. If the transmitting antenna is vertically oriented, the EM wave radiated is vertically polarized, since the electric field is in the direction of the current. Conventionally, we refer to polarization with reference to the surface of the Earth, but in space, the "horizontal" and "vertical" lose their definition, so alignment of linearly polarized sending and receiving antennas is more difficult, which can be somewhat fixed by circular polarization, such that the tip of the electric field vector traces out a circle (when viewed from the direction of propagation).

- Vertical and horizontal are simplest forms and both fall under linear
- Circular polarization can benefit satellite applications by overcoming propagation anomalies' effects, ground plane reflections, and effects of spin in satellites. It can be imagined as a signal propagating from an antenna that is rotating, where the tip of the E vector will trace out a helix or corkscrew as it moves away. It can be seen either right or left handed depending upon the direction of rotation as seen from the transmitter.
- Another form is known as elliptical polarization, a mix of linear and circular polarization (visualized as the tip of the EFV tracing out an elliptically shaped corkscrew.
- It is possible for linearly polarized antennas to receive circularly polarized signals and vice versa. The strength will be equal whether the linearly polarized antenna is mounted in any direction but towards the arriving signal. There will be some degradation b/c the signal will be 3 dB less than if a circularly polarized



antenna were used. The same applies in the opposite situation.

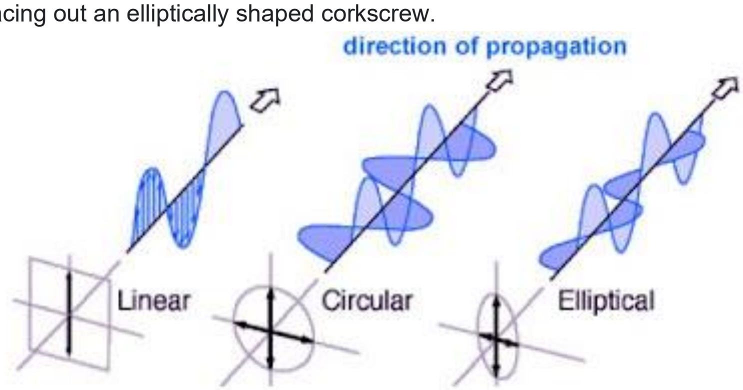


Antenna Polarization

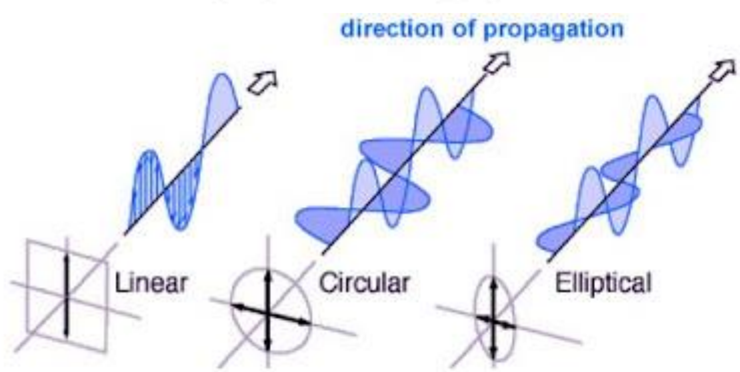
- Polarization of antennas are matched to incoming signal
- **Linear polarization:** Linear polarization is the most common form of antenna polarization. It is

characterized by the fact that all of the radiation is in one plane - hence the term linear:

  - **Horizontal polarization:** This form of antenna polarization has horizontal elements. It picks up and radiates horizontally polarized signals, i.e. electromagnetic waves with the electric field in the horizontal plane.
  - **Vertical polarization:** This form of antenna is typified by the vertical elements within the antenna. It could be a single vertical element. One of the reasons for using vertical polarization is that antennas consisting of a single vertical element can radiate equally around it in the horizontal plane. Typically vertically polarized antennas have what is termed a low angle of radiation enabling a large proportion of their power to be radiated at an angle close to the earth's surface. Vertically polarized antennas are also very convenient for use with automobiles.
  - **Slant polarization:** This is a form of radio antenna polarization that is at an angle to the horizontal or vertical planes. In this way both vertical and horizontally polarized antennas are able to receive the signal.
- **Circular polarization:** This has a number of benefits for areas such as satellite applications where it helps overcome the effects of propagation anomalies, ground reflections and the effects of the spin that occur on many satellites. Circular polarization is a little more difficult to visualize than linear polarization. However it can be imagined by visualizing a signal propagating from an RF antenna that is rotating. The tip of the electric field vector will then be seen to trace out a helix or corkscrew as it travels away from the antenna.
  - **Right hand circular polarization:** In this form of polarization the vector rotates in a right handed fashion.
  - **Left hand circular polarization :** In this form of polarization the vector rotates in a left handed fashion, i.e. opposite to right handed.
- **Mixed polarization:** Another form of polarization is known as elliptical polarization. It occurs when there is a mix of linear and circular polarization. This can be visualized as before by the tip of the electric field vector tracing out an elliptically shaped corkscrew.



-



Applications for different types of antenna polarization

Different types of polarization are used in different applications to enable their advantages to be used. Accordingly different forms of polarization are used for different applications:

General radio communications: Linear polarization is by far the most widely used for most radio communications applications as the radio antennas are generally simpler and more straightforward.
Mobile phones and short range wireless communications: In recent years there has been a phenomenal amount of growth in the use of mobile phone and short range wireless communications. Everything from cellular communications to Wi-Fi and a host of other standards that enable short range wireless communications to be achieved.

Normally linear polarization is used for these devices because linearly polarized antennas are easier to fabricate in these devices, and hence the base stations need to have a similar polarization. Although vertical polarization is often used, many items like Wi-Fi routers have adjustable antennas. Also the fact that these communications often have signal paths that may reflect from a variety of surfaces, the polarization that reaches the receiver can be relatively random, and therefore it can be less of an issue.
Mobile two way radio communications: There are many traditional mobile two way radio communication systems still in use for everything from the emergency services to a host of private mobile radio applications where radio transceivers are located in vehicles.

Vertical polarization is often used for these mobile two way radio communications. This is because many vertically polarized radio antenna designs have an omni-directional radiation pattern and it means that the antennas do not have to be re-orientated as positions as always happens for mobile radio communications as the vehicle moves.
Long distance HF ionospheric communications: Both vertical and horizontal polarization are used:
Horizontal polarization: Wire antennas are widely used for HF communications. These tend to be more easily erected using two poles leaving the wire antenna to be suspended between the two. In this way the antenna is horizontally polarized.

For large multi-element antenna arrays, mechanical constraints mean that they can be mounted in a horizontal plane more easily than in the vertical plane. This is because the RF antenna elements are at right angles to the vertical tower of pole on which they are mounted and therefore by using an antenna with horizontal elements there is less physical and electrical interference between the two.
Vertical polarization: Antennas consisting of a single vertical element are widely used. The vertically polarized antenna provides a low angle of radiation which enables it to provide good long distance transmission and reception.

Radiation Patterns

An antenna’s radiation pattern is a plot showing the strength of radiation output or input in any direction.

Radiation patterns may be graphed in polar (2D) or spherical (3D) coordinates, allowing one to define the strength of emission in terms of the direction (angle).

- Polar coordinates are plotted in terms of radius r (distance from origin) and angle theta (angle from x-axis/polar axis).
- Spherical coordinates are plotted in terms of r, azimuthal angle phi (angle from x-axis), and polar angle theta (angle from z-axis).
- Side lobes - smaller beams that are away from the main beam which can never be completely eliminated
- Main beam - region around the direction of maximum radiation
- Half power point/bandwidth - output power drops to half its value
- First Null Beam Width (FNBW) - angular separation drawn between the null points of the radiation pattern

Antennas’ transmission and reception radiation patterns are always the same; this is called reciprocity. Reciprocity can be extended to all other properties of antennas (means there is no need to design and manufacture separate transmission and reception antennas, but doesn’t mean the same antenna should be used for both purposes).

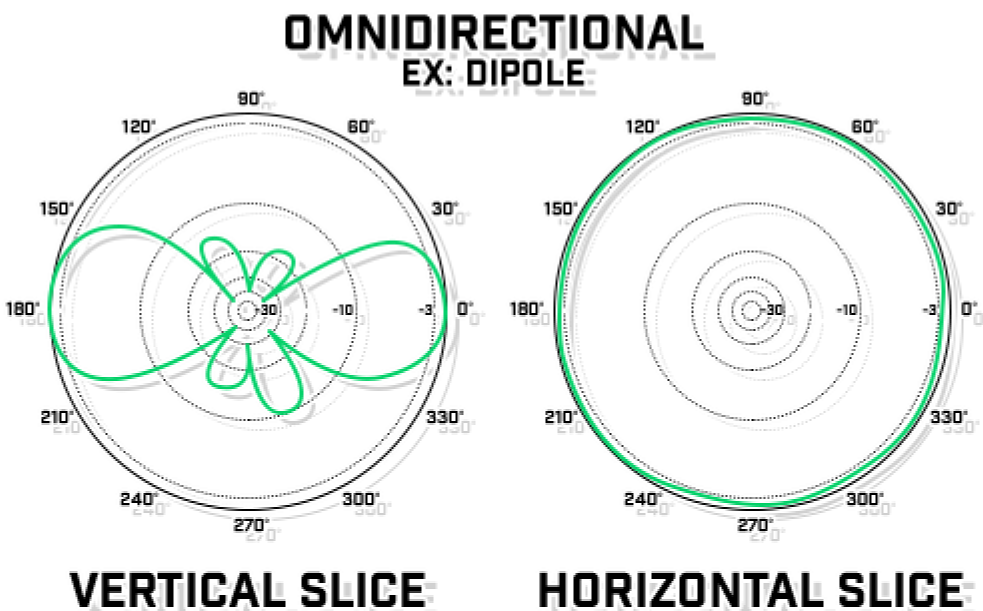
Depending on the application, a transmission antenna with one radiation pattern might be used with a reception antenna with a different pattern. I.e. in a many-to-one network where multiple transmitters in different locations communicate to a single receiver, the transmission antennas can have power output focused in one direction whilst the reception antenna accepts from all directions equally.

In a polar graph, power intensity can be read based on the number of lines out from the origin. However, radiation patterns may be shown with normalized power intensity, or where all values are divided by maximum power intensity (aka scaling it down to 1). This may make it easier to estimate/calculate/compare patterns and directivities of multiple antennas without having to account for relative intensity.

Directionality

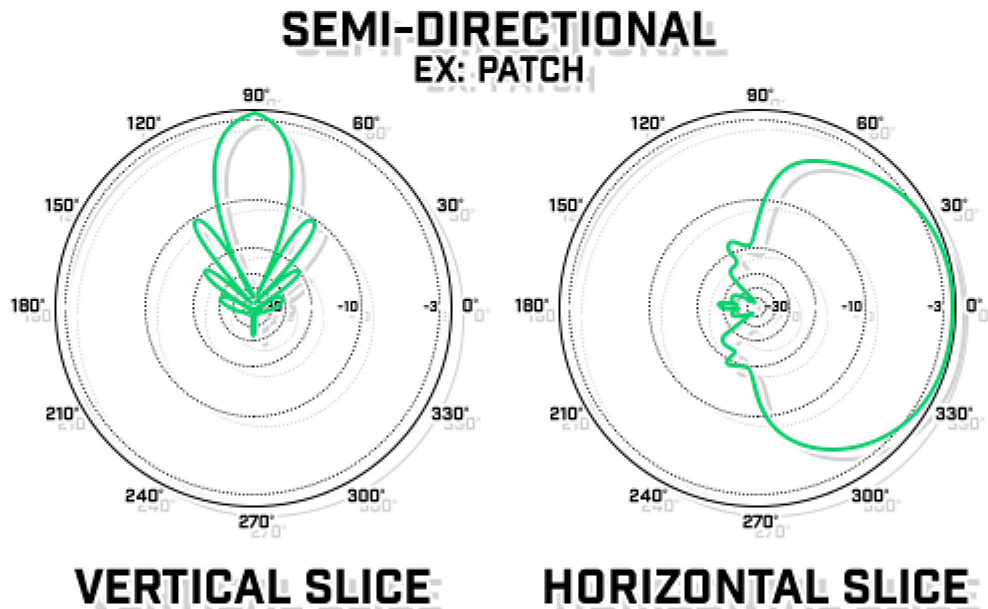
Omnidirectional

When you enter a home or office setting, you don't generally think about the type of antenna that is being used. This is because they are small - or not visible at all - and oftentimes built into the network's router or access point. In these types of environments, omnidirectional antennas, specifically Dipole antennas, are commonly found. Similar to how a floor lamp radiates light, omnidirectional antennas radiate radio frequency (RF) in all directions. Another way to think about the coverage is to imagine putting a bagel on your finger as if it were a ring. Your finger is the antenna and the bagel is the coverage it provides. A perfect omnidirectional antenna would radiate RF signal like a theoretical isotropic radiator, meaning the signal is radiating equally in all directions.



