A gentle introduction to RF concepts for IoT

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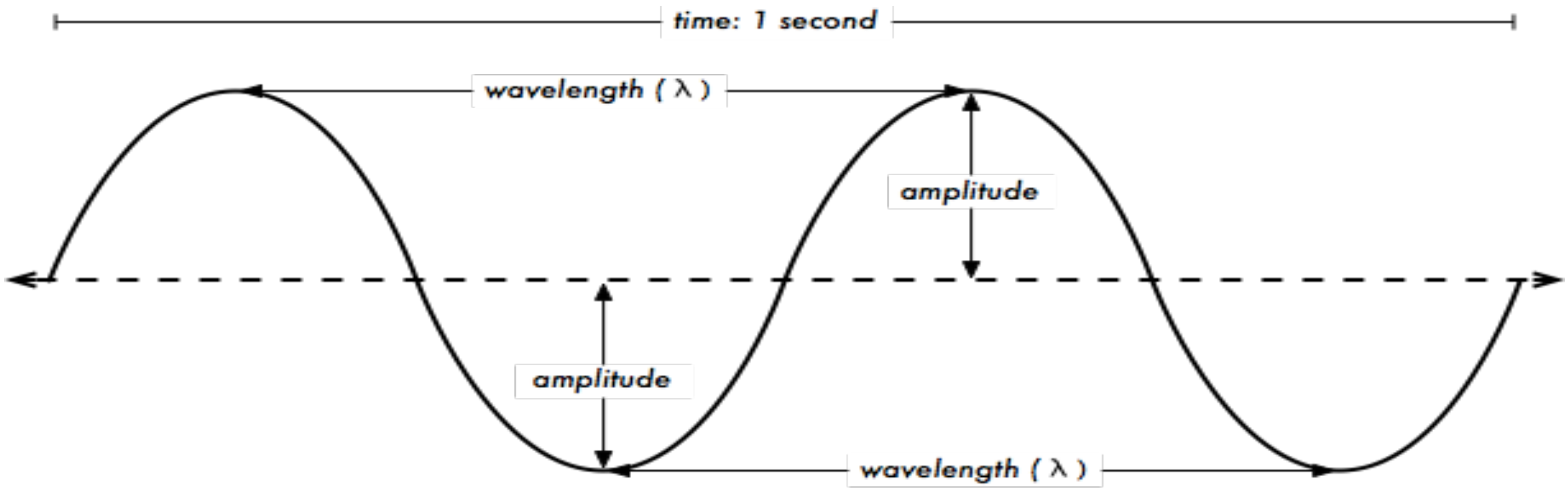
Goals

- To introduce the fundamental concepts related to electromagnetic waves (frequency, amplitude, speed, wavelength, polarization, phase)
- To understand the behavior of radio waves as they move through space (attenuation, absorption, reflection, diffraction, refraction, interference)
- To grasp the differences among different types of antennas and connectors
- To introduce the concept of the Fresnel zone
- To show methods to determine the range of wireless links

Electromagnetic Waves

- Characterized by wavelength, frequency and amplitude
- No need for a carrier medium
- Examples: Light, X rays and radio waves



Multiplying Factor	SI Prefix	Scientific Notation
1 000 000 000 000 000 000 000 000	yotta (Y)	10^{24}
1 000 000 000 000 000 000 000	zetta (Z)	10^{21}
1 000 000 000 000 000 000	exa (E)	10^{18}
1 000 000 000 000 000	peta (P)	10^{15}
1 000 000 000 000	tera (T)	10^{12}
1 000 000 000	giga (G)	10^{9}
1 000 000	mega (M)	10^{6}
1 000	kilo (k)	10^{3}
0.001	milli (m)	10^{-3}
0.000 001	micro (μ)	10^{-6}
0.000 000 001	nano (n)	10^{-9}
0.000 000 000 001	pico (p)	10^{-12}
0.000 000 000 000 001	femto (f)	10^{-15}
0.000 000 000 000 000 001	atto (a)	10^{-18}
0.000 000 000 000 000 000 001	zepto (z)	10^{-21}
0.000 000 000 000 000 000 000 001	yocto (y)	10^{-24}

http://www.npl.co.uk/reference/measurement-units/si-prefixes/

Wavelength and Frequency

$$\lambda = c/f$$

c = speed (meters / second)
f = frequency (cycles per second, or Hz)
λ = wavelength (meters)

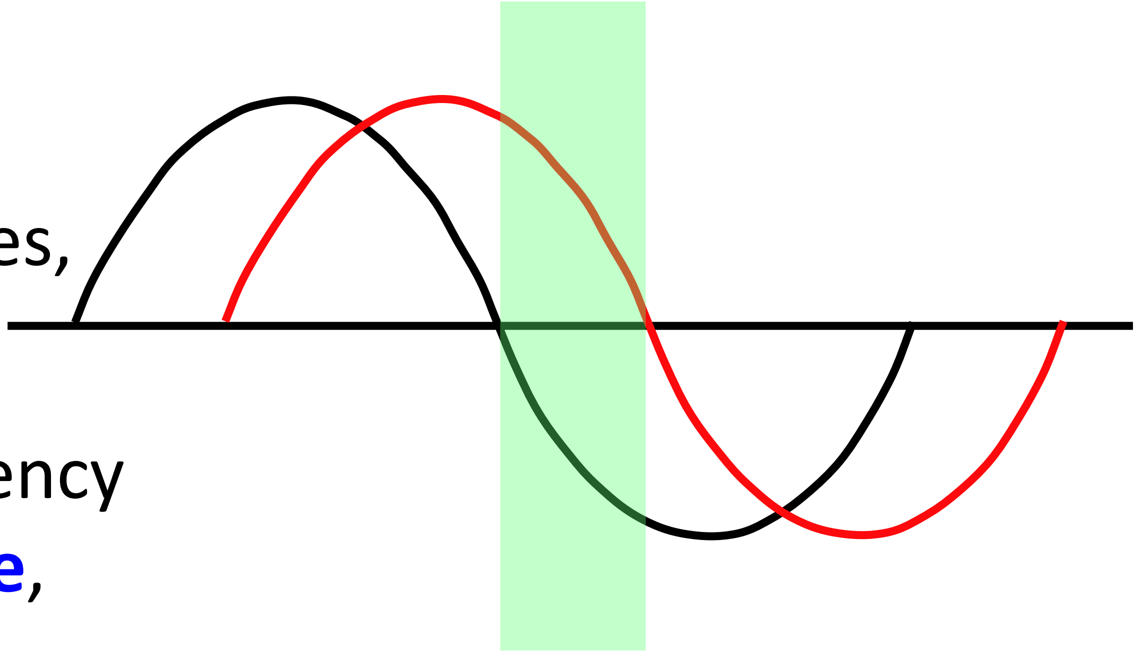
If a wave travels at one meter per second, and it oscillates five times per second, then each wave will be twenty centimeters long:

c =1 meter/second, f = 5 cycles/second = 5 Hz
λ = 1 / 5 meters
λ = 20 cm

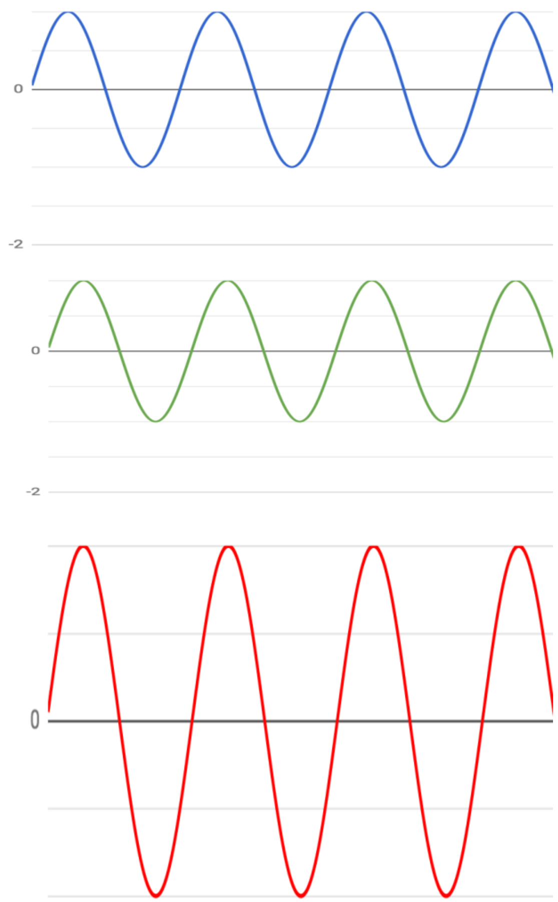
Phase

The **phase** of a wave is the fraction of a cycle that the wave is offset from a reference point. It is always a relative measurement that can be express in different units (radians, cycles, degrees, percentage).

Two waves that have the same frequency but are offset have a **phase difference**, and the waves are said to be out of phase with each other.

