6 Radio and RF

Ref: http://www.asecuritysite.com/wireless/wireless06

6.1 Introduction

The electromagnetic (EM) spectrum contains a wide range of electromagnetic waves, from radio waves up to X-rays (as illustrated in Figure 1). Included in the spectrum are radio waves, microwaves, infrared waves, light waves, ultraviolet waves and X-rays. Electromagnetic waves propagate at the speed of light (c) in free-space (3×10^8 m/s) and vary with their frequency and wavelength. Normally radio waves are referred to by their frequency, and waves above this are referred to by their wavelength. The relationship between frequency and wavelength is:

$$c = f\lambda$$

where c is the speed of light, f is the frequency (Hz) and λ is the wavelength (m). For example Radio Forth FM has a frequency of 97.3MHz. It wavelength will thus be 3.08m, and Virgin Radio has a frequency of 1215 kHz, which gives a wavelength of 246m.

The RF (Radio Frequency) spectrum ranges over the radio wave and the microwave frequencies. The lower the frequency the better the wave propagates around large objects, thus AM radio frequencies propagation better than FM radio. Often FM radio and TV rely on line-of-sight communications, as higher-frequency waves cannot bend around large objects. The frequencies used for IEEE 802.11 communications are 2.4GHz (12.5 cm) for IEEE 802.11b/11g and 5GHz (6cm) for IEEE 802.11a.

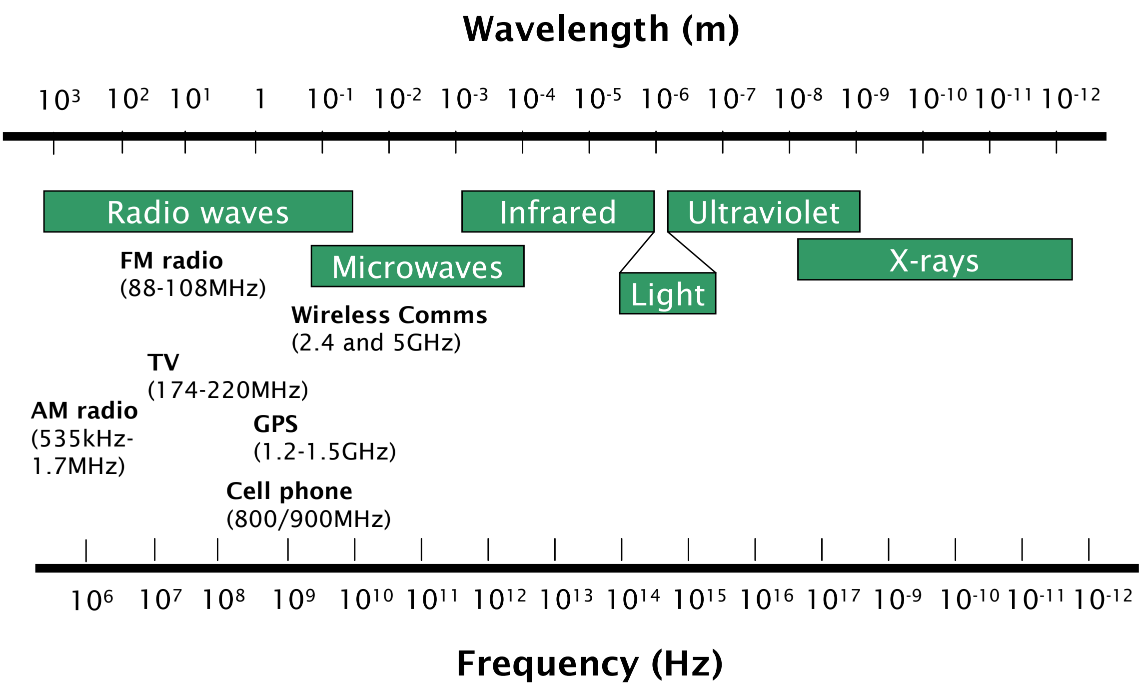

Figure 1 EM wave spectrum

An electromagnetic wave propagates with an electric field (**E**) and a magnetic field (**H**). These are at right angles to each other, and the propagation is at right angles to both the E and H fields. This is defined by the right-hand rule (as illustrated in Figure 2).