Semi-directional

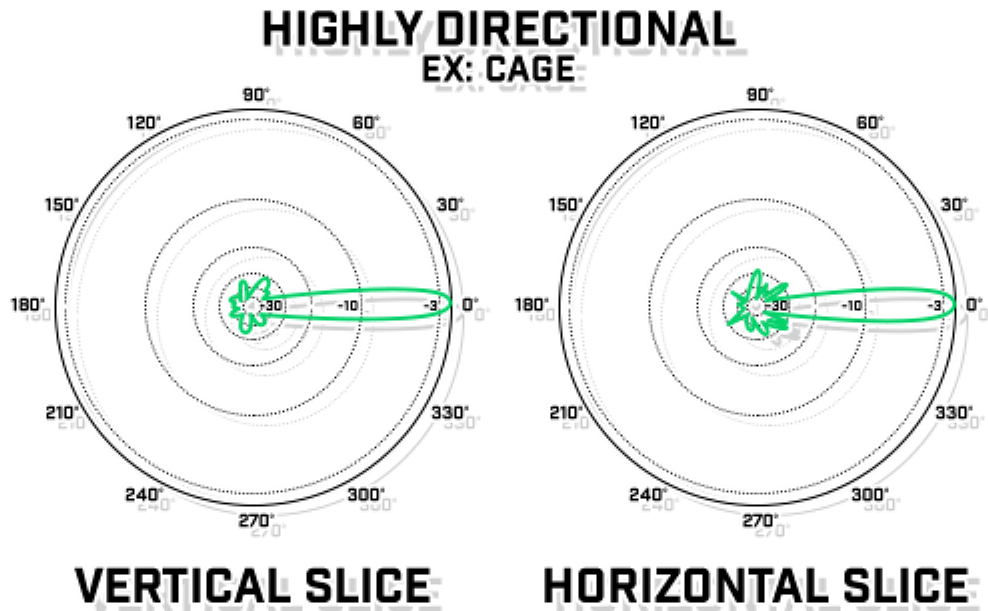
Semi-directional antennas are designed to direct the RF signal in a specific direction for point-to-point communication. Semi-directional antennas are used for short to medium distance communication indoors or outdoors. A good way to think of how the semi-directional antenna radiates RF is to think of it as a street lamp shining down on the street. It is common to use semi-directional antennas in a campus like environment since they can provide a network bridge between two buildings.



The main types of semi-directional antennas are Patch/Panel and Yagi. Patch/Panel antennas are generally found indoors and used to radiate into the forward space. A building with long hallways or shelves, such as retail stores, warehouses, libraries, or hospitals, that would block an omnidirectional antenna's signal would benefit from a semi-directional antenna. A Patch/Panel antenna is placed high on the wall, aiming down an aisle or between rows of shelving. Since the antenna has a horizontal beam width of 180 degrees or less, there is plenty of necessary coverage with minimal bleed through. Yagi antennas span longer distances and are generally used in an outside environment. The main purpose of these antennas is to reach places that an omnidirectional antenna would not be able to reach.

Highly Directional

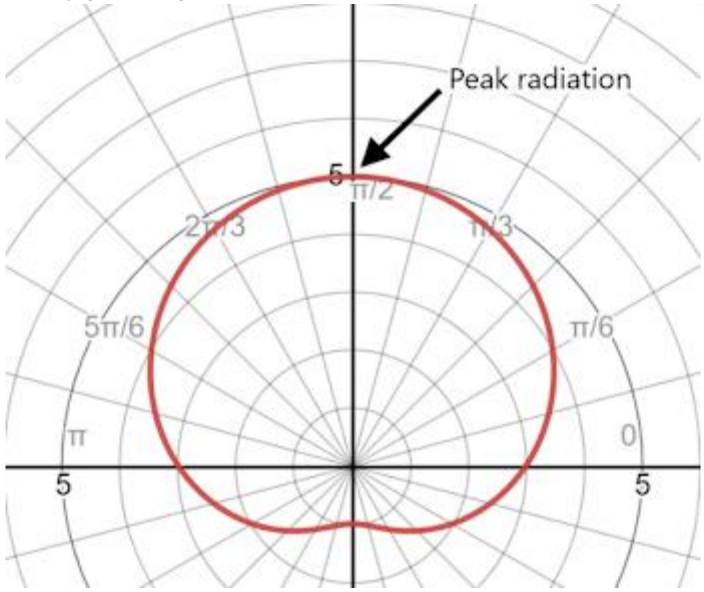
Highly directional antennas are used for long distant point-to-point communication. They are used to bridge networks between two buildings that are far apart. Because these antennas are high gain, they provide the most focused and narrow beam width. Instead of a street light shining down, it is more of a spotlight shining in a specific direction. The two main highly directional antennas are Parabolic (Dish) and Grid. Dish antennas look similar to the TV dish antennas that you would find in a home but are often much larger in size. Grid antennas can also vary in size, but they look like a grill and are designed for outdoor environments with higher winds.



A third type of highly directional antenna is the Sector antenna. Sector antennas consist of a few highly directional antennas, placed back-to-back, that are working together to provide omnidirectional coverage. Each antenna that is part of the array provides a pie shaped coverage pattern. Sector antennas can be mounted high over the terrain and tilted slightly downward, with the tilt of each antenna at an appropriate angle for the terrain it is covering. While omnidirectional antennas can also be mounted high over the terrain, if it is tilted downward, the other side's signal will be wasted up in the air. Therefore, the sector antennas are able to cover much larger areas because they can be directed in any direction the coverage is needed. Compared to omnidirectional antennas, sector antennas have greater throughput since there is more than one antenna in use. These antennas are generally used for cell phone coverage and at sports venues.

Directivity

Directivity of an antenna describes how concentrated the power output of the antenna is in any direction. In an isotropic antenna (perfectly spherical radiation pattern, r is constant), the directivity would be 1. Although directivity is a function that outputs directivity at any given angle, it is often defined as a constant in terms of direction of greatest



radiation, such as pi/2 (90 deg).

On a polar graph, you can often see where the greatest radiation is, and so, you can give it in terms of the angle there (radians).

You can also define a function D(theta) that outputs the directivity at an angle theta.

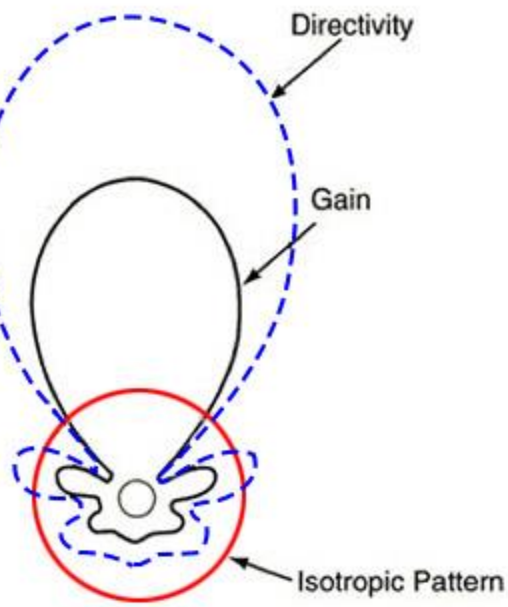
Directivity is proportional to the ratio of max radiation intensity to average radiation intensity. If these are given, the formula is D = (max radiation intensity)/(average radiation intensity), where the value of directivity is unitless. Directivity may also be represented in terms of decibels, using formula D(sub dB) = 10 log (D/D(reference antenna)). Since decibels are a relative unit, a reference antenna must be chosen to compare the directivity, often an isotropic antenna with a unitless directivity of 1, which gives the final value of directivity in terms of the unit "decibels isotropic (dBi)."

Average radiation intensity = TOTAL POWER / 4PI

Antenna Type	**Typical Directivity**	**Typical Directivity (dB)**
Short Dipole Antenna	1.5	1.76
Half-Wave Dipole Antenna	1.64	2.15
Patch (Microstrip) Antenna	3.2-6.3	5-8
Horn Antenna	10-100	10-20

Dish Antenna	10-10,000	10-40

Gain



Gain refers to how much power is emitted in the direction of greatest radiation. Gain is found by multiplying directivity of an antenna by efficiency (takes into account power loss).

Formula: G = nD, where “n” is efficiency
Efficiency: n = P(out)/P(in)

– where P(out) and P(in) are the total power input and output of the antenna; efficiency measures how much of the input power is actually emitted. For one that outputs all power put in, efficiency = 1 and G = D, which occurs in an isotropic antenna.

If directivity is unitless, then gain is in dB, or if D is in dBi, then G is also in dBi. Gain can also be given in comparison to a perfect dipole antenna (no loss), which has a gain of 2.15 dBi, which is a unit called decibels dipole (dBd). G(dBd) = G(dBi) - 2.15. Also, an antenna with gain 2.15 dBi would have a gain of 0 dBd, meaning its gain = that of a perfect dipole. The same idea applies for any values, including gain, which are represented in decibels relative to another antenna.

Gain = intensity radiated in direction of max output at arbitrary distance / intensity radiated at same distance by hypothetical isotropic antenna

Could also see Formulas page

Resolution

Resolution = half of beamwidth between first nulls = ~ HPBW

Impedance

Impedance is a measure of opposition against an antenna's transmission. The idea of impedance is related to resistance in a circuit (resistance measures opposition against the flow of current). However, impedance takes reactance into account (the measure of opposition against the change in current). Although resistance suffices for direct currents, reactance is important for alternating currents (which antennas use).

Direct current (DC) is the flow of electric charge in only one direction. It is the steady state of a constant-voltage circuit. Most well-known applications, however, use a time-varying voltage source. *Alternating current* (AC) is the flow of electric charge that periodically reverses direction. If the source varies periodically, particularly sinusoidally, the circuit is known as an alternating current circuit.

Impedance is measured in ohms (symbol omega) and is written as a complex number in form Z = R + Xi, where R = resistance and X = reactance. However, actual impedance is difficult to determine exactly because it depends on the antenna, operating wavelength, and environment. You can find it by mathematical relations and recorded observations.

Antenna Losses

RF energy travels through transmission lines (coax cables or PCB traces) just like sound travels through an empty room. It is susceptible to reflections and bounces. When sound waves hit the hard walls of an empty room, you can hear the echoes. The loss or reduction of these echoed waves is nearly zero (*zero return loss)*. Imagine the difference when you are in a clothes-packed walk-in closet… no echoes. The fabric around you absorbs sound, and the loss of the sound bounces is high (*high return loss*). When we send RF down a coax or PCB trace, we want it to go into the antenna (then radiate out into the world). We do not want it to bounce back towards us like sound in an empty room.

Additional losses: polarization mismatch, people in the way, earth curvature (obstacle), things in the way of LOS polarization, distance

Return Loss

This bounce back reflection is called "return". Return loss is the measure of how small the "return" or reflection/echo is. We want a small return, so a large loss on the return "echo" is good. Smaller return loss is bad, and means less energy is going into our antenna. RF engineers often measure return loss on a "dB" logarithmic scale, which can make it seem more complicated than it really is. However, just remember better return loss is indicated by bigger return loss numbers, and that is better for your antenna. Here are some examples of the logarithmic scale, or loss in decibels:

Return Loss & VSWR Table

Return Loss in dB	What It Means	VSWR Number
0 dB	100% reflection, no power into the antenna, all reflected back	Infinite
1 dB	80% reflection, 20% power into the antenna	17
2 dB	63% reflection, 37% power into the antenna	9
3 dB	50% reflection, 50% power into the antenna	6
5 dB	32% reflection, 68% power into the antenna	3.5
6 dB	25% reflection, 75% power into the antenna	3
8 dB	16% reflection, 84% power into the antenna	2.3
10 dB	10 dB (10% reflection, 90% power into the antenna)	2

15 dB	15 dB (3% reflection, 97% power into the antenna)	1.4
20 dB	20 dB (1% reflection, 99% power into the antenna)	1.2

As you can see, higher return losses mean more power into the antenna. Although more return loss is better here, there is little benefit above 10 dB return loss, since more that 90% of available power is already being delivered to the antenna. Return losses above 10 dB have little practical benefit.