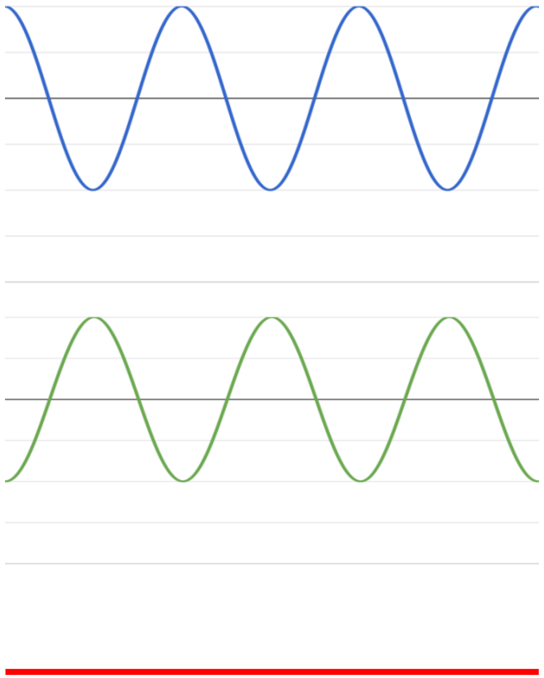


Constructive Interference



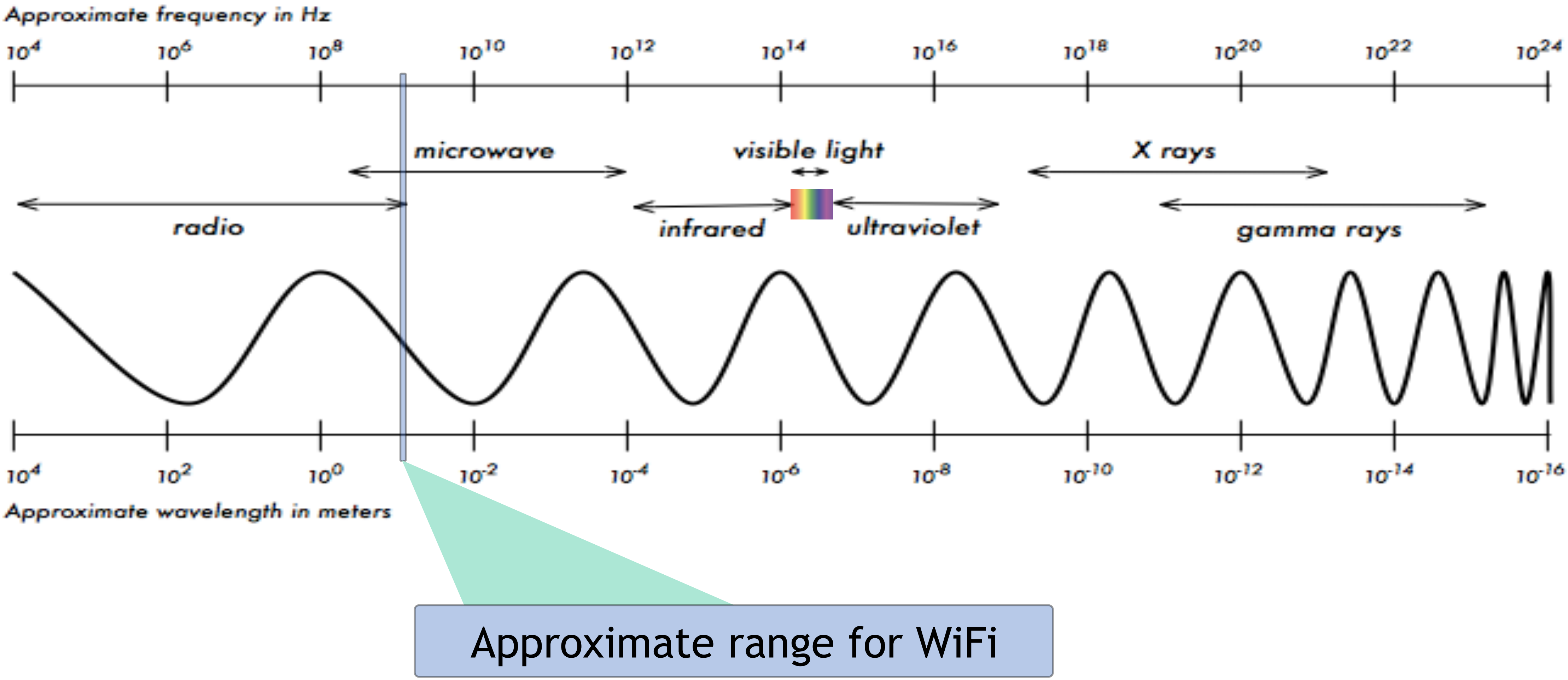
Adding two signals of the same frequency, the same amplitude and the same phase results in a signal of double amplitude.

Destructive Interference

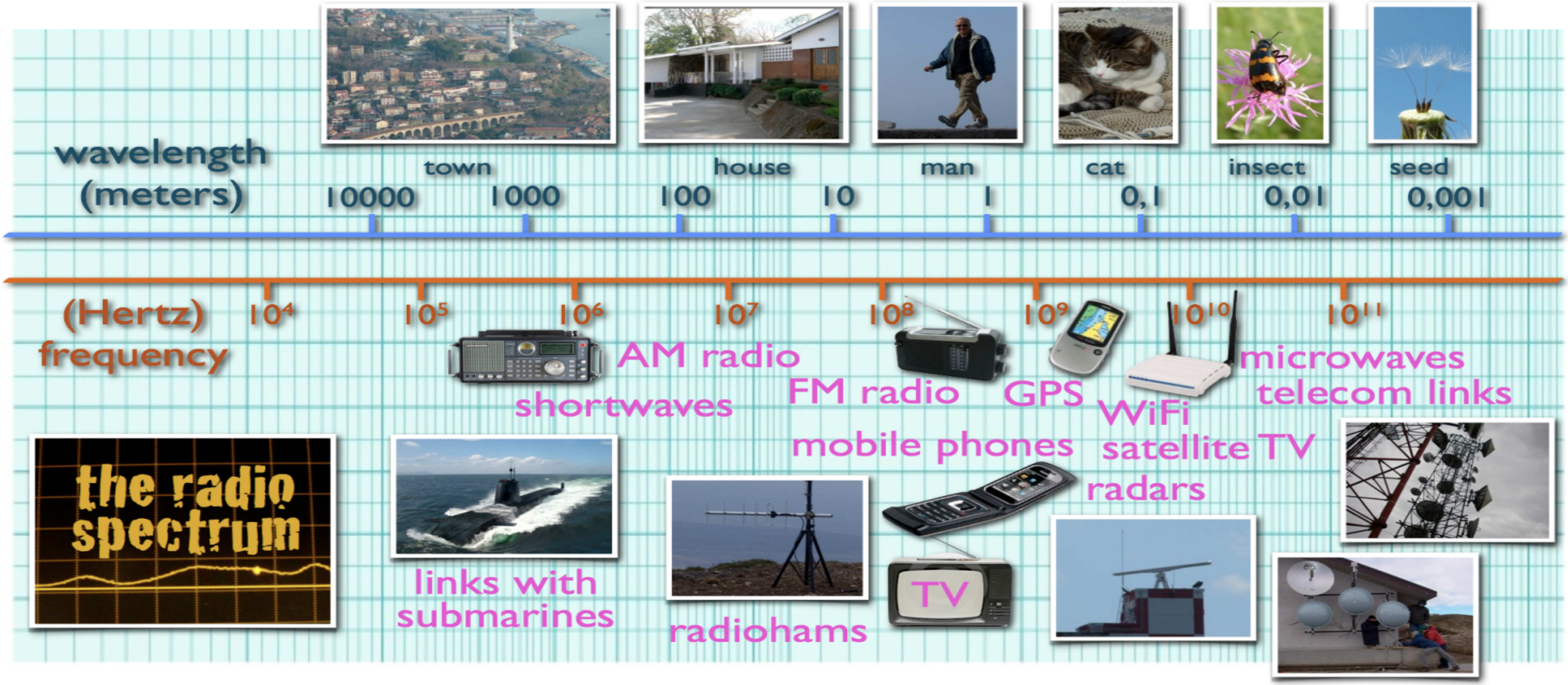


Adding two signals of the same frequency, the same amplitude and the opposite phase results in a signal of zero amplitude, the two signals cancel.