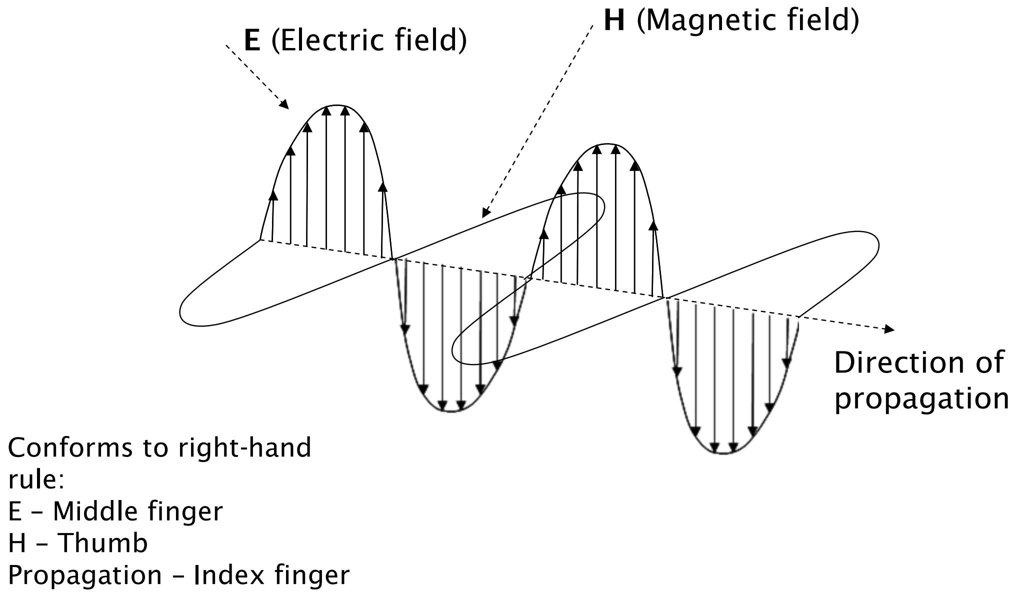

Figure 2 EM wave propagation

6.2 Power and decibels

The unit for electrical power is Watts, which directly relates to electrical energy. Normally in RF systems this is defined in mW (which is one-thousands of a Watt). The gain of a system is defined as the output power divided by the input power:

$$Gain = \frac{P_{output}}{P_{input}}$$

which is a ratio. If the value is less than unity, there is a loss of power (such as in a cable loss), and if it is greater than unity there is a gain in power (such as in an electrical amplifier. Typically gain is defined in a logarithmic scale such as:

$$Gain(dB) = 10\log_{10}\left(\frac{P_{output}}{P_{input}}\right)$$

Thus, for example, if the power output is doubled over the input, then the gain will be:

$$Gain = 10\log_{10}\left(\frac{2 \times P_{input}}{P_{input}}\right) = 10\log_{10}\left(\frac{2}{1}\right) = 3.01\text{dB}$$

also, if the output power is halved then we get:

$$Gain = 10\log_{10}\left(\frac{0.5\times P_{input}}{P_{input}}\right) = 10\log_{10}\left(\frac{0.5}{1}\right) = -3.01\text{dB}$$

Thus +3dB identifies a doubling in power, whereas a -3dB represents a halving in power. Thus +6dB represents a four times increase in power, and +9dB represents an eight times increase in power. By the same token, -6dB represents that the output power is one-quarter of the input power, and so on. Figure 3 shows a logarithmic plot of power in dB's against the value as a ratio. It can be seen that a gain of 10 gives a value of 10dB, and 100 gives 20dB. Thus as the values become large as a ratio, the value in dB's in relatively small.

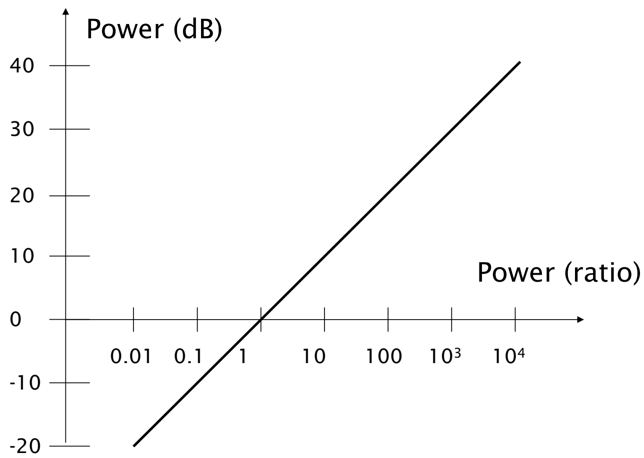

Figure 3 Conversion from a ratio into dB's

In an electrical system with a number of gain and loss stages, the overall gain/loss is the multiplication of as each of the stage gains. For example, if the gain of an amplifier is 20, and the loss in the cable is 0.1, then the overall gain is 2. If the system is defined in dB, then the gain values are added to give the overall gain. Thus an amplifier gain of 12dB, and a cable loss of -3dB will result in an overall gain of 9dB. In the system in Figure 4 the gains are multiplied together as a ratio, but the gains in dB's are added together. It can be seen that it is easier to determine the overall gain if the values are defined in dB's.