VSWR

It officially stands for Voltage Standing Wave Ratio. This dimensionless ratio (no measurement units) is the same parameter as return loss, just expressed in a different scale. VSWR is somewhat old fashioned, and was often measured by the transmitter itself while transmitting into an antenna.

Measuring Return Loss

Measuring return loss during antenna design or verification is a powerful performance tool. Without good return loss, an antenna CANNOT accept your RF energy, and therefore cannot have it available to radiate. It is imperative that return loss goals and specifications be met. However, return loss does not tell the whole story. While it is true that poor return loss means that an antenna cannot radiate: It is NOT true that good return loss guarantees effective antenna radiation. Unfortunately, every week, we see antennas in our lab that radiate poorly, yet have a good return loss. Knowing (not assuming) your radiation efficiency is one of the many benefits of antenna testing.

Radiation Efficiency

Sometimes the problem is that internal losses (radiation inefficiency) in an antenna can also create good return loss, since the lost energy is not being reflected (returned) to the transmitter. But how do we tell if our good return loss is due to radiation (desired) or internal absorption (undesirable)? The most accurate way is to have the antenna evaluated by an antenna testing service, and verify its radiation efficiency. Good radiation efficiency is the ultimate goal for most antennas (not just good return loss).

Bench Check Tricks

- Hand proximity: While monitoring return loss, move your hand in close proximity to your antenna, about 6 inches away. If you see changes in return loss, that means the antenna is “interacting” with its surroundings. This is a good indication of radiation, and that return loss is probably not being dominated by internal losses. If your hand makes little difference to return loss, then your antenna has high internal losses and is not radiating well.
- Bandwidth: Good return loss over a very wide range of frequencies is hard to obtain. Thus, if wide band “good” return loss is observed, there may be serious losses in the antenna or its matching components. (Your antenna is a “dummy load”!)

Beam Efficiency

Main beam efficiency = (power transmitted/power received with core angle)(power transmitted/received by antenna)

Beam Intensity, Quality, and

We define beam intensity as the product of the quantity and quality of the beam during exposure relative to a specific area. Therefore, the beam's intensity is affected by beam quality (kVp) and beam quantity (mAs). The beam intensity is also affected by the distance between the x-ray tube and the exposed area. If we increase the distance, the beam intensity decreases following the inverse square law. For example, if we double the distance between the source and the area of exposure, we will be reducing the intensity of the beam by 25%.

Beam quality describes the shape of the x-ray spectrum. So we will review the x-ray spectrum briefly here. The x-rays coming out of our clinical x-ray tubes are not all one energy. That would be called monoenergetic or monochromatic. Now that we have established what beam quality is, why we care about it and what factors affect it we will discuss how we can measure beam quality. We demonstrated that the beam quality plays a major influence on the image quality in x-ray and CT imaging. Thus, we want to have a means to ensure that the system is delivering an x-ray spectrum which is similar to the spectrum that we expect.

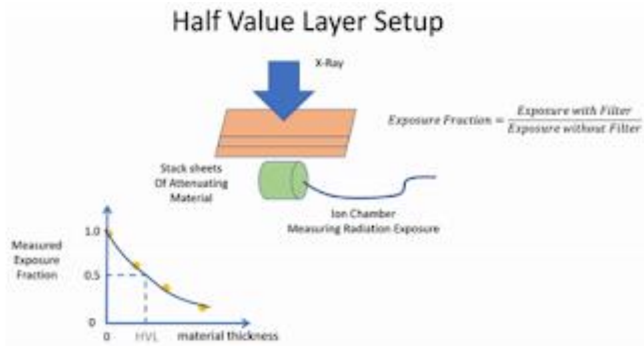
In the clinic if we want to do quality assurance measurements on the system, how can we measure the beam quality?

Can we look at the signal in the detector to determine the x-ray spectrum? Unfortunately, we can not as the detectors we use they typically measure all of the energy under this spectrum. We can't just use measurements from our detector to get a measurement of beam quality.

We need a metric to measure the beam quality and a direct measurement is not feasible in the clinic. Instead of doing a direct measurement, we look for a surrogate measurement of beam quality. We want a quantity that we can measure that we can measure in the clinic and is directly related to beam quality.

The surrogate metric which is related to the beam quality is called the 'half value layer' (HVL). Half value layer is not a direct measure where we put a detector in and we measure the beam quality itself. Rather we are measuring something that's related to the beam quality but the HVL is just one number and does not describe the x-ray spectrum completely.

To measure the half value layer, we show in this figure that you can use an ion chamber to measure the exposure. We've covered this before, but the simple concept is that x-rays are going to ionize the air inside of the ion chamber (i.e. free electrons) and then those ions are going to be collected in order to generate an electric signal. We get a measurement of an electric signal which is proportional to the x-ray exposure incident on the chamber.



We described the setup above and now we are ready to go into the half value layer (HVL) measurement itself. We first perform the measurement without anything in the beam. Just measure with the ion chamber itself, this gives us our reference (i.e. the exposure without any additional filter).

In the plot in the figure all the values will be normalized by this reference value, so the largest number will be 1.0.

After we have made the reference measurement, we insert a thin sheet of metal into the beam. Then we take a second exposure measurement. The measured exposure fraction is the second measurement divided by that exposure without a filter. For each additional thickness of material that is inserted we can make a measurement, and each measurement will generate one point on the curve in the figure.

After we have several points on this curve, we can do a curve fit. From the curve fit we can see the relationship between the material thickness and the exposure fraction. After we have done the curve fit we will be able to estimate the half value layer. Remember, the definition of the half value layer (HVL) is when the exposure is 1/2 of what it is without any material.

Even if we don't have a measurement that's exactly at the half value layer (i.e. the perfect thickness of materials to stop the x-rays) we use curve fit to estimate the HVL. This is demonstrated in the figure. We draw a horizontal line at ½ of the exposure, then where that line intersects the curve we draw a vertical line. The intersection of this vertical line with the x-axis gives the HVL. The HVL will be in distance units, e.g. mm.

These HVL measurements characterize that in our system, we can track that over time or we can compare different systems with that same measurement idea. So, that's called the half value layer. As we have discussed the half value layer is dependent on the beam spectrum and the material.

We have a separate calculator on Beer's law , which is the way that x-rays are attenuated by a given material:

where I is the beam intensity after passing through the material, I0 is the reference intensity without the filtration, μ is the attenuation coefficient for the material for this energy beam, and x is the thickness of material. We can divide both sides by the reference intensity to get:

$$\frac{I}{I_0} = e^{-\mu x}$$

Our goal here is to solve for x since that is the thickness of material. The next step is to take the natural logarithm of both sides since this will help us to cancel out the exponential on the right hand side:

$$\ln\left(\frac{I}{I_0}\right) = \ln\left(e^{-\mu x}\right)$$

$$\ln\left(\frac{I}{I_0}\right) = -\mu x$$

Then we multiply both sides by -1:

Now, we can apply our special situation here where we want to solve for the thickness x that we call the HVL (half value layer) when I/I0=1/2 (the beam intensity is half of the input).

$$HVL = \frac{-\ln\left(\frac{1}{2}\right)}{\mu}$$

After using our calculator to take the natural log of ½ we get the final relationship for the half value layer, where both the HVL and μ depend on the beam quality (i.e. these are really averaged over all of the energies in the x-ray spectrum).

Thus far we have been discussing the concept of a single half value layer of a material. We can generalize this concept to include multiple half value layers where each additional half value layer the beam intensity is cut in half again.

If we use more material then instead of attenuating to where we get just half of the x rays coming out, we could get 1/4 of the X rays coming out. So, if we had two half value layers, we get 1/4 of the X rays coming out. If we had 3 half value layers, then we get (1/8) a little more than 12% of the X rays coming out. If we have four half value layers, we get (1/16) or about six percent.

The relative intensity passing through the beam filter is just 1/2 HVL.This is the definition for multiple half value layers and you can see how this looks pictorially in this figure.

Bandwidth

According to the standard definition, "A band of frequencies in a wavelength, specified for the particular communication, is known as bandwidth."

The signal, when transmitted or received, is done over a range of frequencies. This particular range of frequencies are allotted to a particular signal, so that other signals may not interfere in its transmission.

- Bandwidth is the band of frequencies between the higher and lower frequencies over which a signal is transmitted.
    - range of frequencies over which an antenna can properly radiate
    - range over which the antenna can properly receive energy
- The bandwidth once allotted, cannot be used by others.
- The whole spectrum is divided into bandwidths to allot to different transmitters.
- can also be called Absolute Bandwidth.
- any band of a given width can carry the same amount of information, regardless of where that band is located in the frequency spectrum.[a] For example, a 3 kHz band can carry a telephone conversation whether that band is at

baseband (as in a POTS telephone line) or modulated to some higher frequency. However, wide bandwidths are easier to obtain and process at higher frequencies because the § Fractional bandwidth is smaller.

depending on context, it may specifically refer to *passband bandwidth* or baseband bandwidth. Passband bandwidth is the difference between the upper and lower cutoff frequencies of, for example, a band-pass filter, a communication channel, or a signal spectrum. Baseband bandwidth applies to a low-pass filtered baseband signal; the bandwidth is equal to its upper cutoff frequency.

The particular frequency within a frequency band, at which the signal strength is maximum, is called resonant frequency. It is also called the center frequency (fC) of the band.

- The higher and lower frequencies are denoted as fH and fL respectively.
  - The absolute bandwidth is given by: fH - fL
  - difference between the upper and lower frequencies in a continuous band of frequencies
- To know how wider the bandwidth is, either fractional bandwidth or percentage bandwidth has to be calculated.

The Percentage bandwidth is calculated to know how much frequency variation either a component or a system can handle. According to the standard definition, “The ratio of absolute bandwidth to the center frequency of that bandwidth can be termed as percentage bandwidth.”

$$\text{Percentage bandwidth} = (\text{absolute bandwidth center})/\text{frequency} = (fH - fL)/fc$$

Where

- fH is higher frequency
- fL is lower frequency
- Fc is center frequency

The higher the percentage bandwidth, the wider will be the bandwidth of the channel.

Noise

In telecommunication, **antenna noise temperature** is the temperature of a hypothetical resistor at the input of an ideal noise-free receiver that would generate the same output noise power per unit bandwidth as that at the antenna output at a specified frequency. In other words, antenna noise temperature is a parameter that describes how much noise an antenna produces in a given environment. This temperature is not the physical temperature of the antenna. Moreover, an antenna does not have an intrinsic "antenna temperature" associated with it; rather the temperature depends on its gain pattern and the thermal environment that it is placed in.

The received signal power is meaningless unless compared with the power received from unwanted sources over the same bandwidth. Such noise sources include thermal radiation from the earth and sky, cosmic background radiation, and random thermal processes in the receiving system. In today’s wireless environment, additional noise due to nonstationary radio frequency interference from pagers, cellular phones, etc., often needs to be considered.

Antenna noise temperature has contributions from several sources:

- Galactic radiation
- Earth heating
- The sun
- Electrical devices

- The antenna itself

Galactic noise is high below 1000 MHz. At around 150 MHz, it is approximately 1000 K. At 2500 MHz, it has leveled off to around 10 K.

Earth has an accepted standard temperature of 288 K.

The level of the sun's contribution depends on the solar flux. It is given by

Ta = 3.468F(y^2) x 10^(G/10)

where

F is the solar flux,

y is the wavelength,

and

G the gain of the antenna in decibels.

The antenna noise temperature depends on antenna coupling to all noise sources in its environment as well as on noise generated within the antenna. That is, in a directional antenna, the portion of the noise source that the antenna's main and side lobes intersect contributes proportionally.

For example, a satellite antenna may not receive noise contribution from the earth in its main lobe, but sidelobes will contribute a portion of the 288K earth noise to its overall noise temperature.

Information

Information theory is the field of study concerned with quantifying information for communication. It is a subfield of mathematics and is concerned with topics like data compression and the limits of signal processing.
Information – defined as any form of uncertainty or randomness in a system that allows it to store meaning
Ex. “qwerty,” “radio”
When information is stored and transmitted, it is usually not done so in a human-readable form. It may be represented using the binary system transmitted as voltage by computers or using the amplitudes and frequencies of radio waves transmitted by an antenna. These are not understandable or perceivable to humans, but still store information that can be understood or decoded into something like music or text.
Information is measured using entropy, which measures the unexpectedness or “surprise factor” associated with an event.
Ex. a single fair coin with two sides carries one bit of information on average, either heads or tails (where bit refers to the fact that there are two outcomes with equal probabilities). If it were unfair, one of the outcomes would be more likely than the other, so it would contain less than one bit of information on average, because one outcome would be more expected.
Ex. If given the letter “q” as the first letter of a word and asked for the following letter, the letter “u” would contain very little information, since knowing the general rules of English, you can assume that “u” follows the letter “q.” But, if the next letter were “i,” this would be surprising, so the letter “i” coming after the letter “q” has high entropy and thus more information.
Using entropy, engineers can determine a way to code (or translate) messages into a signal. For example, the bigram “qu” can be treated like a single letter since after a q is almost always a “u,” which is more simple and cost-efficient than sending letters “q” and “u” separately.
Message coding is important to communication theory because sending large amounts of long and inefficient messages can cost energy. The measurement of entropy is typically made based on the use case, as entropy is a relative measurement and there is no way of comparing the entropies of two amounts without knowing the entire set of possible events and then calculating the probability of each event separately.