Electromagnetic Spectrum

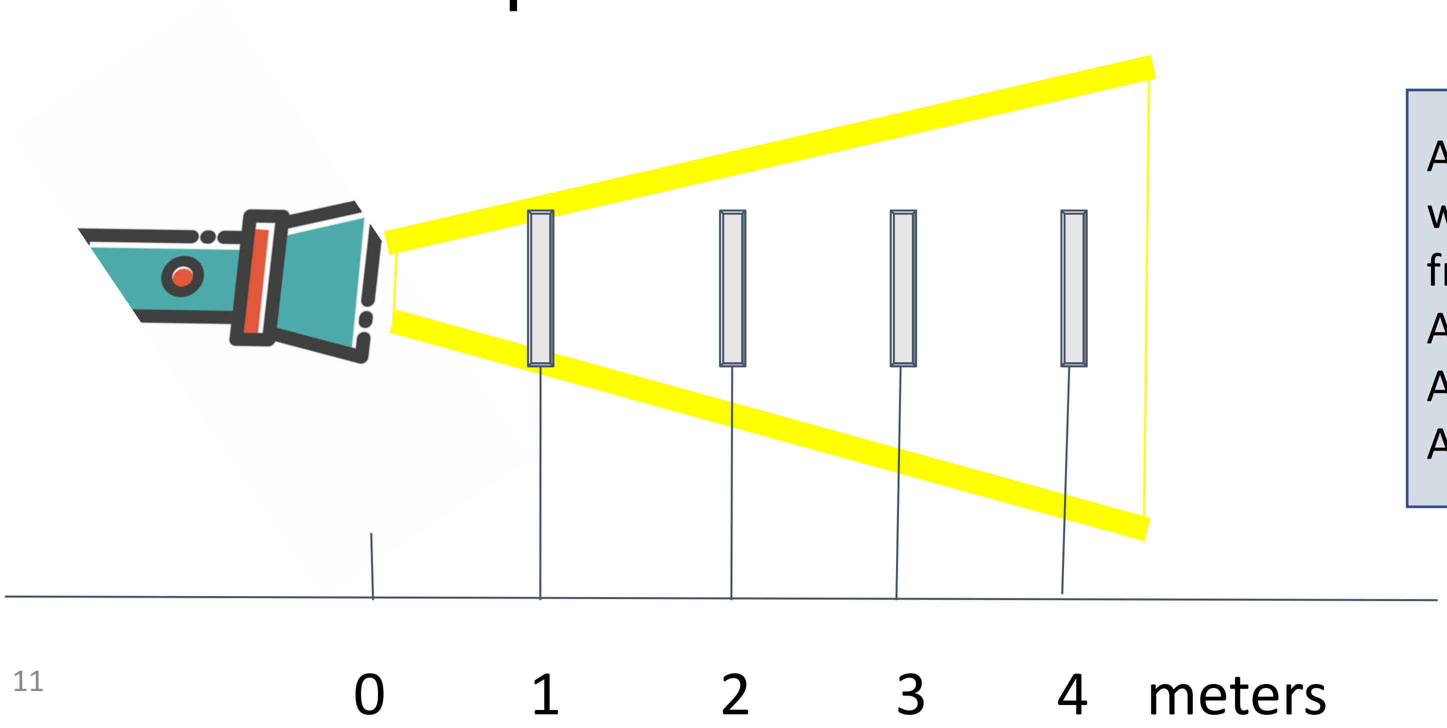


Perspective



Free Space Loss (FSL)

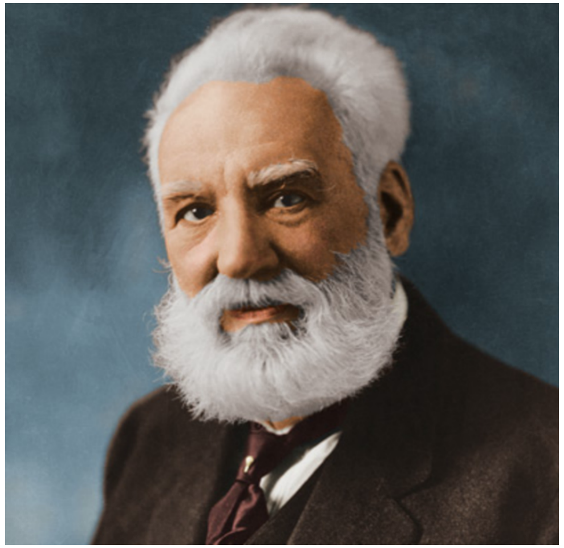
As the wave propagate from the source it spreads over an ever increasing area, so an antenna of a given size would be able to capture a fraction of the wavefront that decreases with the square of the distance. This causes attenuation.



A screen at 1 m distance would capture all the light from the torch.
At 2 m would capture 1/4
At 3 m would capture 1/9
At 4 m would capture 1/16

Intro to dB

- The ***decibel*** (***dB***) is 10 times the decimal logarithm of the ratio between two values of a variable. The calculation of decibels uses a logarithm to allow very large or very small relations to be represented with a conveniently small number.
- On the logarithmic scale, the reference cannot be zero because the log of zero does not exist!
- $L = 10\log_{10} (P_2/P_1)$
- Therefore, $P_2/P_1 = 10^L$



Alexander Graham Bell
Inventor of telephone

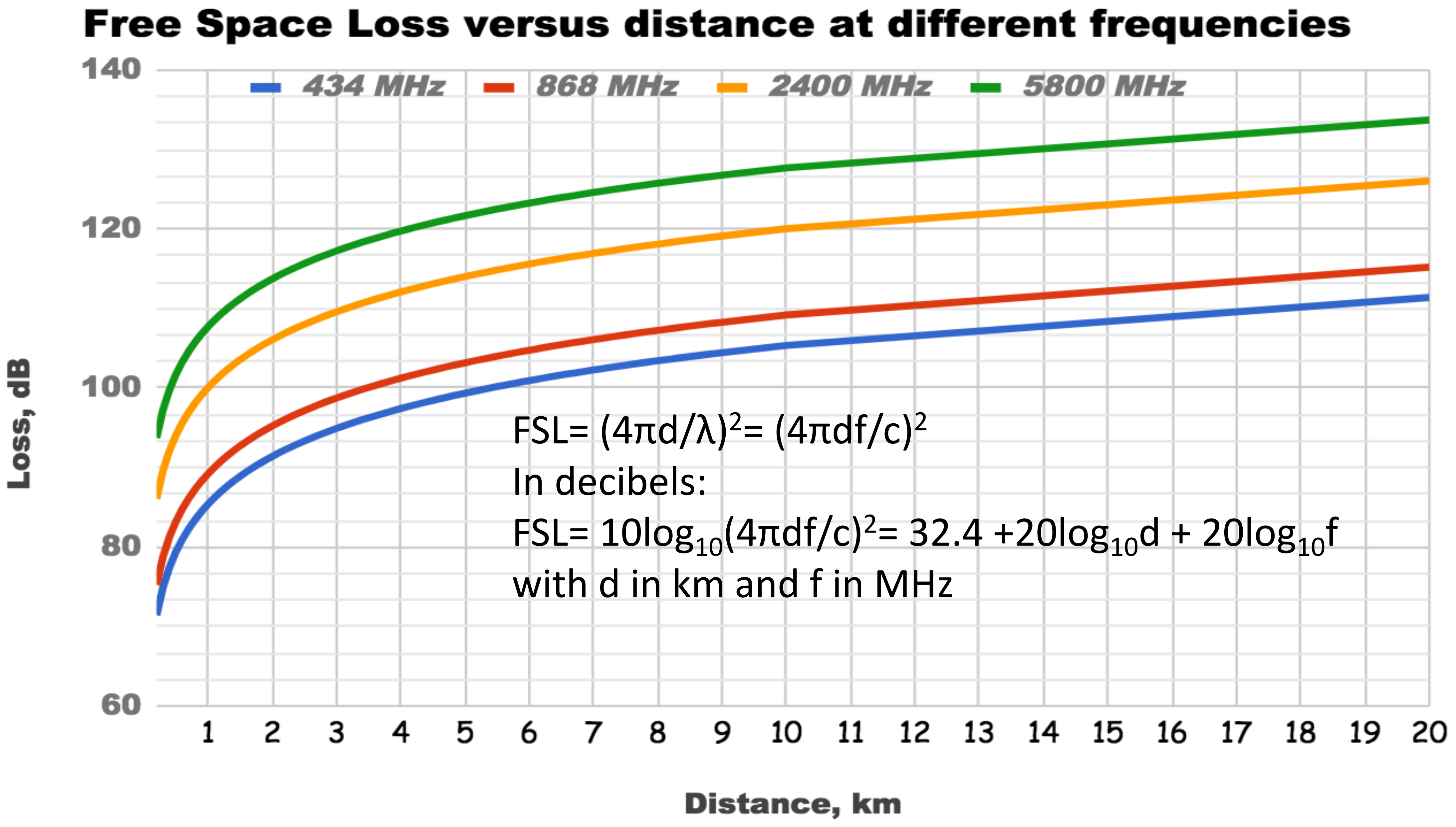
Using dB

Commonly used (and easy to remember) dB values:

```
+10 dB = 10 times the power
-10 dB = one tenth power
 +3 dB = double power
 -3 dB = half the power
```

For example:

```
some power + 10 dB  = 10 times the power
some power - 10 dB  = one tenth power
some power + 3 dB   = double power
some power - 3 dB   = half the power
```



$FSL = (4\pi d/\lambda)^2 = (4\pi df/c)^2$

In decibels:

$FSL = 10\log_{10}(4\pi df/c)^2 = 32.4 + 20\log_{10}d + 20\log_{10}f$

with d in km and f in MHz

dBm and mW

- What if we want to measure an absolute power with dB?
  We **have to define a reference**.
- The reference point that relates the logarithmic dB scale to the linear watt scale is:

$$1 \text{ mW} = 0 \text{ dBm}$$

- The new **m** in dBm refers to the fact that the reference is one **m**W, and therefore a **dBm** measurement is a measurement of absolute power with reference to 1 mW.

dBm and mW

- To convert power in mW to dBm:

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

10 times the *logarithm in base 10* of the "Power in mW"

- To convert power in dBm to mW:

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

10 *to the power of* ("Power in dBm" divided by 10)

Using dB

- When using dB, gains and losses are ***additive***.

Remember our previous example:

```
some power + 10 dB  = 10 times the power
some power - 10 dB  = one tenth power
some power + 3 dB   = double power
some power - 3 dB   = half the power
```

You can now imagine situations in which:

```
10 mW + 10 dB of gain  = 100 mW = 20 dBm
10 dBm = 10 mW = one tenth of 100mW
20 dBm - 10 dB of loss = 10 dBm = 10mW
50 mW  + 3 dB = 100 mW = 20 dBm
17 dBm + 3 dB = 20 dBm = 100 mW
 100mW - 3 dB = 50 mW  = 17 dBm
```

Behavior of radio waves

There are a few simple rules of thumb that can prove useful when planning a wireless network:

- The ***longer*** the wavelength, the further it goes
- The ***longer*** the wavelength, the better it travels through and around things
- The ***shorter*** the wavelength, the more data it can potentially transport

These rules are worth to keep in mind.