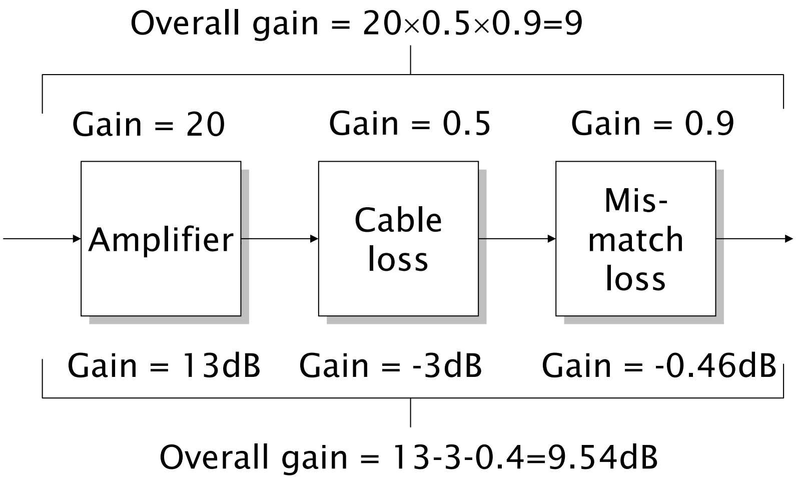

Figure 4 Example system

Often a power value is referenced to 1mW, and is defined in dB's as:

$$\text{Power(dBm)} = 10\log_{10}\left(\frac{P_{value}}{1\times10^{-3}}\right)$$

Thus 1mW is represented as 1dBm, 10mW is 10dBm, 100mW is 20dBm, and 1W is 30dBm. It is then possible to easily calculate output power if the input power and the gain elements are defined in dB's. For example, if the input power is 100mW, and the amplifier gain is 13dB, with a cable loss of 3dB, then the output power is:

P_{out}(dBm)= P_{in}(dBm) + Gain (dB) – Losses (dB)
P_{out}(dBm)=30+13–3 = 40dBm

To convert dBm's to dB's, a value of 30 is added.

6.3 System losses

In the transmitter system, losses are typically caused by:

- **Attenuation in cables**. The attenuation is normally linear, and is typically defined in a dB loss for every meter. This varies over frequency, where the higher the frequency the higher the loss (due to the skin effect). For example if the cable loss is 3dB/km, then the overall loss for a 10km will be 30dB. Typical cables for RF communications are coaxial, which has an inner core separated from a grounded sheath by a dielectric.
- **Mismatches in terminations**. Cables and connections have a defined characteristic impedance, and must always be matched to each other, in order to minimize reflections of the terminations, and maximize the power transfer. Most RF equipment use a cables and connectors with a characteristic impedance of 75Ω. Any mismatch in the termination causes reflections, and can cause a distortion of the RF signal.

A typical low loss cable gives a loss of 6.7 dB per 100 feet (30m). Thus for every 100 feet the signal strength reduces by:

$$\text{Reduction} = \frac{1}{10^{6.7/10}} = 0.213$$

which means that only around 21% of the signal remains after 100 feet.

6.4 Multipath problems

A major factor in wireless LANs is the multipath problem where waves can take differing paths to get to a destination. These multipaths can cause fading and distortion of the radio wave form. If different waves arrive at a receiver with different time delays they can distort the received signal. One of the way to overcome this problem is to use **diversity** which uses more than one antenna. It is likely that one of the antennas will experience less multipath problems than the other antennas. It is thus important that diversity antennas are physically separated from each other, and, so as to reduce the problem of null points, they can be moved around the physical space. The antenna can be set for both the transmit and receive options. These can be:

- **Diversity**. With this the WAP uses the antenna in which the best signal is being received.
- **Right**. This where the antenna is on the right of the WAP, and is highly directional.
- **Left**. This where the antenna is on the left of the WAP, and is highly directional.

and the configuration is as follows:

```
# config t
(config)# int dot11radio0
(config-if)# antenna ?
(config-if)# antenna transmit ?
(config-if)# antenna transmit diversity
(config-if)# antenna receive left
(config-if)# exit
(config)# exit
```

6.5 Isotropic radiators

An antenna can produce different radiation patterns. An **isotropic radiator** sends out radio waves in equal power in all direction. This type of radiator is useful when the radiation pattern is required to reach every direction. It can be seen from Figure 3 that power drops off with the inverse of the square of the distance. Thus a double in distance causes the power to drop by one quarter.