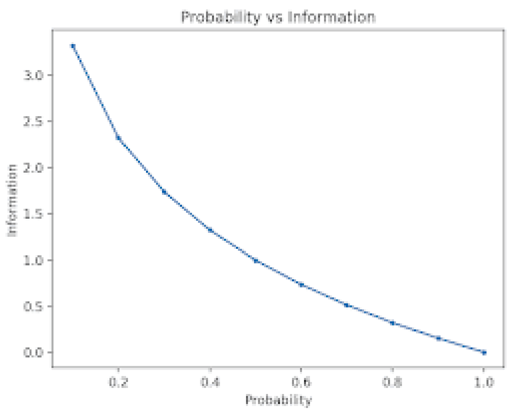
Low Probability Event: high information (surprising)
High Probability Event: low information (unsurprising)

It is possible to calculate the amount of information there is in an event by using the probability of the event. This is called “Shannon information,” “self-information,” or the “information.” It can be calculated for a discrete event x:

- information(x) = -log(p(x))

Where log() is the base-2 logarithm and p(x) is the probability. The negative sign always ensures that the result is always positive or zero.

- Log of base b (x) = log(x)/log(b) where log() is base-10



Information will be zero when the probability of an event is 1.0 or a certainty, e.g. there is no surprise. Low probability events have more information.

Entropy can be calculated for a random variable *X* with *k* in *K* discrete states as follows:

- H(X) = -sum(each k in K p(k) * log(p(k)))

That is the negative of the sum of the probability of each event multiplied by the log of the probability of each event.

- If there are a number of outcomes, the entropy is the summation of the base two logarithms of each outcome’s probability multiplied by the probability of each outcome

Also, information/entropy may be calculated using other logarithms, such as base-e (Euler’s number), in which case the units are called “nats.”

Antenna Types

Omnidirectional Antenna

- A class of antenna that radiates equal radio power in all directions perpendicular to an axis with power varying with elevation angle (3D), such that the radiation pattern in 3D looks like a donut.
- Omnidirectional Antennas are monopole antennas and vertical dipole antennas.
- Antenna gain (G) is defined as antenna efficiency (e) multiplied by directivity (D), or
  $G = eD$

Directional Antenna

- An antenna which radiates or receives greater power in specific directions, allowing increased performance and reduced interference from unwanted sources. They provide increased performance over omnidirectional antennas in general when a greater concentration of radiation in a certain direction is needed.
- A high-gain antenna (HGA) is directional and has a focused radiowave beam width, used commonly during space missions and in open, flat areas.
- All practical antennas are somewhat directional, though the only considered direction is

Isotropic Antenna

- The simplest antenna but purely theoretical and cannot be constructed or designed. Its main purpose is to serve as a reference for properties of real antennas (e.g. efficiency, directivity, and gain).
- It is possible to construct a nearly-isotropic antenna by making an antenna much smaller than the wavelength it emits, so that the near-field radiation pattern will look nearly-isotropic, due to the distance traveled by the waves being too short for any losses to occur. This is similar to the principle applied in the design of short dipoles.

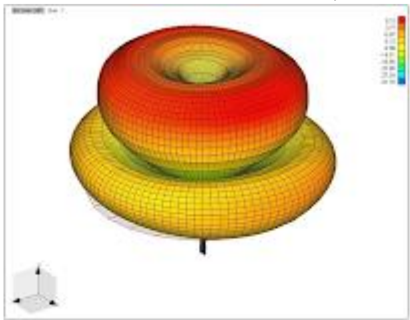
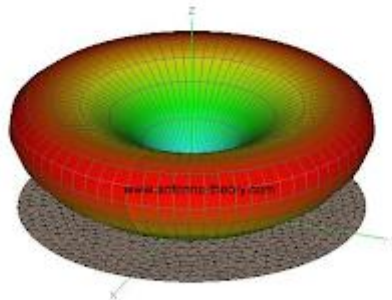
More Specific Categories

Wire Antennas

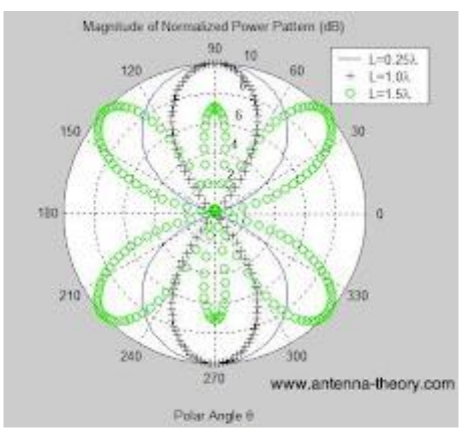
Monopole Antenna (aka ground plane antenna)
● These consist of a single radiating element, like a rod or wire, directly linked to the transmission line. They are positioned normal to their supporting plane or structure, which has the effect of reducing impedance in comparison to the dipole (only half the current is being carried).
    ○ Consists of straight flexible wire or rod
    ○ Applications:
        ■ Most common type of monopole is a whip antenna; used on top of (older) cars
            ● Length of it depends on the length of the radio waves it’s used with
            ● Most common: quarter-wave whip; ¼ wavelength long
                ○ Impedance of quarter wave monopole: 37.5 ohms
            ● HF, VHF, and UHF bands
            ● Cordless phones, walkie-talkies, FM radio, boom boxes
● Examples:
    ● inverted F – has compactness and good matching (no need for separate network), commonly used in cell phones
    ● Umbrella – very large wire with narrow bandwidth, used on VLF bands; consists of central radiating tower with multiple wires attached at top, extending out radially; high capacitive reactance, minimal radiation resistance
    ● Whip – used on mobile and portable radios in VHF and UHF bands, made of a flexible rod, often telescoping segments
    ● inverted-L and T – long horizontal wire suspended between two towers with insulars with a vertical wire hanging down attached to a feedline to receiver/transmitter; used on LF and VLF bands; vertical wire is shorter than a quarter wavelength; increased gain, narrow bandwidth. Commonly used to transmit from radio stations.
    ● folded unipole – vertically aligned loop which inductively loads antenna; modified mast antenna with parallel wires
    ● mast radiator – a radio tower with the tower itself serving as the antenna; often used for AM radio, MF, LF transmitters; often mounted on ceramic insulator to isolate it from the ground

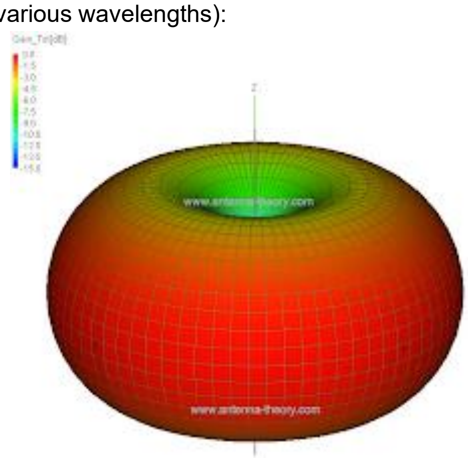
- rubber ducky – used on portable two-way radios and cordless phones; very compact, consisting of electrically short wire helix; resonant, low gain
- Ground plane – whip antenna with several rods extending horizontally from base attached to ground side of feedline; increased gain; used for police, ambulance, taxi dispatchers

- Radiation pattern:
    - 3D (without and with the ground plane):

<u>Dipole Antenna</u> (includes short dipoles and half-wave dipoles)
- These are very simple and commonly-used and serve as the foundation for many more complex antennas.
- A dipole antenna consists of two rods, wires (or other uniform conducting material pointing out in two different directions (often opposite)). They can be further classified into: short, half-wave, full-wave, and folded.
    - Has two conductors in the same axis and a shorter wire length compared to wavelength
- The short dipole is based on the principle used to mimic isotropic antennas (this antenna is usually ~10 times smaller than the operating wavelength). In reality, the pattern is closer to that of an omnidirectional antenna.
- The half-wave dipole is the most common dipole design; they are characterized by having a total length nearly equal to half the wavelength they operate at. The radiation being transmitted lines up with each monopole (the wires or rods pointing out), a property called resonance. This results in an omnidirectional antenna with optimal impedance, so it is useful for communication, and in the past, television.

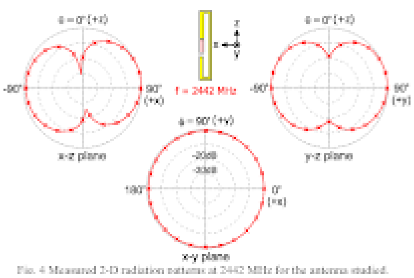
- Has electrical current flowing
- Resonates on higher frequency if lengthened
- Radiation pattern (2D picture- radiation patterns for various wavelengths):
    - 

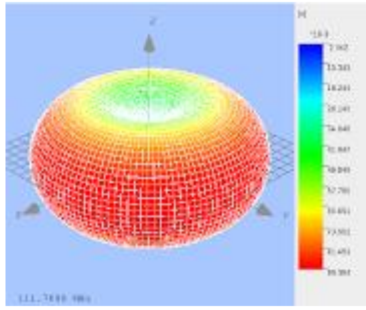


    - Omnidirectional radiation pattern

<u>Loop Antenna</u>
- How it works: idk
- Applications: aircraft direction finders, ultra high frequency transmitters
    - Commonly used for radio waves in ULF bands

- Radiation patterns:





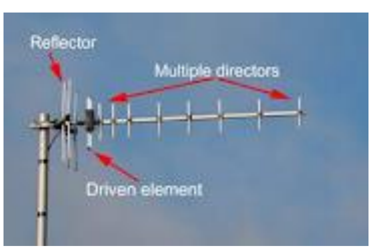

- Will become resonant as it reaches one wavelength in size
- Self resonance is important because loop antennas have a perimeter and you don't want high impedance

Travelling Wave Antennas

- Not resonant, have inherently broad bandwidth
- Wire antennas that are multiple wavelengths long, through which voltage and current waves travel in one direction instead of forming standing waves
- Have linear polarization (except helical)
- Inefficient as transmitting antennas but removes half of incident radio noise when receiving
  - Types: Beverage (simplest unidirectional traveling-wave antenna), Rhombic (four equal wire sections shaped like rhombus), leaky wave (microwave antennas consisting of waveguide or coaxial cable with slot or apertures cut in), helical (wire in shape of helix above reflecting screen radiating circularly polarized waves, typical gain 15 dBi), yagi uda (??), spiral

Yagi-Uda Antennas

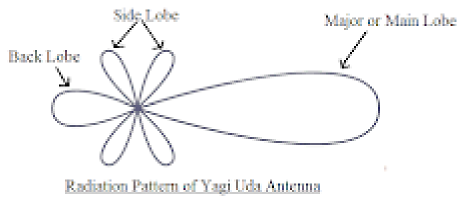
- The Yagi-Uda antenna consists of multiple dipoles systematically placed together at different distances. As a result, they have higher directivity and gain. Disadvantages: can be noisy, only operate from 30 MHz to 3 GHz. In addition, since design depends on wavelength (thus, frequency), a single antenna cannot be used for multiple frequencies. Most commonly used as receptors for television.
- One of the arms in a Yagi-Uda antenna is driven by a current
- Yagi-Uda antennas also rely on some destructive and constructive interference in order to create different directivity levels

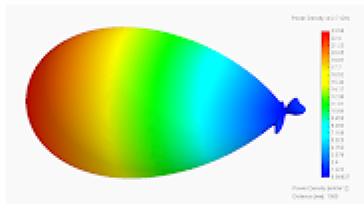



- Uses a dipole
- Used for tv signals along with radar and satellites
- ***Driven element:*** The driven element is the Yagi antenna element to which power is applied. It is normally a half wave dipole or often a folded dipole.
- ***Reflector:*** The reflector element is made to be about 5% longer than the driven element. The Yagi antenna will generally only have one reflector. This is behind the main driven element, i.e. the side away from the direction of maximum sensitivity. Further reflectors behind the first one make no noticeable difference to the antenna performance. However many designs use reflectors consisting of a reflecting plate, or a series of parallel rods simulating a reflecting plate. This gives a slight improvement in performance, reducing the level of radiation or pick-up from behind the antenna, i.e. in the backwards direction. This can help in reducing the levels of interference received.
Typically a reflector will add around 4 or 5 dB of gain in the forward direction.
- ***Director:*** The director or directors are made to be shorter than the driven element. There may be none, one or more reflectors in

the Yagi antenna. The director or directors are placed in front of the driven element, i.e. in the direction of maximum sensitivity. Typically each director will add around 1 dB of gain in the forward direction, although this level reduces as the number of directors increases.