Traveling radio waves

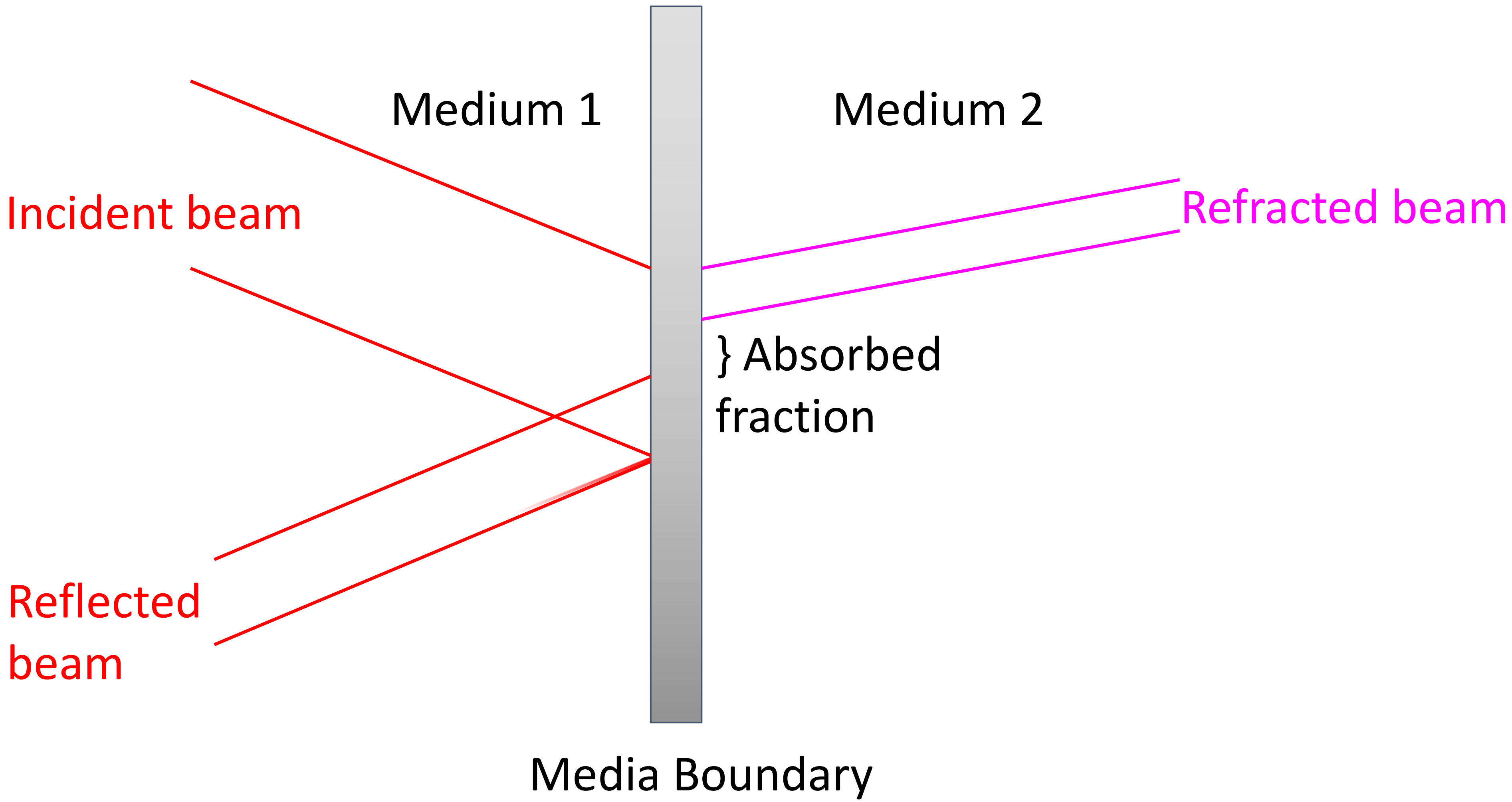
Radio waves do not move in a strictly straight line. On their way from “point A” to “point B”, waves may be subject to:

- Attenuation
- Absorption
- Reflection
- Refraction
- Diffraction
- Scattering (also called diffuse reflection)

Reflection

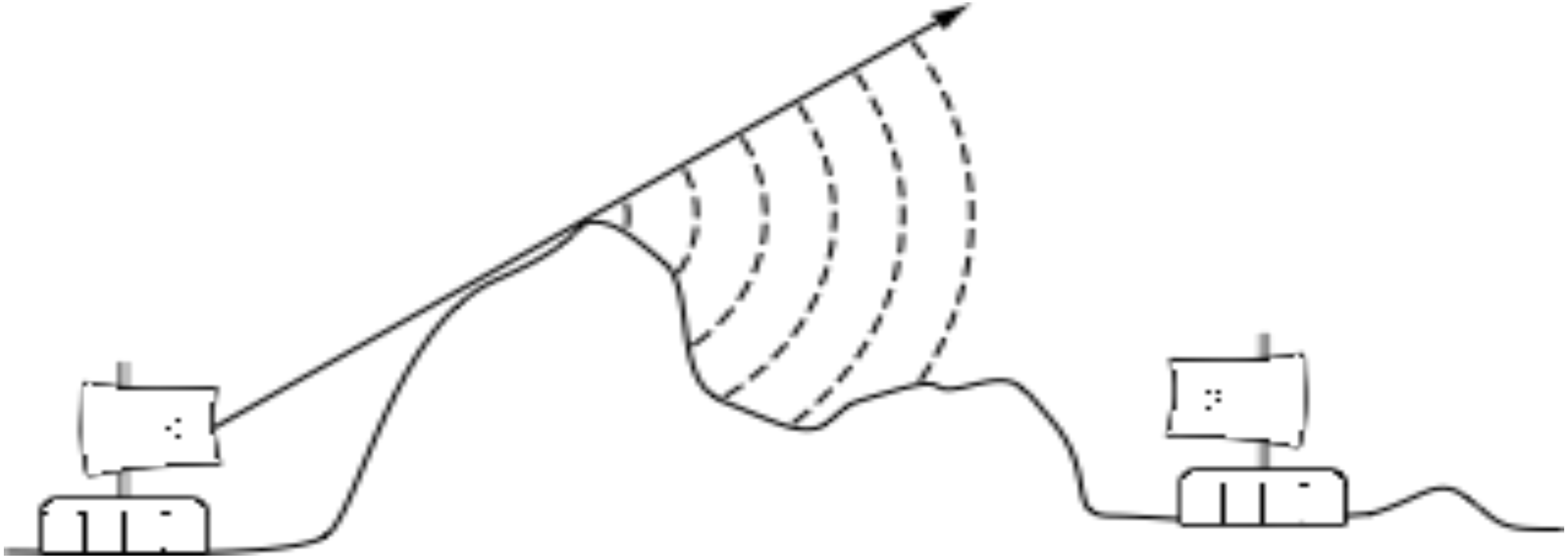
Specular reflection in a good conducting surfaces introduces very little loss.
The reflection coefficient for vertical polarization in general is different from the one for horizontal polarization.
Reflection over calm sea water is very strong and can cause severe interference with the direct wave at the receiver in what is known as multipath.
Metal billboards can also be strong reflectors at microwave frequencies impairing the received signal

Reflection, Refraction, Absorption



Diffraction

Because of the effect of diffraction, waves will "bend" around corners or through an opening in a barrier.



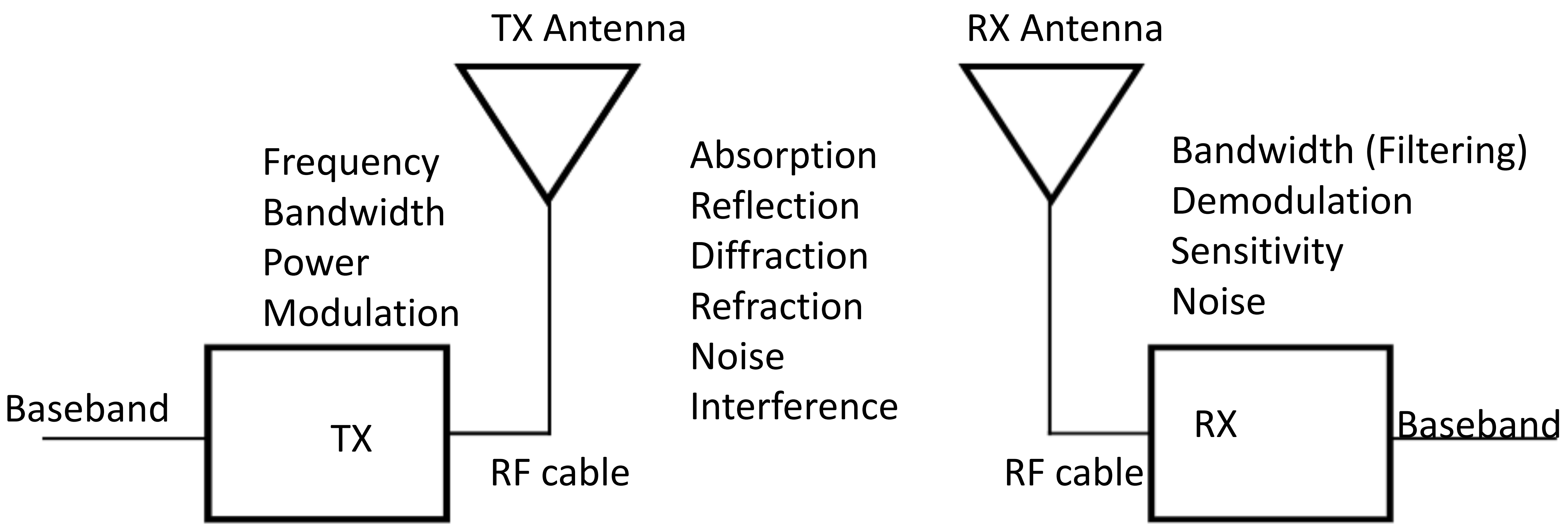
Diffraction

- Diffraction is more pronounced when the wave encounters a sharp edge and less so with smooth obstacles.
- Longer wavelengths are more diffracted than shorter wavelengths.
- Transmission at short distances when the line of sight is blocked is achieved thanks to the diffraction and/or reflection of the waves in nearby objects.