An antenna is measured for its field strength in both the azimuth and the elevation (as illustrated in Figure 6). The azimuth map shows the field strength in the x-y direction, while the elevation gives the electric field strength above the antenna (x-z direction).

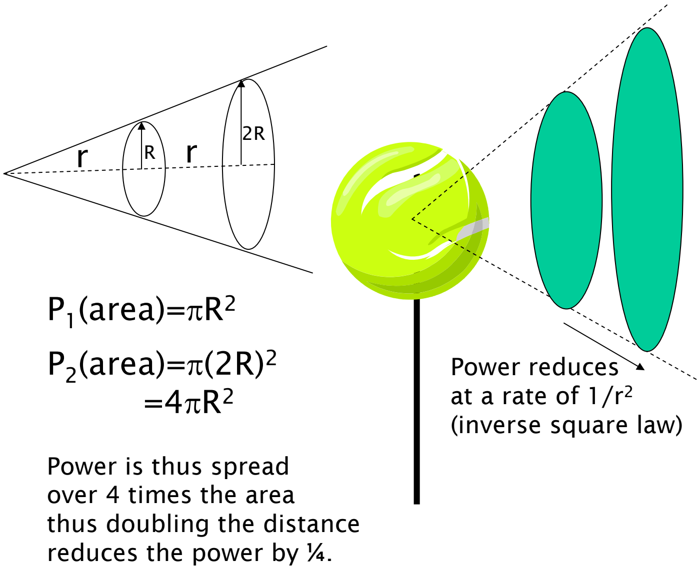

Figure 5 Isotropic radiator

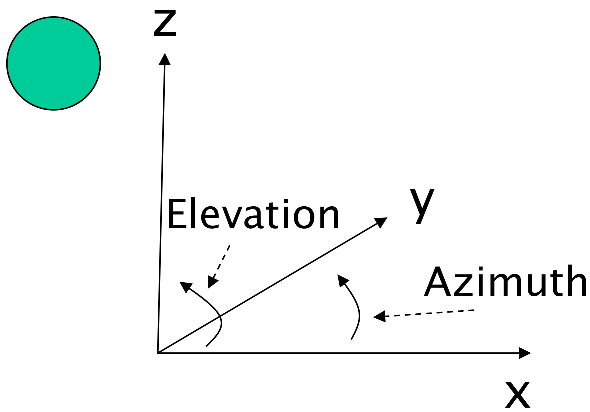

Figure 6 Measurement of antenna field pattern

6.6 Monopoles and Dipoles

The isotropic radiator cannot be made practically. The nearest that it possible is an **omnidirectional** antenna, as illustrated in Figure 7. It contains a single resonator element, where the electric field radiates outwards in parallel to the antenna (vertical) and the magnetic field in the loops around the antenna (horizontal). A dipole antenna uses a center feed into two conducting elements of $\lambda/4$ (Figure 5), which gives it a total length of $\lambda/2$. At 2.4GHz, the length with be 12.5cm, and at 5GHz it is 6cm. This produces a doughnut shaped radiation pattern, as illustrated in Figure 9.