- Has gain, max gain of 20db
- Longer = higher gain





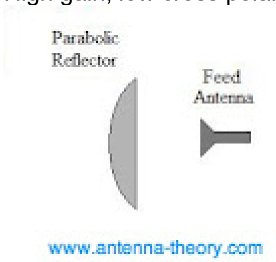
Array Antenna (not on antennatheory for some reason)

- Made up of a system of multiple antennas; has ability to increase directivity by having signals interfere constructively and destructively to boost/cancel power in specific directions. This is done by adding different phase shifts to the signals of each antenna (shifts in the position of a wave used to create interference). This results in high directivity, and thus they are used for everything from broadcasting to astronomy.
  - Collinear – consists of dipoles in a vertical line; high-gain (8-10 dBi), omnidirectional (more power radiated in horizontal directions); used for land mobile radio systems
  - Yagi-Uda
  - Reflective array
  - Phased array
  - Curtain array
  - Half-square antenna
  - Batwing/superturnstile
  - Microstrip

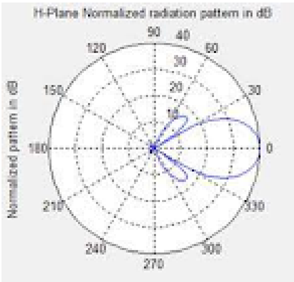
Reflector Antennas

Parabolic Reflector (Dish Antenna)

- How it works:
  - Concentrates signals onto a feedhorn which focus it onto a probe which is processed by a pcb
  - Could be considered a dipole antenna
- Properties:
  - Focus all the signals onto one point- high directivity
  - High gain, low cross polarization

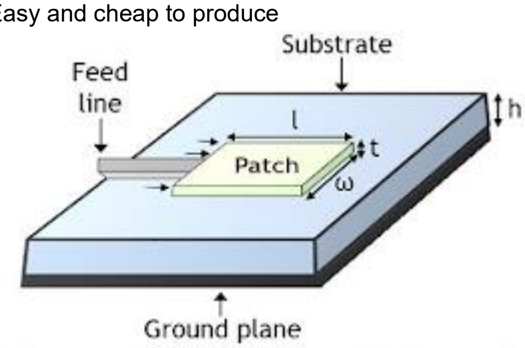


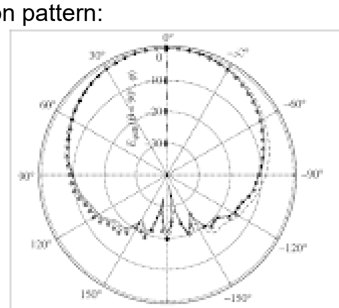
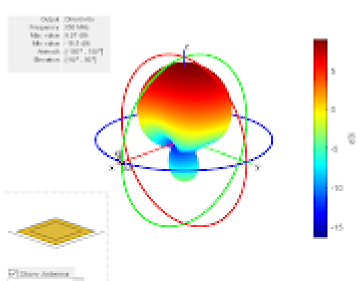
  -
  - Reflecting dish is larger than a wavelength in size
- Applications:
  - Communicate with machines (satellites) in orbit
- Radiation pattern:



Microstrip Antennas

Rectangular Microstrip (Patch) Antennas

- How it works:
    - Made up of a rectangular metallic (conductive) patch usually photo-etched on a dielectric coated ground plane. Excitation is provided through feed lines connected to the patch.
        - The patch can also be other shapes (circular, triangular, square, etc.)
    - When a current through the feed line reaches the patch, EM waves are generated and radiated through the width side.
- Properties:
    - Very small bandwidth, not very efficient
    - Easy and cheap to produce
    - 

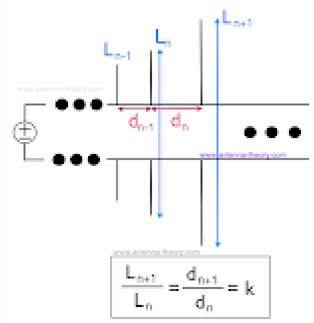
- Applications:
    - Became popular in the 1970s for space applications
    - Can be used in cars and mobile phones (bluetooth and wireless connectivity)
    - Can be put on the surface of any missile, satellite, or aircraft
    - Can also be used in the Internet of Things (IoT), radar, and medical things
- Radiation pattern:
    -  

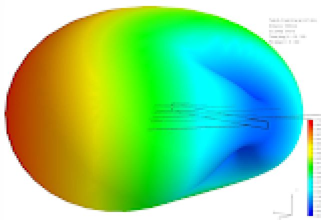
Log-Periodic Antennas

Very large bandwidths

- How large the structure is determines bottom limit and how precise finer features determine higher limit

Is a multi-element, directional narrow beam antenna that works on a wide range of frequencies

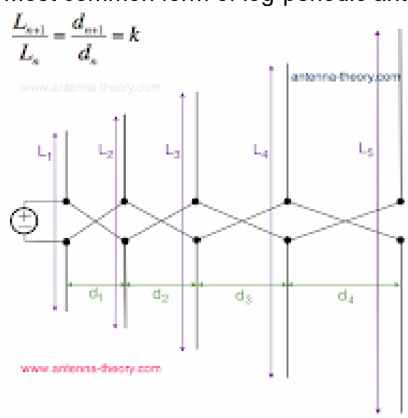




- Frequencies radiated at are all a multiple of k

Log-Periodic Dipole Array

- Most common form of log-periodic antenna



Aperture Antennas

Radio analogue of optical telescope, used for radio telescopes. Consists of small dipole or loop feed antenna embedded inside larger 3D surrounding structure guiding waves in a particular direction, often dish or funnel-shaped, large compared to a wavelength, with an opening to emit the waves in only one direction. Since outer structure itself is not resonant, can be used for wide range of frequencies.

- Parabolic – highest gains up to 60 dBi, but dish must be large relative to wavelength
- Horn – simple antenna, moderate gain 15-25 dBi. Popularized in wwii to be used alongside radar.

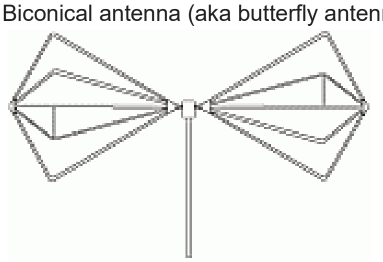
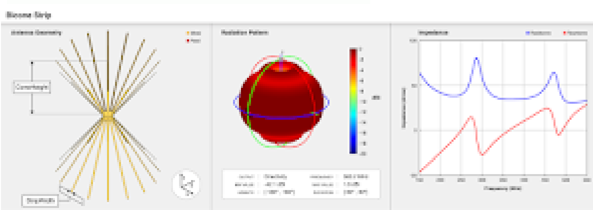
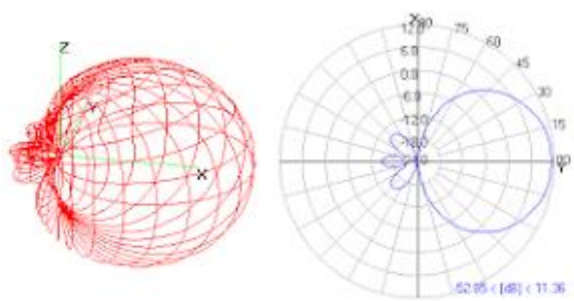
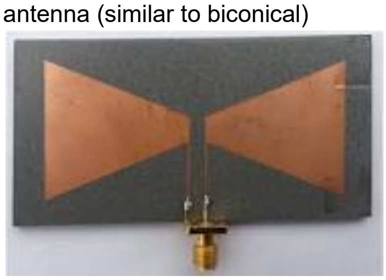
41. (5.00 pts) Match the horn antenna types to its numbered description.

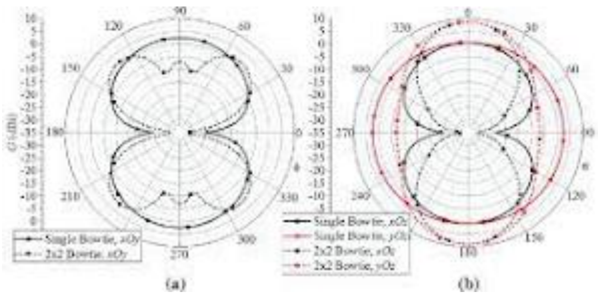
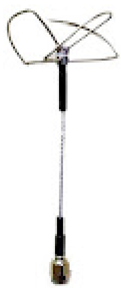
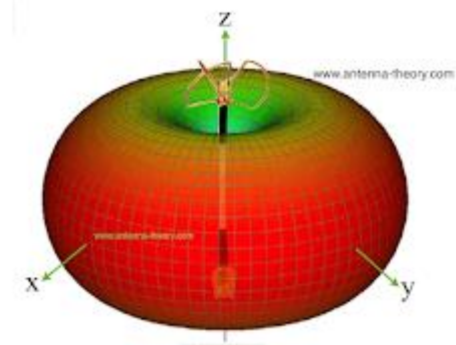
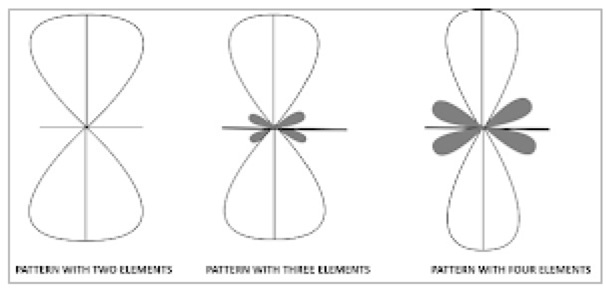
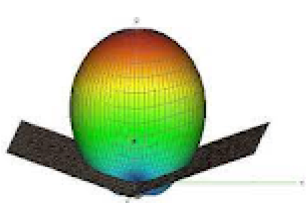
A) Pyramid horn	1) One side of this antenna flares and the other remains parallel
B) Sectoral horn	2) This antenna is the most widely used one for satellite dishes and radio telescopes. It has parallel slots on the inside of the horn.
C) Conical horn	3) The cross section through this antenna is rectangular, as is the end of the antenna. It is normally used with a rectangular waveguide.
D) Exponential horn	4) This antenna has a circular cross section and uses a circular waveguide.
E) Corrugated horn	5) This antenna type has a minimum of internal reflections and it has curved sides along with a constant impedance

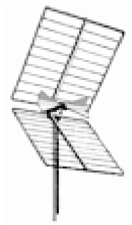
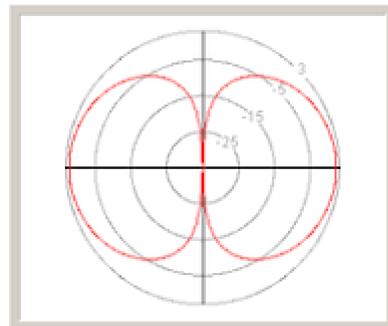
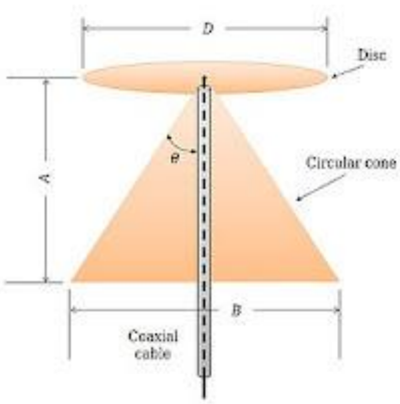
Expected Answer: A3 B1 C4 D5 E2