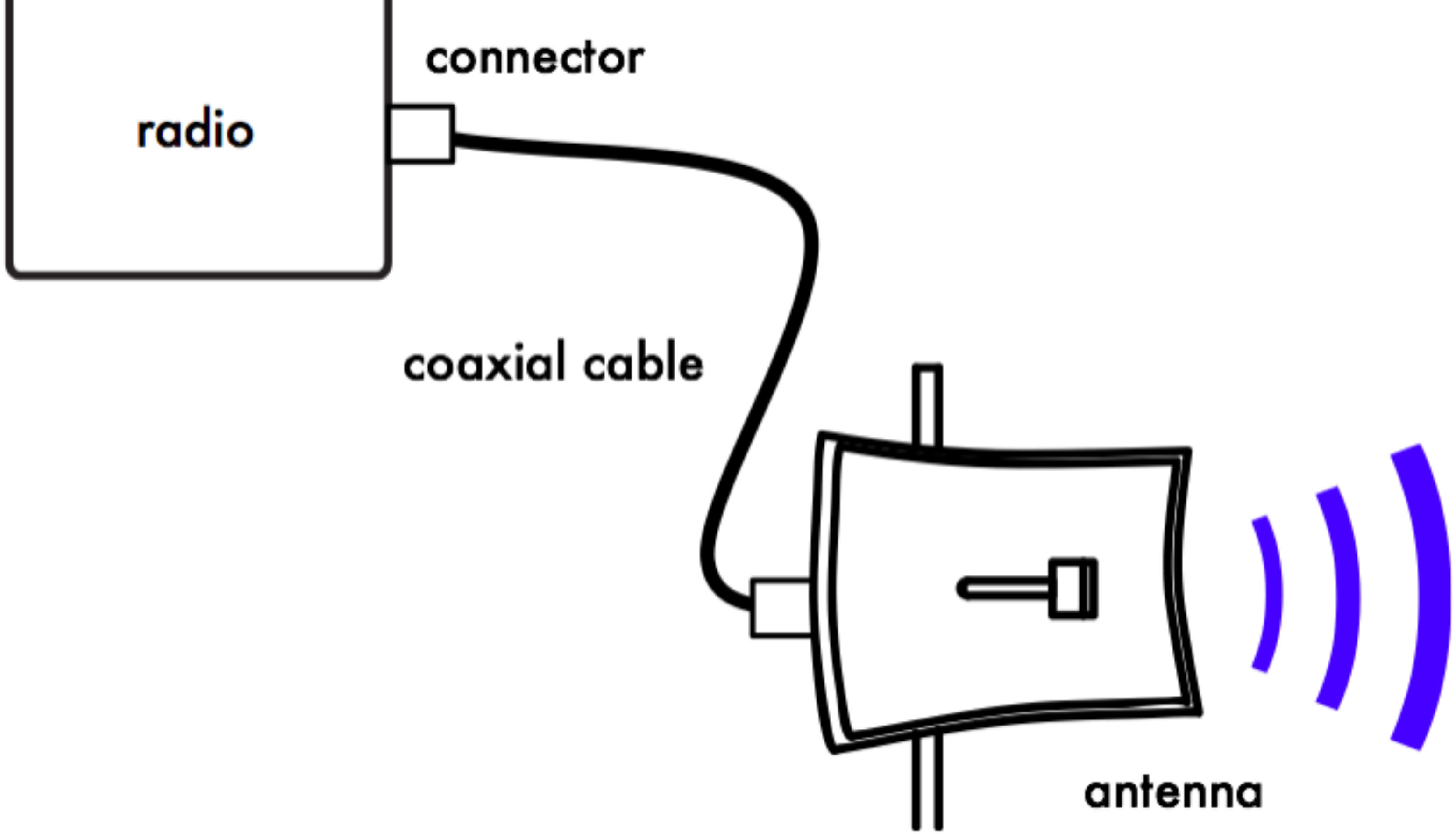
Scattering

- When a wave encounters an irregular reflecting surface it will be scattered in many rays in different directions, and even different polarizations, each carrying only a tiny fraction of the original power.
- This has been used to reach beyond the earth curvature in a technique called tropospheric scattering which requires great amounts of transmitted power achieved by means of powerful transmitters and huge antennas.

Wireless Link



Wireless system components



Antenna and transmission line irrigation analogy

Irrigation requires:

A hose to transport the water to the sprinkler

transmission line

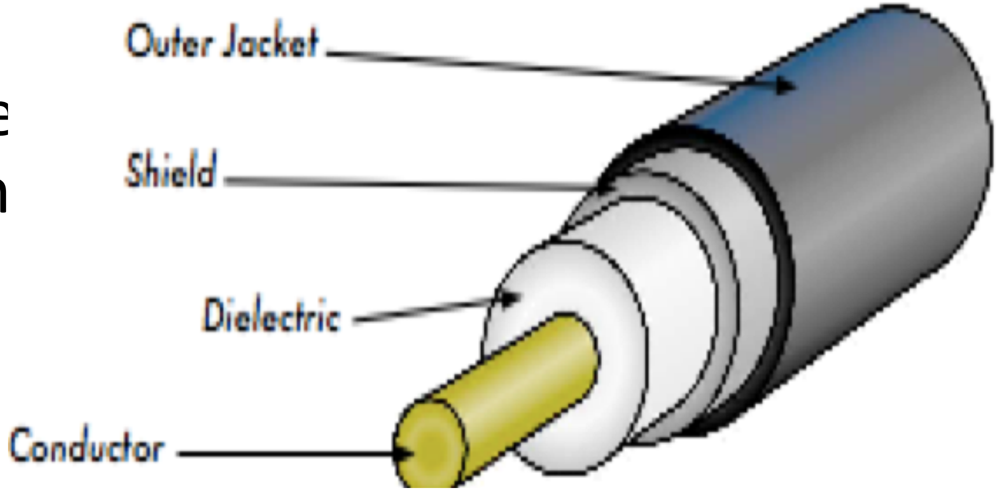
A sprinkler to direct the water to the specific area we want to irrigate

antenna

Transmission Line

The transmission line normally is a coaxial cable that connects the radio to the antenna.

It should attenuate the least possible and have enough bandwidth to accommodate that of th signal.The attenuation is proportional to the length of the cable and inversely proportional to the diameter.



The quality of the dielectric also affects the attenuation.

Connectors

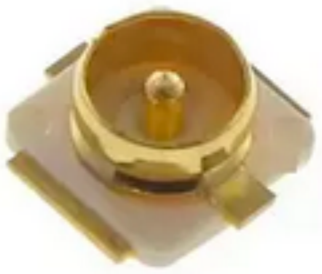
sma male

sma female

sma male reverse polarity

sma female reverse polarity

Type N male



U.Fl
Ipx
Hiroshi

Type N female

Adapters and pigtails

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


SMA female to N male


N male to N male


N female to N female


SMA female to U.FL pigtail


U.FL to RP-TNC male pigtail


U.FL to N male pigtail


SMA male to N female

Isotropic antenna

An ***isotropic antenna*** radiates the energy fed into it equally in every direction in space. It is only an ideal model and cannot be built. Real-world antennas are characterized by their ability to radiate more strongly in some directions than in others; this is called ***directivity***.

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

G = Efficiency X Directivity

Isotropic antenna

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

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

Omnidirectional antenna

An omnidirectional antenna spreads the signal evenly in every direction of the plane

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Directional Antenna

A directional antenna forms a very narrow beam in a specific direction and very little energy is directed elsewhere.

If the beam becomes much wider we will have a sectorial antenna

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Sectorial Antenna

Spreads the signal in certain angle of the plane, for instance 45 degrees, 60 degrees, etc.

Often combined in a base station to provide 360 degree coverage, for instances 3 sectors of 120 degrees each.

Omnidirectional and directional antennas

Dipole for 434 MHz

Monopole for 2400 MHz

High gain Yagi antenna
for 868 MHz

Omnidirectional Antennas

Directional Antenna

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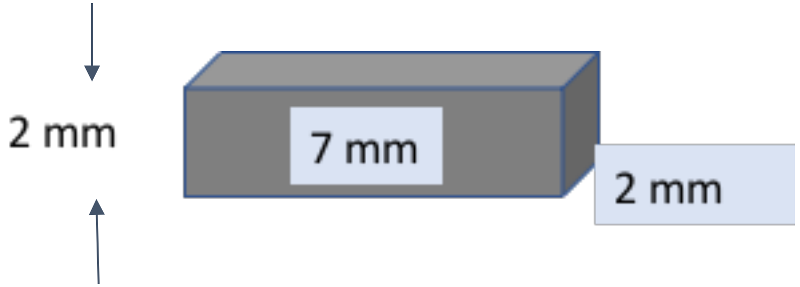
Ceramic Antenna



- Ceramic antennas are based on the principle of the dielectric resonator.
- They are commonly used at frequencies above 700 MHz and are quite useful for IoT devices.
- The dimension of a ceramic antenna are of the order of $\lambda_o/\sqrt{\epsilon}$ so

for $10 < \epsilon < 100$ significant size reductions can be achieved by using a suitable dielectric.