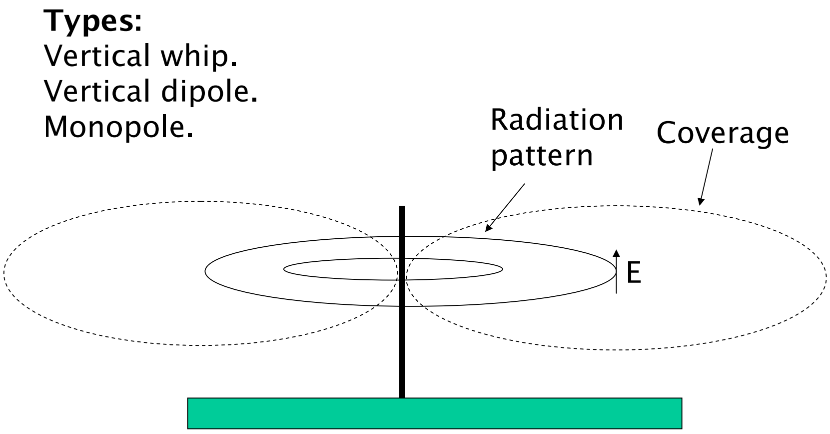

Figure 7 Omnidirectional antenna

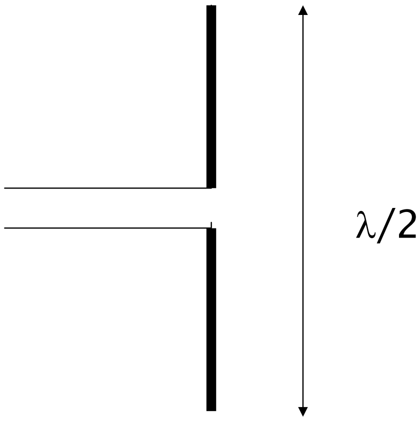

Figure 8 Dipole antenna

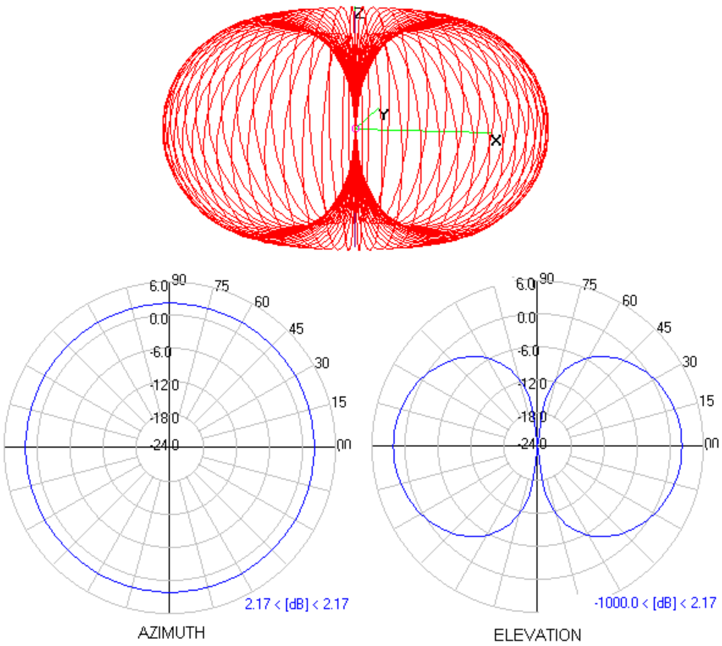

Figure 9 Pattern produced by a dipole antenna [1]

6.7 Antenna Gain

Antennas are never perfect isotropic radiators, as they encounter losses, and they also do not typically radiate their power in every direction equally. The more focused the radiation pattern the higher the power will be in the beam, as compared with an isotropic radiator. The gain of an antenna refers to the increase in power of an antenna for a given direction as related to a perfect isotropic radiator which has the same input power. If a direction is not given, it is normally taken as the maximum value of the power in any given direction. It is given by:

$$Gain = \frac{P_m}{P_i}$$

$$Gain(dB) = 10\log_{10}\left(\frac{P_m}{P_i}\right)$$

For example, if the power is increase by a factor of 2:

$$Gain(dB) = 10\log_{10}\left(\frac{2P_i}{P_i}\right) = Gain(dB) = 10\log_{10}(2) = 3dB$$

For example, if the power is increase by a factor of 4:

$$Gain(dB) = 10\log_{10}\left(\frac{4P_i}{P_i}\right) = Gain(dB) = 10\log_{10}(4) = 6dB$$

It can be seen that there is an increase in 3dB for every double in power. This gain is often referred to as **dBi** (isotropic reference) which is the gain related to an perfect isotropic radiator. Unfortunately isotropic antennas are impossible to produce, thus a more useful measure is the reference to a dipole antenna, and is defined as **dBd** (dipole reference). A dipole antenna has a gain of 2.14dBi, thus add dBd value can be converted into a dBi value by adding 2.14 onto it.

$$Gain(dBi) = Gain(dBd) + 2.14$$

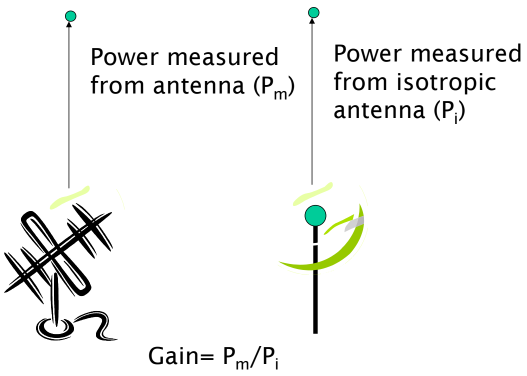

Figure 10 Antenna gain

6.8 Polarization

The direction of the electric field defines the polarization direction. This normally lies along the conducting rod element in the antenna. The polarisation direction should be at right angles to the line-of-sight direction between the transmitter and the receiver. Normally, in wireless networks, the polarization is vertical, but it can also be horizontal. A helix antenna creates a circularly polarized wave (which can, of course, by right handed or left handed polarization).