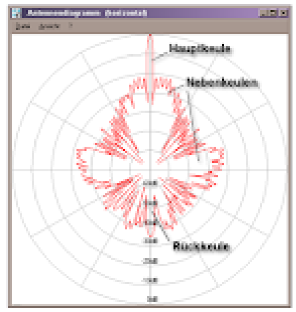
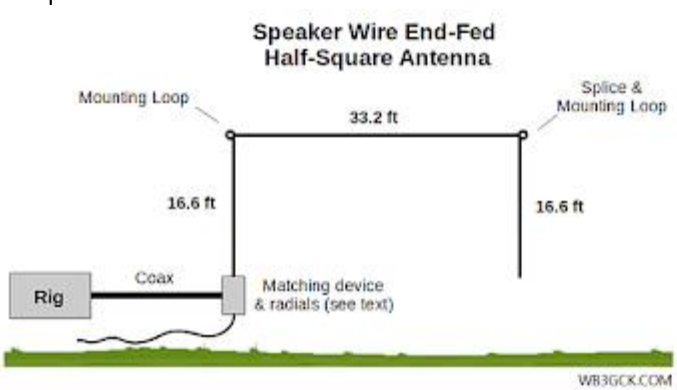
- Slot – waveguide with one or more slots cut in to emit microwaves
- Lens – layer of dielectric or metal screen or multiple waveguide structure of varying thickness in front of a feed antenna, acting as a lens to refract radio waves
- Dielectric resonator – consists of small ball or puck-shaped piece of dielectric material excited by aperture in waveguide, used at mm frequencies
- Notch antenna: Includes vivaldi: normally operates at 1-2 GHz and is located in x-y plane

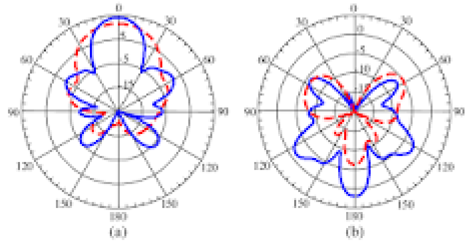
Antenna Pictures (alphabetized)

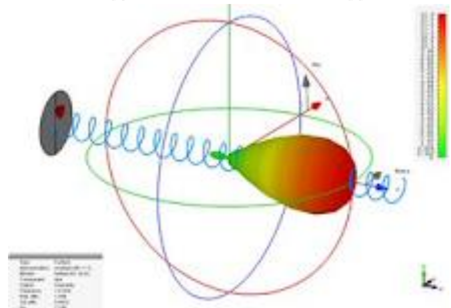
Batwing antenna 	A batwing or super turnstile antenna is a type of broadcasting antenna used at VHF and UHF frequencies, named for its distinctive shape which resembles a bat wing or bow tie. Stacked arrays of batwing antennas are used as television broadcasting antennas due to their omnidirectional characteristics.[1] Batwing antennas generate a horizontally polarized signal. The advantage of the "batwing" design for television broadcasting is that it has a wide bandwidth. It was the first widely used television broadcasting antenna.[1]
Biconical antenna (aka butterfly antenna)  	• Traveling wave antenna • Biconical antennas (also known as Bowtie or Butterfly antennas) are broadband dipole antennas that are made up of two roughly conical conductive objects, nearly touching at their points. These antennas have dipole-like characteristics, with a wider bandwidth achieved (3 octaves or more) due to the double cone element structure. ○ Might be referred to as conical antennas? • omni-directional radiation pattern in the H-plane similar to a dipole antenna. • Used for: electromagnetic interference (EMI) testing either for immunity testing, or emissions testing.
Biquad antenna 	
Bow Tie antenna (similar to biconical) 	• Used for short range UHF tv reception

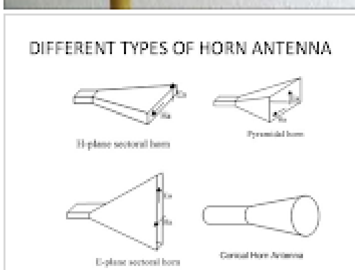
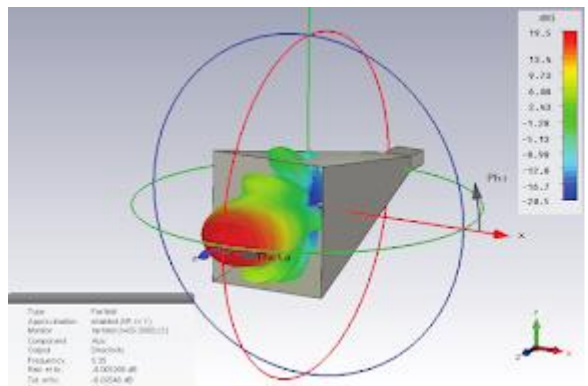
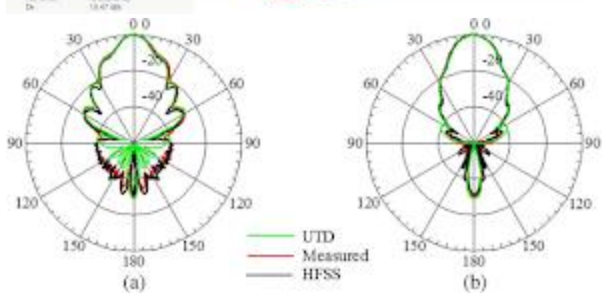
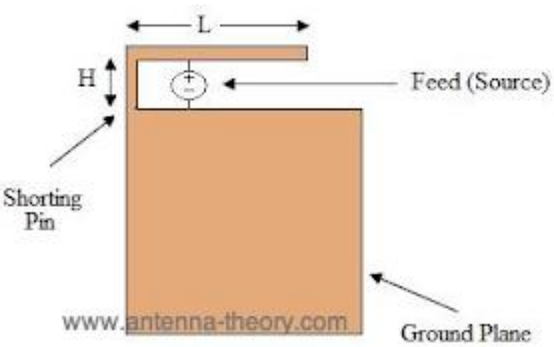
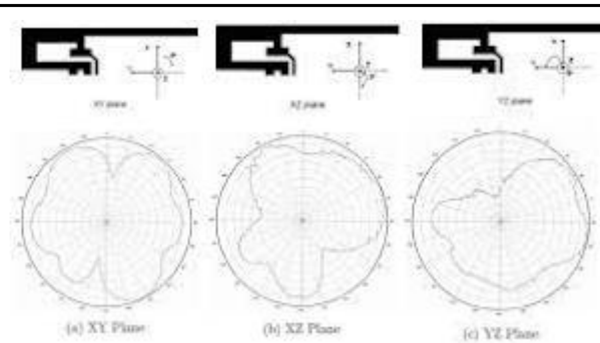
	
Cloverleaf antenna 	
Collinear antenna 	
Corner reflector antenna  	Directive antenna with moderate gain about 8 dBi, often used at UHF; consists of a dipole mounted in front of two reflective metal screens joined at an angle, often 90
Corner reflector with bowtie	

	
Dipole 	
Dipole 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 nulls in the radiation pattern), with horizontal polarization in directions coplanar 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.
Discone antenna 	
Dish antenna (parabolic antenna)	

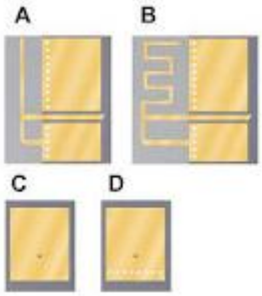
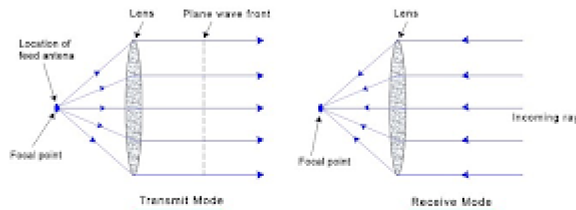
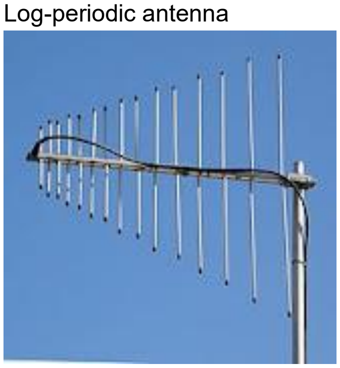
	 Hauptkeule (german): main lobe Nebenkeulen: side lobes Ruckkeule: back lobe
Folded unipole 	
Ground plane antenna (monopole) 	Half of a dipole, mounted vertically (monopole…)
Half-square antenna 	The Half Square antenna is a wire antenna with two vertical radiators fed in phase. One vertical element (1/4-wave) is fed at the top where it is attached to a SO-239. The other side of the SO-239 is attached to a horizontal half-wave phasing line and then connected to another vertical element (1/4-wave) aiming down to the ground. So basically what you have is two vertical elements spaced one half-wave apart and fed in phase. This will produce a bidirectional radiation pattern with almost an S unit of gain, compared to a dipole, broadside to the antenna. Seeing this antenna is fed at the top of the vertical element, the current portion of the antenna is high in the air where it really counts. The antenna is a direct match to a 50-ohm system so there is no need for a matching network.

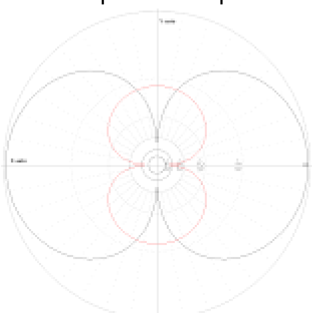
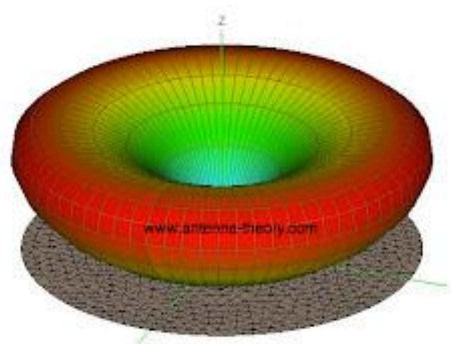
<table>
<tr>
<td>Helical antenna
</td>
<td>

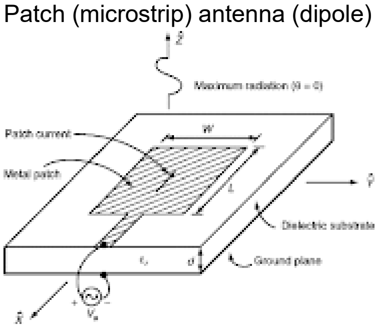
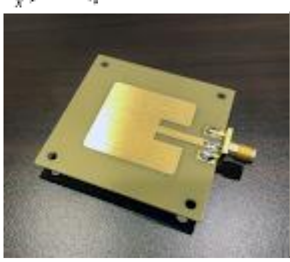
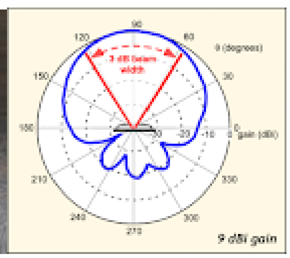
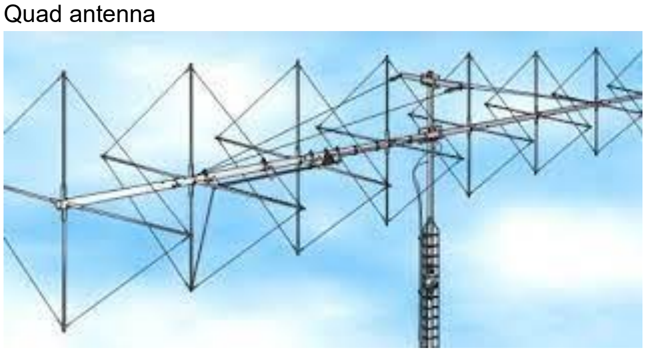
</td>
</tr>
<tr>
<td>Horn antenna