- They are quite efficient and less affected by surrounding objects than printed circuits antennas.

Antenna Features

What should we consider when choosing an antenna?

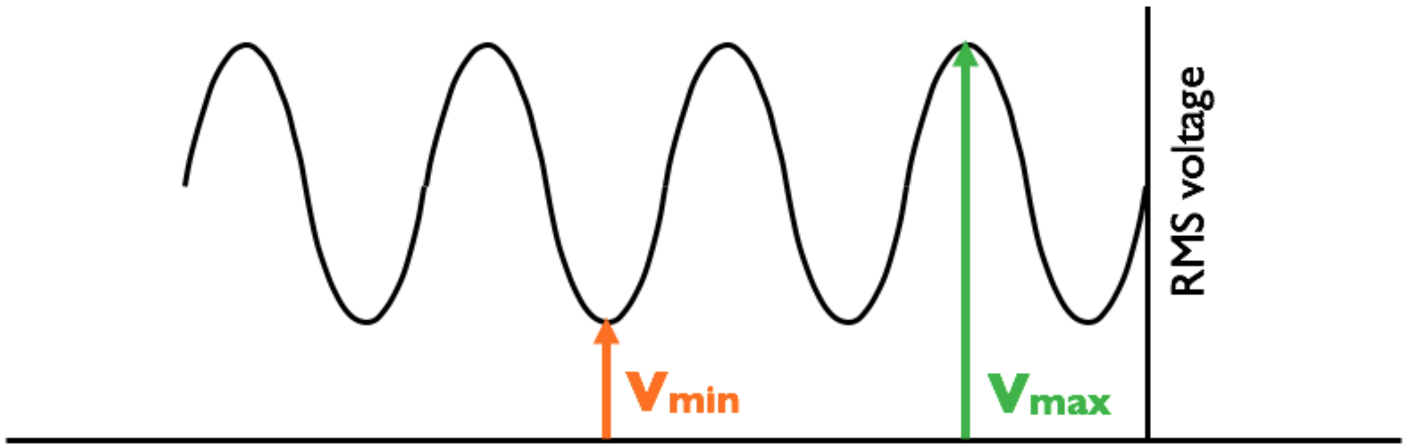
- Usable frequency range (highest and lowest frequency)
- Input Impedance
- Radiation pattern (how is the radiation distributed in space)
- Maximum gain
- Physical size and wind resistance
- Polarization
- Cost

Impedance

- All materials will oppose the flow of an alternating current to some extent. This opposition is called ***impedance***, and is analogous to resistance in DC circuits.
- Most commercial communication antennas have an impedance of 50 ohms, while TV antennas and cables are usually 75 ohms.
- Make sure that the characteristic impedance of the cable between the radio and the antenna is 50 ohms. Any mismatch will cause undesired reflections and power loss.

Reflections and VSWR

- Impedance mismatch causes reflections in a cable.
- The reflected wave interferes with the direct wave and the net result is a stationary wave in the cable that wastes energy.

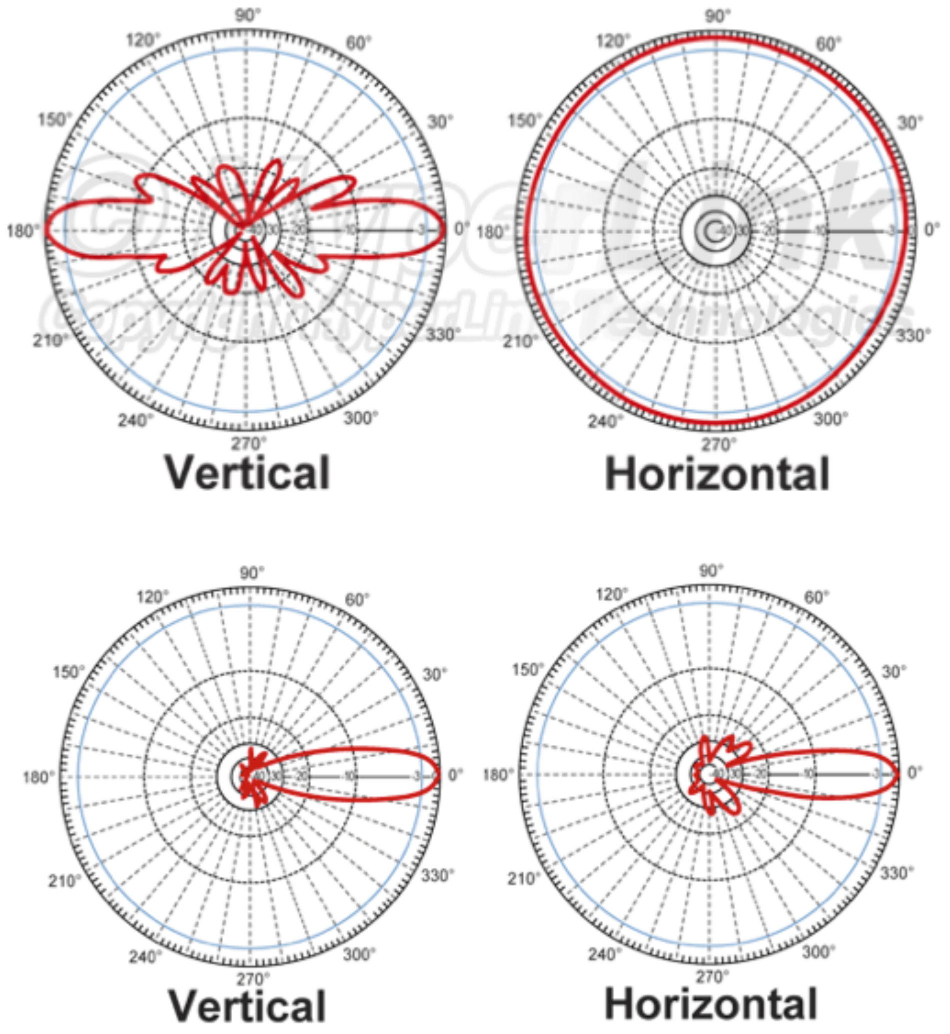


$$\text{Voltage Standing Wave Ratio VSWR} = \frac{V_{max}}{V_{min}}$$

Antenna radiation pattern

The ***radiation pattern*** of an antenna describes the distribution of the power radiated from, or received by, the antenna.

The tridimensional object is presented by the horizontal and vertical projections as a function of direction angles centered on the antenna.



Reciprocity

All the antenna features like gain, radiation pattern, impedance and bandwidth are the same when the antenna is used as a transmitter as when it is used as a receiver.

Antennas are reciprocal devices.