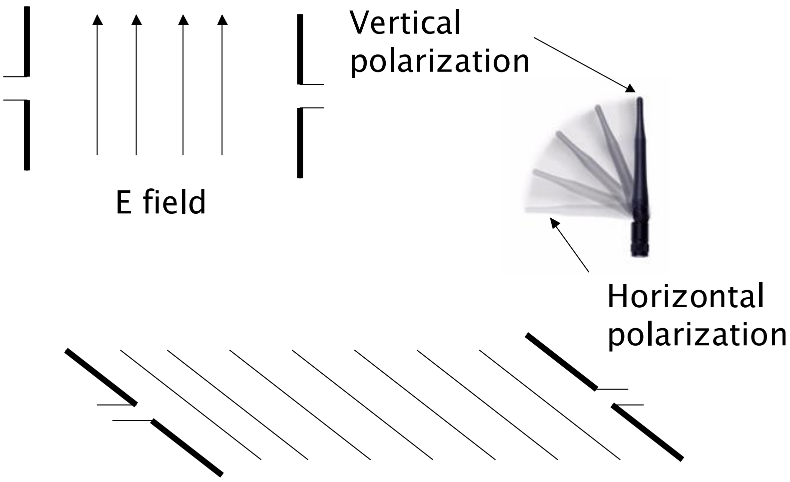

Figure 11 Polarization

6.9 Signal attenuation

Along with signal losses in the transmitter, the radio wave fades as it propagates through free space. The amount of this attenuation and scattering is typically related to the amount of moisture in the air. This, of course, depends on rainfall levels and humidity. The higher the frequency of the wave the more the attenuation is. A typical table is (at 6GHz):

Rainfall (inch/hr)	Path loss (dB/mile)
0.15	0.015
0.7	0.1
1.5	1

6.10 EIRP

The EIRP value of a transmitter measures the maximum from the transmitter, and will be given by:

EIRP = transmitter power + antenna gain – cable loss

This must be within the maximum limits required by the national laws. For example a 100mW (20dBi) power source with an antenna with a 6dBi gain will give an EIRP of 26dBi. In most situations an EIRP of 36dBi should not be exceeded.

6.11 Antenna types

The following define some typical antenna used in wireless LANs [2].

Feature	ANT5959	ANT2410Y-R	ANT2012	ANT3213	ANT1728	ANT4941	ANT3549	ANT1729
Description	Diversity omni-directional ceiling mount	Yagi mast or wall mount	Diversity patch wall mount	Pillar mount diversity omni-directional	Omnidirectional ceiling mount	2.2 dBi dipole antenna	Patch wall mount	Patch wall mount
Application	Indoor unobtrusive antenna, best for ceiling mount. Excellent throughput and coverage solution in high multipath cells and dense	Indoor/outdoor directional antenna for use with Access Points or Bridges	Indoor/outdoor unobtrusive medium range antenna	Indoor, unobtrusive medium-range antenna	Indoor medium-range antenna, typically hung from crossbars of drop ceilings	Indoor omni-directional coverage	Indoor, unobtrusive, long-range antenna (can also be used as a medium-range bridge antenna)	Indoor, unobtrusive, medium-range antenna (can also be used as a medium-range bridge antenna)
Gain	Two separate 2 dBi omnidirectional elements; Minimum gain 2.0. Maximum gain 2.35	10 dBi	6.5 dBi with two radiating elements	5.2 dBi with two radiating elements	5.2 dBi	2.2 dBi	9 dBi	6 dBi
Approximate indoor range at 1 Mbps	350 ft (105 m)	800 ft (244 m)	547 ft (167 m)	497 ft (151 m)	497 ft (151 m)	350 ft (106m)	Access point: 700ft (213 m)	Access point: 542ft (165 m)
Approximate indoor range at 11 Mbps	130 ft (45 m)	230 ft (70 m)	167 ft (51m)	142 ft (44 m)	142 ft (44 m)	130 ft (40 m)	Access point: 200 ft (61 m) Bridge: 3390 ft (1032 m)	Access point: 155 ft (47 m) Bridge: 1900 ft (580 m)
Beam width	360° H 80° V	47° H 55° V	80° H 55°V	360° H 30° V	360° H 38° V	360° H 65° V	60° H 60° V	75° H 65° V
Cable length	3 ft (0.91 m)	3 ft (0.91 m)	3 ft (0.91 m)	3 ft (0.91 m)	3 ft (0.91 m)	N/A	3 ft (0.91 m)	3 ft (0.91 m)

6.12 Fresnel zones

Radio waves often suffer from multipath problems. A major one is a direct line of sight connection where an alternative path is provided where the wave is received by the alternative path which is 180° out-of-phase with the direct line-of-sight path. Figure 12 shows an example of this problem.