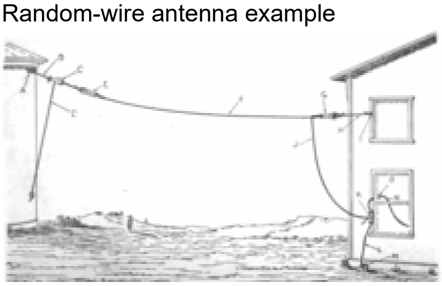

</td>
<td>

</td>
</tr>
<tr>
<td>Inverted-F antenna

</td>
<td>

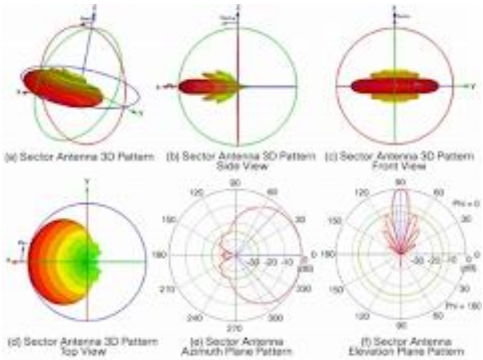
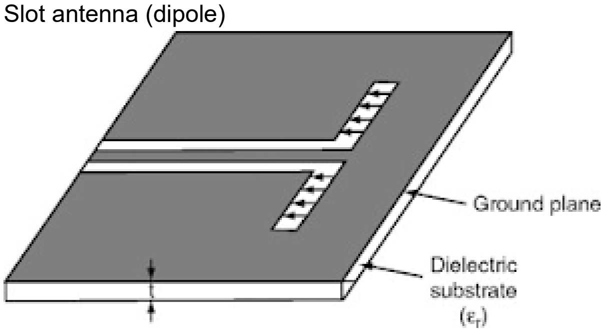
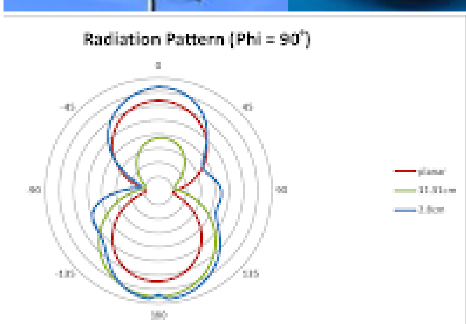
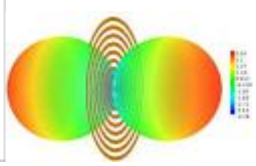
The inverted-L antenna is a monopole antenna bent over to run parallel to the ground plane. It has the advantage of compactness and a shorter</td>
</tr>
</table>

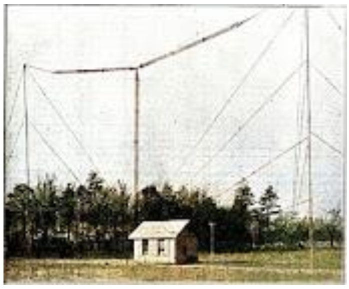
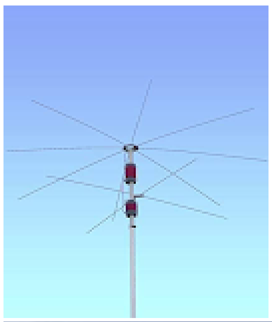
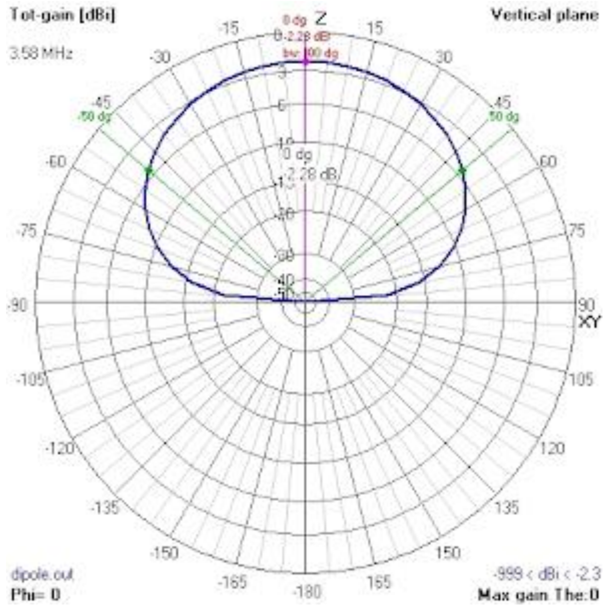
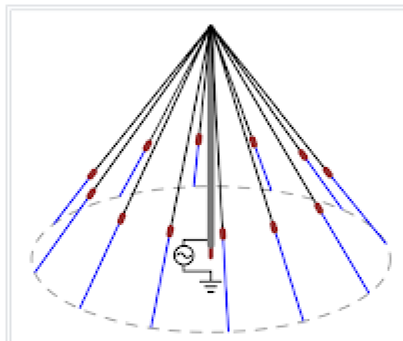
 	length than the quarter wave monopole, but the disadvantage of a very low impedance Might be classified as a microstrip antenna too
Lens antenna 	
Log-periodic antenna 	Often confused with the Yagi-Uda, this consists of many dipole elements along a boom with gradually increasing lengths, all connected 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.
Log-periodic tooth array 	
Loop (halo) antenna	Consists of a loop/coil of wire interacting directly with magnetic field rather than electric field, relatively insensitive to electrical nose within ⅙ wavelength of antenna - Large loops have highest radiation resistance and highest efficiency of all antennas (resistances of several hundreds of ohms)

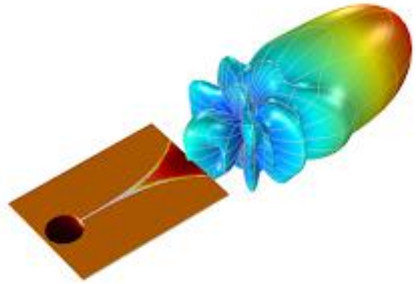
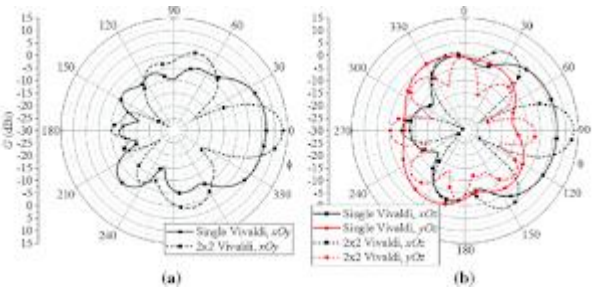
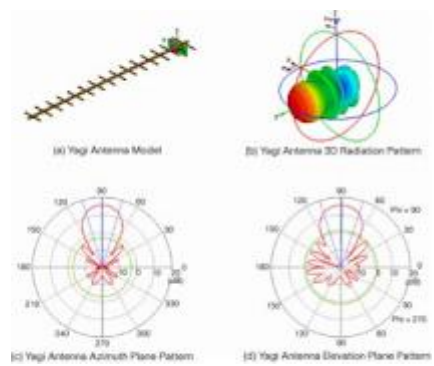
<table>
<tr>
<td>
Small loop radiation pattern
</td>
<td>- Halo is in between – loops that are exactly ½ wavelength in perimeter/circumference with a small gap cut in loop; intermediate in form and function between small and large; similar to half-wavelength dipole folded into circle
- Small loops – small radiation resistance, inefficient for transmitting, effective for receiving especially at low frequencies</td>
</tr>
<tr>
<td>Mast radiator
</td>
<td></td>
</tr>
<tr>
<td>Monopole
</td>
<td></td>
</tr>
<tr>
<td>Moxon antenna</td>
<td>The Moxon antenna or Moxon Rectangle is a simple and mechanically robust two-element parasitic array, single-frequency antenna.[1] It takes its name from the amateur radio operator and antenna handbook author Les Moxon[2] (call sign G6XN).[1]
The Moxon antenna design is rectangular, with slightly less than half of the rectangle being the driven element (radiator) and the other</td>
</tr>
</table>

	part (slightly more than half) being the reflector. It is a two element Yagi-Uda antenna with folded dipole elements, and with no director(s). Because of the folded ends, the element lengths are approximately 70% of the equivalent dipole length. The two element design gives modest directivity (about 2.0 dB) with a null towards the rear of the antenna, yielding a high front-to-back ratio: Gain up to 9.7 dBi can be achieved at 28 MHz.[3] Because the placement and size of the parasitic reflector both depend highly on wavelength, each Moxon antenna functions properly on only one frequency.
Patch (microstrip) antenna (dipole)   	Elements consisting of metal sheets mounted over a ground plane; gain of about 6-9 dBi; popular in modern wireless devices; often integrated into surfaces like aircraft or in wireless devices Low profile, which can be mounted on a surface. It consists of a planar rectangular, circular, triangular, or any geometrical sheet or "patch" of metal, mounted over a larger sheet of metal called a ground plane. In order for the antenna to be resonant, a length of microstrip transmission line slightly shorter than one-half the wavelength at the frequency is used. mainly practical at microwave frequencies, at which wavelengths are short enough that the patches are conveniently small. It is widely used in portable wireless devices because of the ease of fabricating it on printed circuit boards. Multiple patch antennas on the same substrate (see image) called microstrip antennas, can be used to make high gain array antennas, and phased arrays in which the beam can be electronically steered.
Quad antenna 	
Quarter-Wave Whip antenna (monopole)	

	
Rabbit ears (dipole variant for VHF tv) 	
Random-wire antenna example 	Receives shortwave radio, consisting of random wire length strung between supports connected to receiver at one end. They are categorized as folded monopoles if lengths are quarter-wave or less, end-fed dipoles if half-wave or more until one or two wavelengths; and then when greater, operate similar to traveling-wave
Rubber ducky antenna (monopole) 	used in portable handheld radio equipment at VHF and UHF frequencies in place of a quarter wavelength whip antenna Like walkie talkies
Sector antenna  	Directional microwave antenna with a sector-shaped radiation pattern. The word "sector" is used in the geometric sense; some portion of the circumference of a circle measured in degrees of arc. 60°, 90° and 120° designs are typical, often with a few degrees 'extra' to ensure overlap and mounted in multiples when wider or full-circle coverage is required (see photos below). The largest use of these antennas is as antennas for cell phone base-station sites. They are also used for other types of mobile communications, for

	example in WiFi networks. They are used for limited-range distances of around 4 to 5 km.
Slot antenna (dipole) 	½ wavelength long
Spiral antenna  	A type of traveling wave antenna Used for wide-band communication, monitoring frequency spectrum, and gps • Very large bandwidth $$f_{Low} = \frac{c}{\lambda_{Low}} = \frac{c}{2\pi R_{Spiral}}$$ Rspiral = radius of outer spiral Flare rate = rate at which spiral grows, common is a = 22 Feed structure = most be controlled by balun, commonly infinite balun, $$f_{Upper} = \frac{c}{\lambda_{Upper}} = \frac{c}{4R_0}$$ R0 = inner radius
T-antenna (monopole)	widely used as transmitting antennas for amateur radio stations, and long wave and medium wave AM broadcasting stations. They can also be used as receiving antennas for shortwave listening.

	
Umbrella antenna   	  Diagram of base fed umbrella antenna. The red cylinders are insulators. Buried under the antenna is a radial wire ground system *(not shown)*.

Vivaldi antenna 	 
Yagi Uda antenna 	

Miscellaneous Information

Quantity	DC	Single Phase AC	Three Phase AC
Current (I) Amp	• $I = V/R$ • $I = P/V$ • $I = \sqrt{P/R}$	• $I = P / (V \times \cos\theta)$ • $I = (V/Z)$	• $I = P / \sqrt{3} \times V \times \cos\theta$
Voltage (V) Volts	• $V = I \times R$ • $V = P / I$ • $V = \sqrt{(P \times R)}$	• $V = P/(I \times \cos\theta)$ • $V = I \times Z$	• $V_L = \sqrt{3}\, V_{PH}$ or $V_L = \sqrt{3}\, E_{PH}$ • $V_L = V_{PH}$
Power (P) Watts	• $P = IV$ • $P = I^2R$ • $P = V^2/R$	• $P = V \times I \times \cos\theta$ • $P = I^2 \times R \times \cos\theta$ • $P = (V^2/R) \times \cos\theta$	• $P = \sqrt{3}\, V_L I_L \cos\Phi$ • $P = 3\, V_{Ph} I_{Ph} \cos\Phi$
Resistance (R) Ω	• $R = V/I$ • $R = P/I^2$ • $R = V^2/P$	• $Z = \sqrt{(R^2 + X_L^2)}$ • $Z = \sqrt{(R^2 + X_C^2)}$ • $Z = \sqrt{(R^2 + (X_L - X_C)^2}$ WWW.ELECTRICALTECHNOLOGY.ORG	

Electrical Current Formulas

Electrical Current Formulas in DC Circuit

- I = V/R
- I = P/V
- I = √P/R

Electrical Current Formulas in Single Phase AC Circuit

- I = P / (V x Cosθ)
- I = (V/Z)

Electrical Current Formulas in Three Phase AC Circuit

- I = P / √3 x V x Cosθ

Voltage or Electrical Potential Formulas

Electrical Potential or Voltage Formula in DC Circuits

- V = I x R
- V = P / I
- V = √ (P x R)

Voltage or Electrical Potential Formulas in Single Phase AC Circuits

- V = P/(I x Cosθ)
- V = I x Z

Voltage Formulas in Three Phase AC Circuits

- $VL = \sqrt{3}\ VPH$ or $VL = \sqrt{3}\ EPH$
- $VL = VPH$

Electric Power Formulas

Power Formulas in DC Circuits

- $P = V \times I$
- $P = I2 \times R$
- $P = V2/R$

Power Formulas in Single Phase AC Circuits

- $P = V \times I \cos\theta$
- $P = I2 \times R \cos\theta$
- $P = (V2/R) \cos\theta$

Power Formulas in Three Phase AC Circuits

- $P = \sqrt{3} \times VL \times IL \cos\theta$
- $P = 3 \times VP \times IP \cos\theta$

Electrical Resistance Formulas

Electrical Resistance & Impedance Formulas in DC Circuits

- $R = V/I$
- $R = P/I2$
- $R = V2/P$

Electrical Resistance & Impedance Formulas in AC Circuits
In AC Circuits (capacitive or inductive load), Resistance = Impedance i.e., R = Z

- $Z2 = R2 + X2$ … In case of resistance and reactance
- $Z = \sqrt{(R2 + XL2)}$ … In case of Inductive load
- $Z = \sqrt{(R2 + XC2)}$ … In case of Capacitive load
- $Z = \sqrt{(R2 + (XL - XC)2}$… In case of both inductive and capacitive loads.