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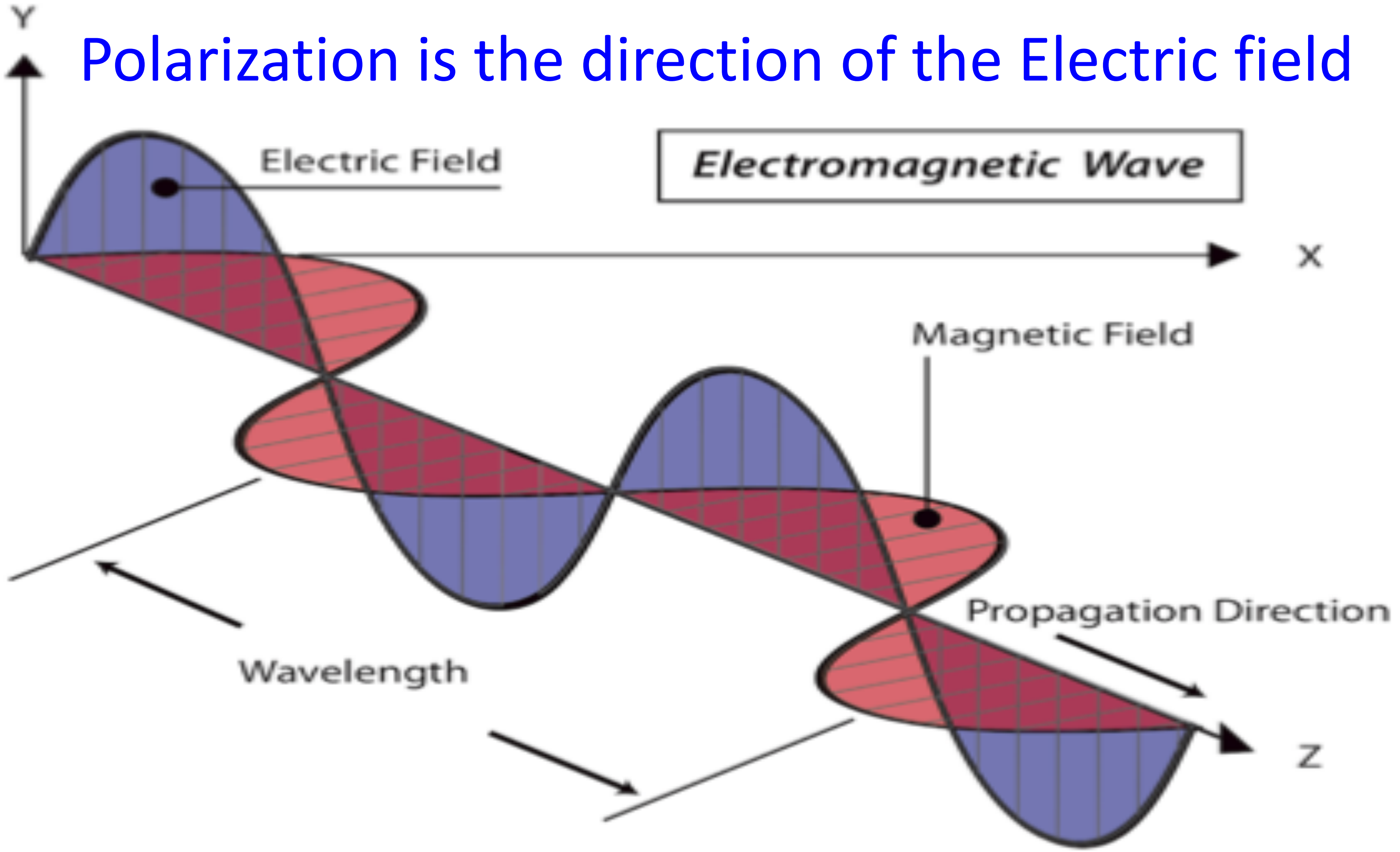
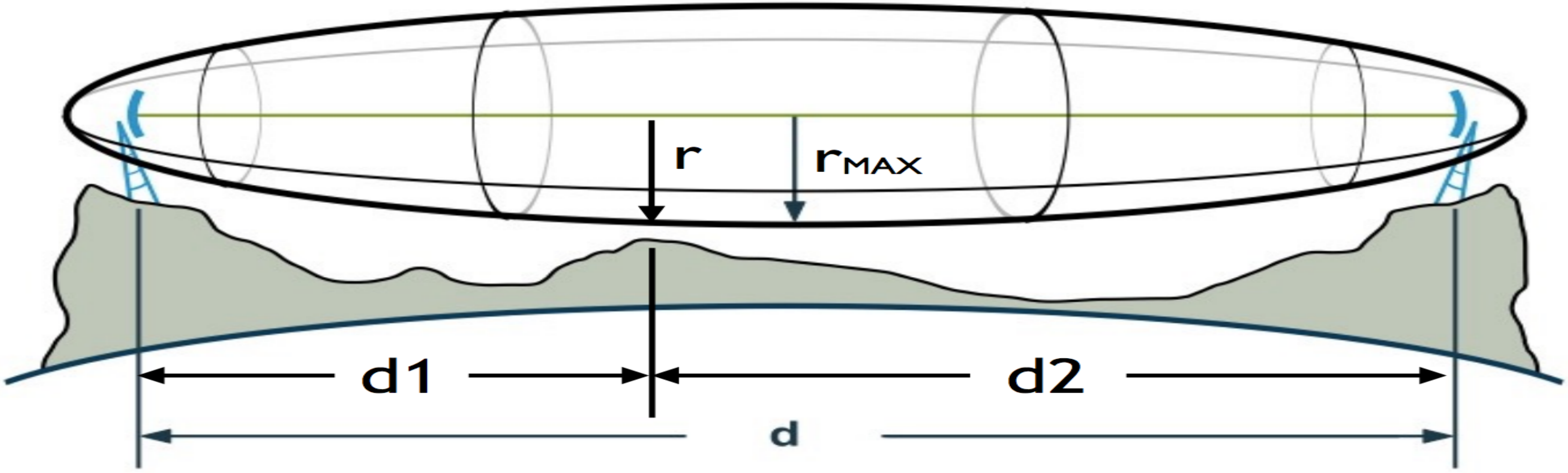
Polarization

Polarization is the direction of the Electric field



Fresnel Zone



$$r = \mathrm{sqrt}(\lambda * d1 * d2 / d)$$

$$r_{MAX} = 1/2 * \mathrm{sqrt}(\lambda * d)$$

where all the dimensions are in meters

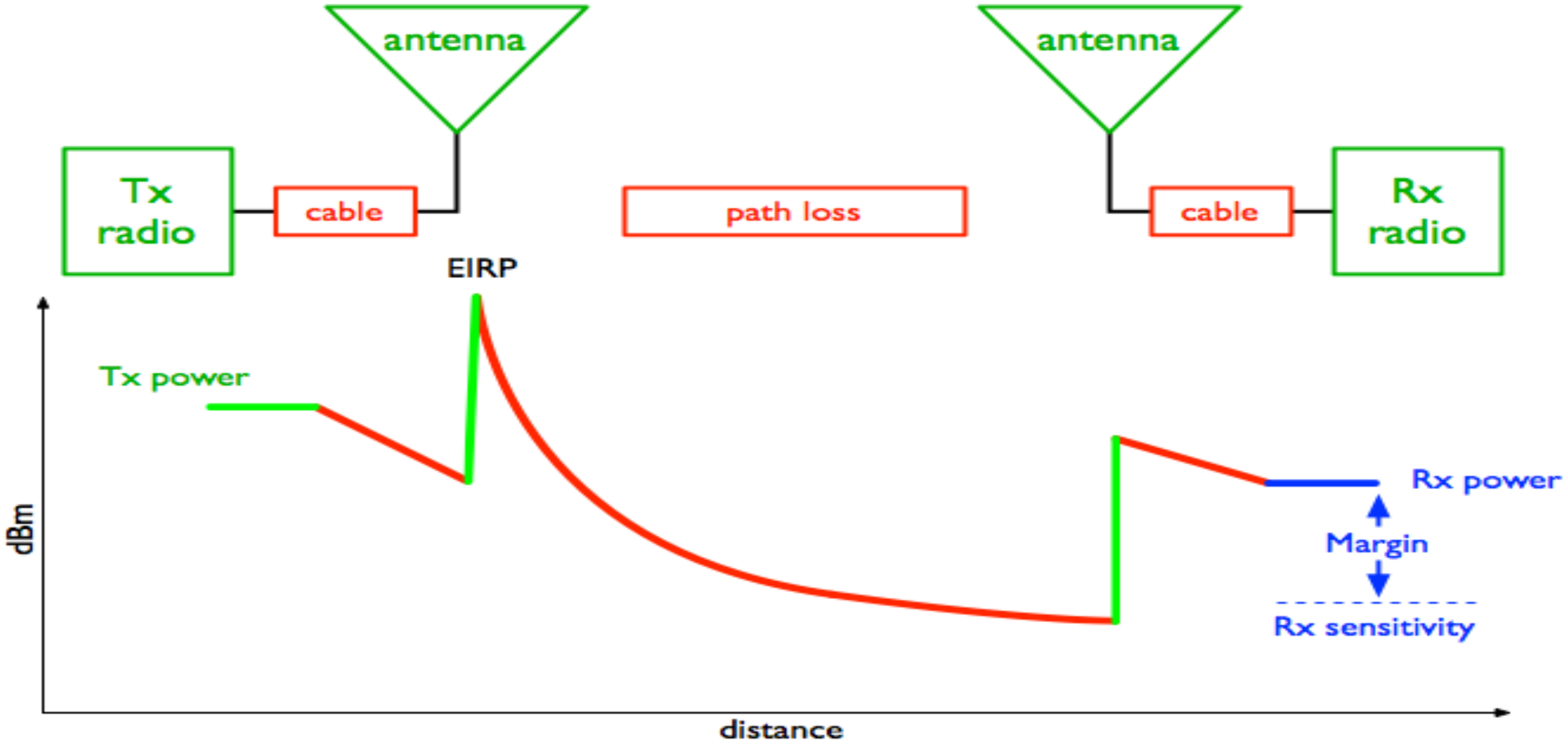
Fresnel Zone

The First Fresnel Zone is an ellipsoid-shaped volume around the Line-of-Sight (LOS) path between transmitter and receiver.

The Fresnel Zone clearance is important to the integrity of the RF link because it defines a volume around the LOS that must be clear of any obstacle for the the maximum power to reach the receiving antenna.

Objects in the Fresnel Zone as trees, hilltops and buildings can considerably attenuate the received signal, even when there is an unobstructed line between the TX and RX.

Power in a wireless system



Link budget

Link budget is a way of quantifying the link performance.

- The received power in an wireless link is determined by the following factors: transmitter power, loss of the cable between transmitter and antenna, transmitting antenna gain, *transmission path loss*, receiving antenna gain, and loss of the cable between the antenna and the receiver.
- If that power is greater than the ***sensitivity*** of the receiving radio, then the link is feasible.

Link budget

- The transmitter power is limited by the regulations of each country, and depends on the type of service.
- In the 2.4 GHz unlicensed band the maximum allowed EIRP is 20 dBm in Europe while it is 30 dBm in US.
- The allowed transmit power can be higher in licensed bands, broadcasters can transmit at thousand of watts.
- When using a high gain transmitter antenna the conducted power of the transmitter might have to be reduced to comply with the allowed EIRP.

Path loss simulation tool

- There are many commercial software tools to simulate links, and a few are available for free.
- Radio Mobile is a free and powerful simulation tool for the Windows operating system. There is also an on-line version at: http://www.ve2dbe.com/rmonline.html
- BotRf is very simple to use android app based on Telegram

BotRf: a telegram application for wireless links

To install the tool, first install the telegram application from the *play store* in your device.

You need to have a cell phone to receive an sms with the code that will grant you access. It does not need to be a smart phone.