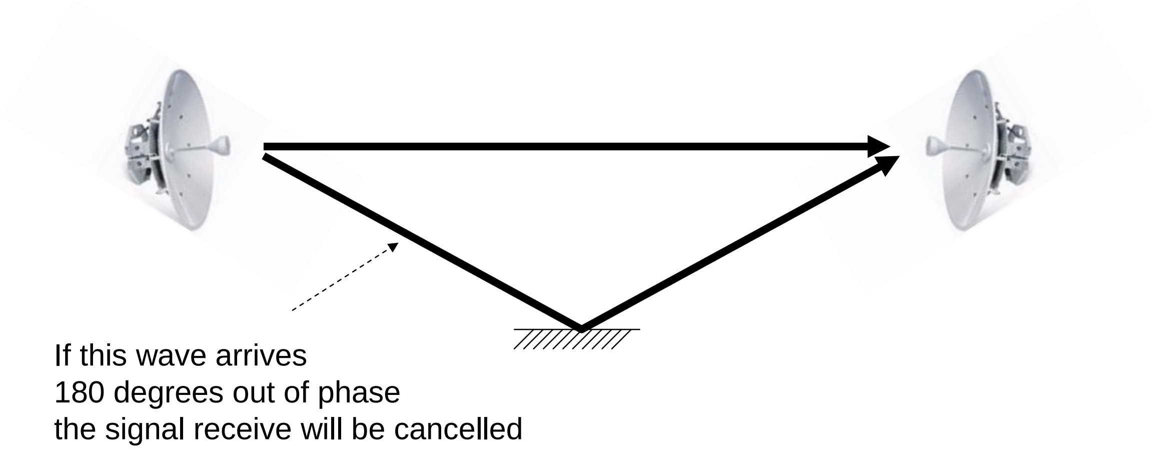

Figure 12 Out-of-phase reception

Fresnel zone depends an elliptical area which defines the region in which there should not be any objects within the region which could cause a reduction in the received signal strength (Figure 13).

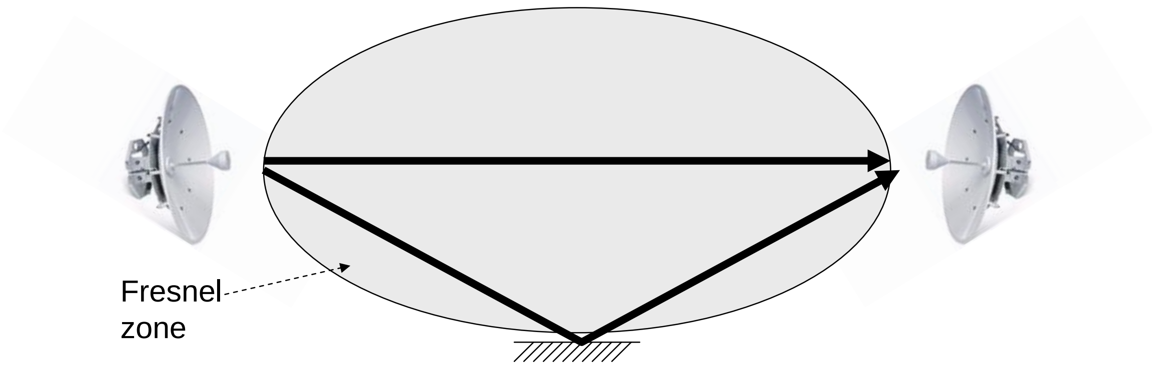

Figure 13 Fresnel zone

Overall the Fresnel zone varies as the distance between the antennas and the operating frequency. The radius of the Fresnel zone (in meters) is given by (Figure 14):

$$r = 17.32 \times \sqrt{\frac{d}{4 \times f}}$$

where

d is the distance (in km).

f is the frequency (in GHz).