Impedance is the resistance of AC circuits i.e. resistive, capacitive and inductive circuit (already mentioned above). Where "Z" is the impedance in ohms, "R" is resistance in Ohms and "X" is the reactances in Ohms.

Good to know:

- I = Current in Amperes (A)
- V = Voltage in Volts (V)
- P = Power in Watts (W)
- R = Resistance in Ohm (Ω)
- Z = impedance = Resistance of AC Circuits in Ohms
- Cosθ = Power factor = Phase difference between voltage and current in AC circuits
- VPH = Phase Voltage
- VL = Line Voltage

Also,

- XL = Inductive reactance
- $XL = 2\pi f L$…Where L = Inductance in Henry

And;

- XC = Capacitive reactance
- XC = 1/2πfC… Where C = Capacitance in Farads.
- $\omega = 2\pi f$

Other Additional Electrical Quantities Formulas

Conductance: G = 1 / R

It is the reciprocal (i.e. inverse) of resistance. The unit of conductance is Siemen or Mho and represented by the symbol of “G” or “℧”.

Capacitance: C = Q / V

Where “C” is capacitance in farads, “Q” is charge in coulombs, and “V” is voltage in volts. The unit of capacitance is Farad “F” or microfarad “μF”.

Inductance: VL = -L (di / dt)

Where “L” is inductance in Henrys, “VL” is the instantaneous voltage across the inductor in volts and “di/dt” is the rate of changes in current in Amperes per second. The unit of Inductance “L” is Henrys “H”. It is also known as Ohm’s law for inductance.

Charge: Q = C x V

Where “Q” is the charge in coulombs, “C” is the capacitance in farads and “V” is the voltage in Volts.

Miscellaneous Definitions

Emission – passes through a surface from inside to outside
Reflection – bounces off a surface without passing through
Absorption – allows something to pass through it from outside to inside

Good emitter → good absorber, bad reflector

Good reflector → smooth surface, poor emitter

Li-Fi

Li-Fi (also written as **LiFi**) is a wireless communication technology which utilizes light to transmit data and position between devices. The term was first introduced by Harald Haas during a March 2011 TEDGlobal talk in Edinburgh.

Li-Fi is a light communication system that is capable of transmitting data at high speeds over the visible light, ultraviolet, and infrared spectrums. In its present state, only LED lamps can be used for the transmission of data in visible light.

In terms of its end user, the technology is similar to Wi-Fi — the key technical difference being that Wi-Fi uses radio frequency to induce a voltage in an antenna to transmit data, whereas Li-Fi uses the modulation of light intensity to transmit data. Li-Fi is able to function in areas otherwise susceptible to electromagnetic interference (e.g. aircraft cabins, hospitals, or the military).

Bg-Fi is a Li-Fi system consisting of an application for a mobile device, and a simple consumer product, like an IoT (Internet of Things) device, with color sensor, microcontroller, and embedded software. Light from the mobile device display communicates to the color sensor on the consumer product, which converts the light into digital information. Light-emitting diodes enable the consumer product to communicate synchronously with the mobile device.

Technology Details

Li-Fi is a derivative of optical wireless communications (OWC) technology, which uses light from light-emitting diodes (LEDs) as a medium to deliver network, mobile, high-speed communication in a similar manner to Wi-Fi. The Li-Fi market was projected to have a compound annual growth rate of 82% from 2013 to 2018 and to be worth over $6 billion per year by 2018. However, the market has not developed as such and Li-Fi remains with a niche market.

Visible light communications (VLC) works by switching the current to the LEDs off and on at a very high speed, beyond the human eye's ability to notice. Technologies that allow roaming between various Li-Fi cells, also known as handover, may allow to seamlessly transition between Li-Fi. The light waves cannot penetrate walls which translates to a much shorter range, and a lower hacking potential, relative to Wi-Fi. Direct line of sight is not always necessary for Li-Fi to transmit a signal and light reflected off walls can achieve 70 Mbit/s.

Li-Fi can potentially be useful in electromagnetic sensitive areas without causing electromagnetic interference. Both Wi-Fi and Li-Fi transmit data over the electromagnetic spectrum, but whereas Wi-Fi utilizes radio waves, Li-Fi uses visible, ultraviolet, and infrared light. Researchers have reached data rates of over 224 Gbit/s, which was much faster than typical fast broadband in 2013. Li-Fi is expected to be ten times cheaper than Wi-Fi. The first commercially available Li-Fi system was presented at the 2014 Mobile World Congress in Barcelona.

Disadvantages

Although Li-Fi LEDs would have to be kept on to transmit data, they could be dimmed to below human visibility while still emitting enough light to carry data. This is also a major bottleneck of the technology when based on the visible spectrum, as it is restricted to the illumination purpose and not ideally adjusted to a mobile communication purpose, given that other sources of light, for example the sun, will interfere with the signal.

Since Li-Fi's short wave range is unable to penetrate walls, transmitters would need to installed in every room of a building to ensure even Li-Fi distribution. The high installation costs associated with this requirement to achieve a level of practicality of the technology is one of the potential downsides.

History

Professor Harald Haas, Professor of Mobile Communications at the University of Edinburgh, coined the term "Li-Fi" at his 2011 TED Global Talk where he introduced the idea of "wireless data from every light".[22]

The general term "visible light communication" (VLC), whose history dates back to the 1880s, includes any use of the visible light portion of the electromagnetic spectrum to transmit information. The D-Light project at Edinburgh's Institute for Digital Communications was funded from January 2010 to January 2012.[23] Haas helped start a company to market it.[24]

In October 2011, a research organization Fraunhofer IPMS and industry Companies formed the Li-Fi Consortium, to promote high-speed optical wireless systems and to overcome the limited amount of radio-based wireless spectrum available by exploiting a completely different part of the electromagnetic spectrum.[25]

VLC technology was exhibited in 2012 using Li-Fi.[26] By August 2013, data rates of about 1.6 Gbit/s were demonstrated over a single color LED.[27] In September 2013, a press release said that Li-Fi, or VLC systems in general, do not absolutely require line-of-sight conditions.[28] In October 2013, it was reported Chinese manufacturers were working on Li-Fi development kits.[29]

In April 2014, the Russian company Stins Coman announced the development of a Li-Fi wireless local network called BeamCaster. Their current module transfers data at 1.25 gigabytes per second (GB/s) but they foresee boosting speeds up to 5 GB/s in the near future.[30] In 2014 a new record was established by Sisoft (a Mexican company) that was able to transfer data at speeds of up to 10GB/s across a light spectrum emitted by LED lamps.[31]

In July 2015, IEEE operated the APD in Geiger-mode as a single photon avalanche diode (SPAD) to increase the efficiency of energy-usage and makes the receiver even more sensitive.[32] This operation could also be performed as quantum-limited sensitivity that makes receivers able to detect weak signals from a far distance.[33]

In June 2018, Li-Fi passed a test by a BMW plant in Munich for operating in an industrial environment.[34]

in August 2018, Kyle Academy, a secondary school in Scotland, had pilot the use of Li-Fi within the school. Students are able to receive data through a connection between their laptop computers and a USB device that is able to translate the rapid on-off current from the ceiling LEDs into data.

In June 2019, French company Oledcomm tested their Li-Fi technology at the 2019 Paris Air Show.

Standards

Like Wi-Fi, Li-Fi is wireless and uses similar 802.11 protocols, but it also uses ultraviolet, infrared and visible light communication.

One part of VLC is modeled after communication protocols established by the IEEE 802 workgroup. However, the IEEE 802.15.7 standard is out-of-date: it fails to consider the latest technological developments in the field of optical wireless communications, specifically with the introduction of optical orthogonal frequency-division multiplexing (O-OFDM) modulation methods which have been optimized for data rates, multiple-access, and energy efficiency. The introduction of O-OFDM means that a new drive for standardization of optical wireless communications is required.

Nonetheless, the IEEE 802.15.7 standard defines the physical layer (PHY) and media access control (MAC) layer. The standard is able to deliver enough data rates to transmit audio, video, and multimedia services. It takes into account optical transmission mobility, its compatibility with artificial lighting present in infrastructures, and the interference which may be generated by ambient lighting. The MAC layer permits using the link with the other layers as with the TCP/IP protocol.

The standard defines three PHY layers with different rates:

- The PHY 1 was established for outdoor application and works from 11.67 kbit/s to 267.6 kbit/s.
- The PHY 2 layer permits reaching data rates from 1.25 Mbit/s to 96 Mbit/s.
- The PHY 3 is used for many emissions sources with a particular modulation method called color shift keying (CSK). PHY III can deliver rates from 12 Mbit/s to 96 Mbit/s.[38]

The modulation formats recognized for PHY I and PHY II are on-off keying (OOK) and variable pulse-position modulation (VPPM). The Manchester coding used for the PHY I and PHY II layers includes the clock inside the transmitted data by representing a logic 0 with an OOK symbol "01" and a logic 1 with an OOK symbol "10", all with a DC component. The DC component avoids light extinction in case of an extended run of logic 0's.

Applications

Home and building automation

Many experts foresee a movement towards Li-Fi in homes because it has the potential for faster speeds and its security benefits with how the technology works. Because the light sends the data, the network can be contained in a single physical room or building reducing the possibility of a remote network attack. Though this has more implications in enterprise and other sectors, home usage may be pushed forward with the rise of home automation that requires large volumes of data to be transferred through the local network.[39]

Underwater application

Most remotely operated underwater vehicles (ROVs) are controlled by wired connections. The length of their cabling places a hard limit on their operational range, and other potential factors such as the cable's weight and fragility may be restrictive. Since light can travel through water, Li-Fi based communications could offer much greater mobility.Li-Fi's utility is limited by the distance light can penetrate water. Significant amounts of light do not penetrate further than 200 meters. Past 1000 meters, no light penetrates.[41]

Aviation

Efficient communication of data is possible in airborne environments such as a commercial passenger aircraft utilizing Li-Fi. Using this light-based data transmission will not interfere with equipment on the aircraft that relies on radio waves such as its radar.[42]

Hospital

Increasingly, medical facilities are using remote examinations and even procedures. Li-Fi systems could offer a better system to transmit low latency, high volume data across networks.[*citation needed*] Besides providing a higher speed, light waves also have reduced effects on medical instruments. An example of this would be the possibility of wireless devices being used in MRIs similar radio sensitive procedures.[42] Another application of LiFi in hospitals is localisation of assets and personnel.[43]

Vehicles

Vehicles could communicate with one another via front and back lights to increase road safety. Street lights and traffic signals could also provide information about current road situations.[44]

Industrial automation

Anywhere in industrial areas data has to be transmitted, Li-Fi is capable of replacing slip rings, sliding contacts, and short cables, such as Industrial Ethernet. Due to the real-time of Li-Fi (which is often required for automation processes), it is also an alternative to common industrial Wireless LAN standards. Fraunhofer IPMS, a research organization in Germany states that they have developed a component which is very appropriate for industrial applications with time-sensitive data transmission.[45]

Advertising

Street lamps can be used to display advertisements for nearby businesses or attractions on cellular devices as an individual passes through. A customer walking into a store and passing through the store's front lights can show current sales and promotions on the customer's cellular device.[46]

Warehousing

In warehousing, indoor positioning and navigation is a crucial element. 3D positioning helps robots to get a more detailed and realistic visual experience. Visible light from LED bulbs is used to send messages to the robots and other receivers and hence can be used to calculate the positioning of the objects.[47]