With that code, you can run telegram in any web browser capable device, laptop, tablet or desktop, besides an android phone.

Once telegram is running choose BotRf as a contact, and you are set.

BotRf: a telegram application for wireless links

BotRf will fetch the required digital elevation maps to:

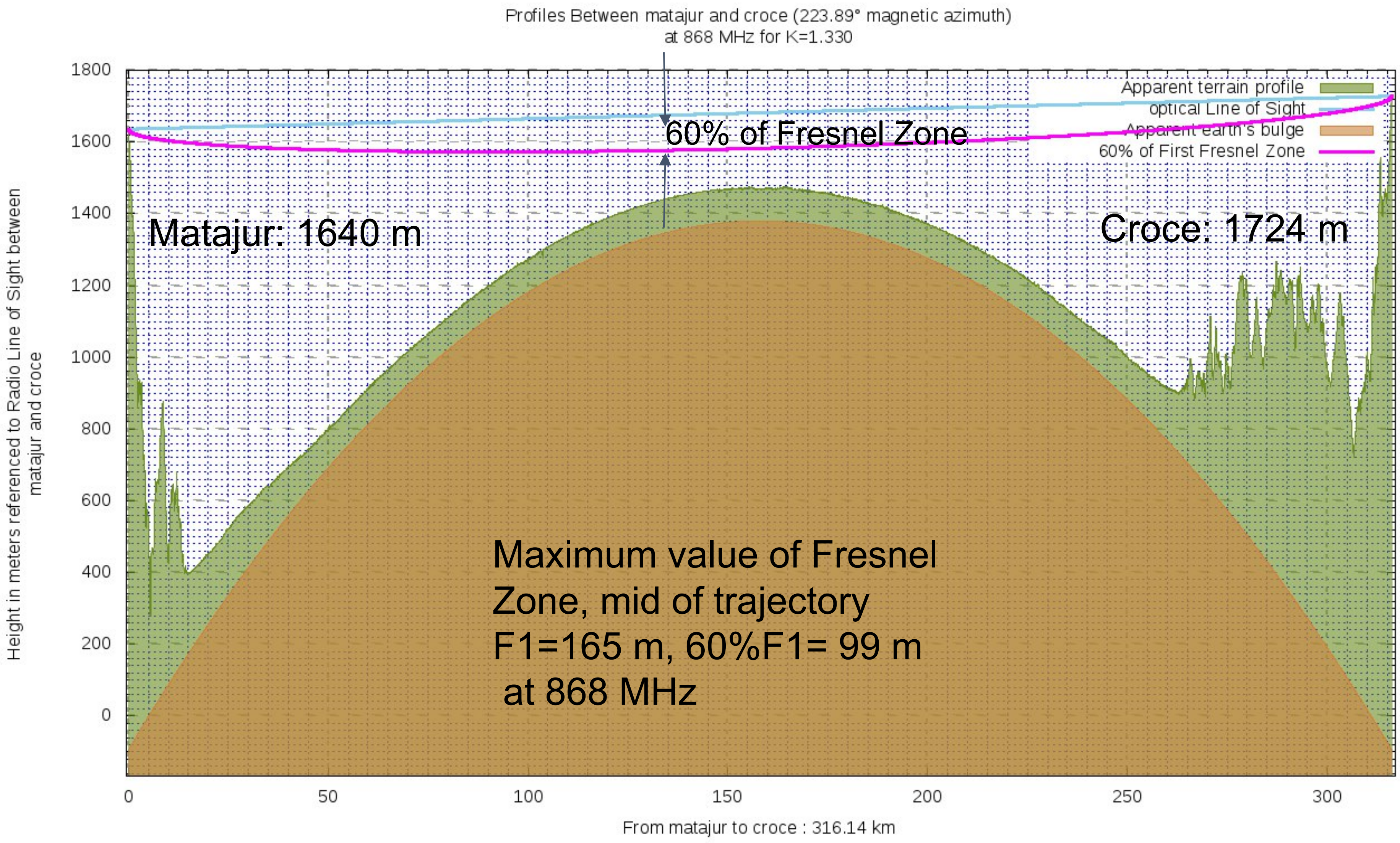
- Draw the first Fresnel zone ellipsoid and optical line of sight
- Draw the apparent earth curvature for the specified refraction index
- Calculate the distance and the angles between both antennas
- Calculate the free space loss on the path and the estimated attenuation introduced by obstacles, if present
- Show a profile of the terrain between the antennas

BotRf: a telegram application for wireless links

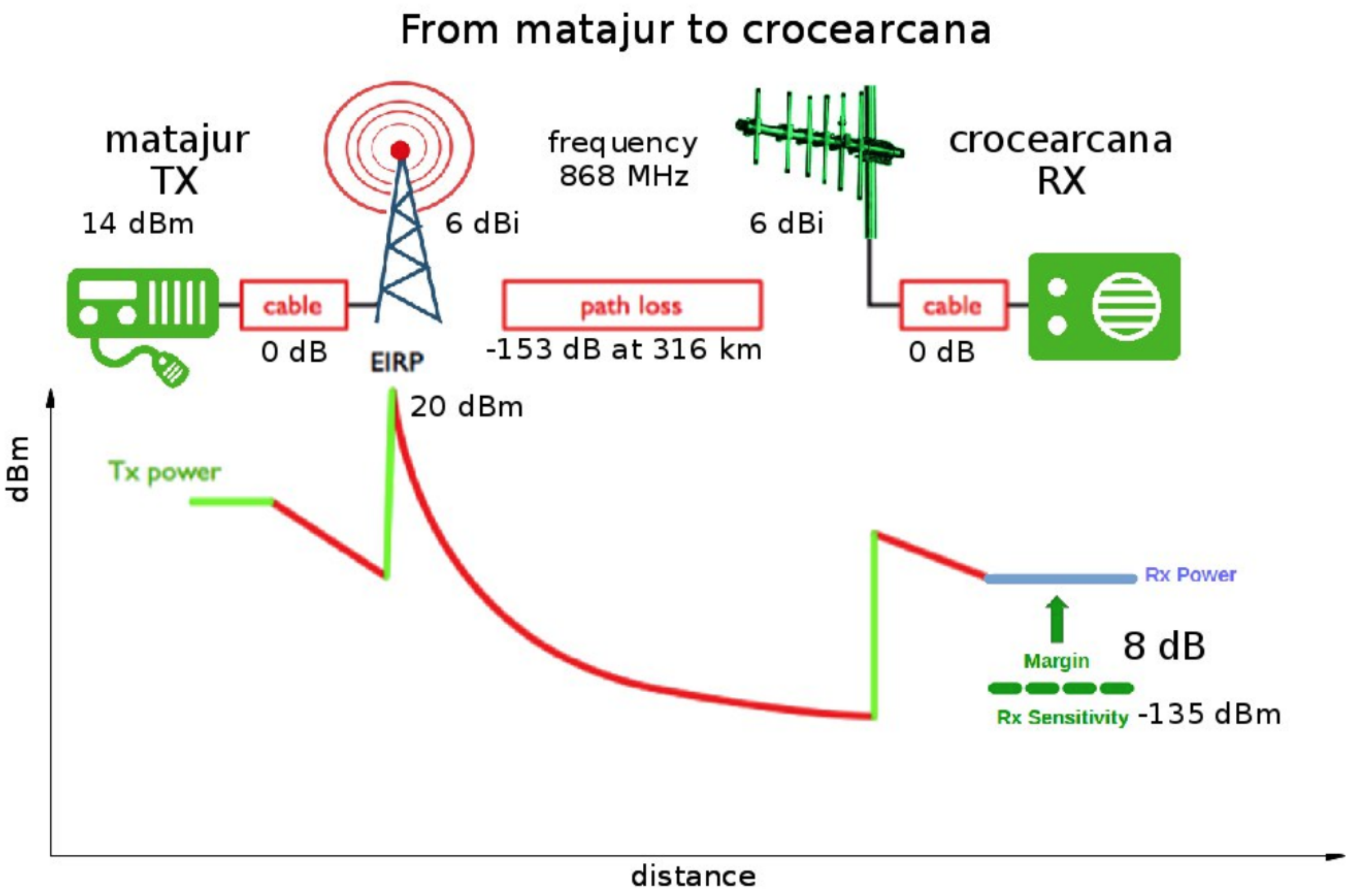
BotRf will also:

- Draw a graph of power versus distance along the link
- Calculate the estimated received power and the link margin
- Draw a map of the the area surrounding the two end points
- Present a view from one end point to the other, identifying relevant landmarks
- Additionally, BotRf will do many magnitude and units conversions to facilitate the planning of the link

Example of BotRf simulation



Example of BotRf simulation



Exercise

Install the Telegram application in your device of choice: smart phone, laptop (any operating system since it can be used as a web browser application).
Once telegram is running choose BotRf as a contact.
Using the s command, insert the name and coordinates of two sites, as well as the heights of the antennas above the ground.
The r command will then generate a complete report.

Link assessment with Google Earth

- Google earth can be used to determine LOS over short distance links.
- But it does not consider the curvature of the earth nor the bending of the radio waves because of the variation of the refractive index, so it is not a good simulation tool for radio links.

Conclusions

- Radio waves have a characteristic wavelength, frequency and amplitude, which affect the way they travel through space.
- There are a great number of services that make use of the electromagnetic spectrum
- Lower frequencies travel further, but at the expense of throughput.
- Antennas must be chosen considering the radiation pattern, frequency of operation and impedance.
- Radio waves occupy a volume in space, the Fresnel zone, which should be unobstructed for optimum reception.