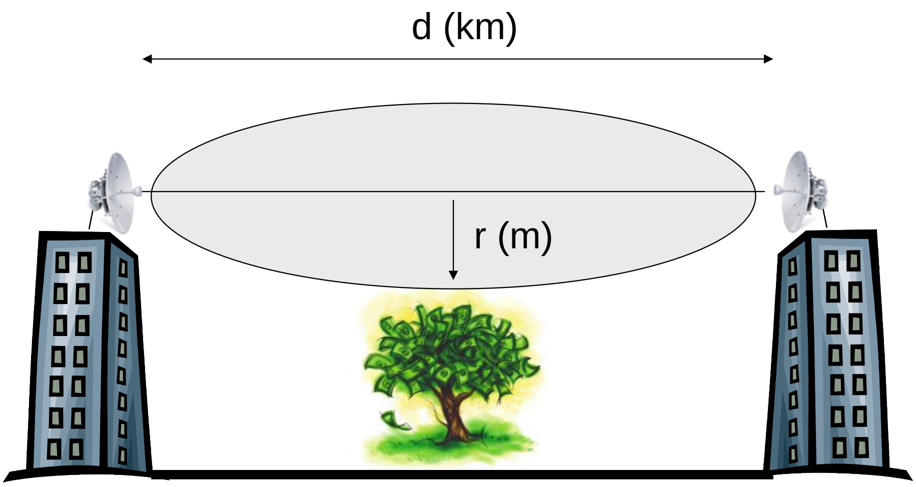

Figure 14 Fresnel zone

For example, if the distance between the antennas is 1km, and the frequency is 2.4GHz, then the maximum Fresnel radius will be:

$$r = 17.32 \times \sqrt{\frac{1}{4 \times 2.4}} = 5.58m$$

Thus, in this case, it must be sure that there is no obstacles in the path which are within this region.

6.13 Free-space loss

The loss due to free space propagation can be estimated with:

$$\text{Free space Loss(dB)} = 20\log_{10} f + 20\log_{10} d + 36.6\,\text{dB}$$

where f is the frequency is MHz, and d is the distance in miles. For example with a frequency of 2.4GHz and a distance of 1mile gives a free-space loss of 104.2dB.

6.14 References

[1] http://www.trevormarshall.com/byte_articles/byte1.htm
[2] Ref: http://www.cisco.com/univercd/cc/td/doc/pcat/ao____o1.htm

6.15 Tutorial

1. Calculate the wavelength of an EM wave in free space for the following frequencies:

   (i) 100MHz
   (ii) 1GHz
   (iii) 5GHz

Ans: 3m, 30cm, 6cm

2. Determine the dBm values for the following powers:

   (i) 1 mW (ii) 20mW
   (iii) 150mW (iv) 1W (v) 0.1mW

   Ans: 0dBm, 13 dBm, 21.8 dBm, 30 dBm, -10dBm

3. Determine the mW values for the following dBm values:

   (i) 10 dBm (ii) 1dBm
   (iii) -3dBm (iv) 20dBm

   Ans: 10mW, 1.3mW, 0.5mW, 100mW

4. Determine the output power for the following cables lengths with a 100mW input power. Assume a cable loss of 6.7 dB per 100 feet (30m).

   (i) 200 feet (ii)1000 feet

   Ans: 6.6dBm, -47 dBm.

5. A dipole antenna is fed with 10mW. What is the maximum output power of the antenna within the mean beam? [Ans: 2.14dBm]

6. A dipole antenna is fed with 100mW, with a standard dipole antenna. What is the maximum EIRP value? [Ans: 22.14dBm]

7. How long does it take a radio wave to travel 100km? [Ans: 333.3 μs]

8. If two antennas are located at a distance of 5km apart, and are operating at 2.4GHz. What is the Fresnel radius? [Ans: 12.5m]

9. If two antennas are located at a distance of 5km apart, and are operating at 5GHz. What is the Fresnel radius? [Ans: 8.66m]

10. An antenna is placed in South Queensferry and another is placed in North Queensferry, at the crossing near the Forth Rail Bridge. What is the minimum high of the antenna masts so that the water is not part of the Fresnel zone for a 2.4Hz link? [Ans: 8.89m]

11. An antenna mast is located in England, and another in France, at the widest distance of the English Channel. What is the minimum high of the antenna masts so that the water is not part of the Fresnel zone for a 5Hz link? [Ans: 51.96m]

12. If two antennas are place two miles apart and operate at a frequency of 2.4GHz. What is the free space loss? [Ans: 110.2m]

13. If two antennas are place two miles apart and operate at a frequency of 2.4GHz. The power transmitted is 10W (10dB). What is the received power in dBs? [Ans: -100.2dB]