

# 1 Radio Basics

## 1.1 The RF Spectrum

### 1.1.1 Overview

Radio Frequencies are a sub-set of the electromagnetic spectrum. While the electromagnetic spectrum runs from DC to Daylight, the ends of the Radio Frequency (RF) spectrum are fuzzy, a moving target, and have expanded over the years. RF may eventually extend from a slightly positive frequency into particle physics. More practically, and to help avoid discussions on the welfare of Schrödinger's<sup>1</sup> cat, the RF spectrum ranges from just below 10 kHz to well over 40 GHz.

**Table 1-1: The RF Spectrum**

Wavelength (m)	10 <sup>4</sup>	10 <sup>2</sup>	10 <sup>0</sup>	10 <sup>-2</sup>	10 <sup>-4</sup>	10 <sup>-6</sup>	10 <sup>-8</sup>	10 <sup>-10</sup>	10 <sup>-12</sup>	10 <sup>-14</sup>	10 <sup>-16</sup>
Frequency (Hz)	10 <sup>4</sup>	10 <sup>6</sup>	10 <sup>8</sup>	10 <sup>10</sup>	10 <sup>12</sup>	10 <sup>14</sup>	10 <sup>16</sup>	10 <sup>18</sup>	10 <sup>20</sup>	10 <sup>22</sup>	10 <sup>24</sup>
	Radio Spectrum					IR	☞	UV	x-ray		Cosmic

### 1.1.2 Microwave Bands

Microwave refers to very short wavelength. Definitions vary but in general, all frequencies above 1000 MHz are called microwave<sup>2</sup>.

**Figure 1-2: Microwave Bands<sup>3</sup>**

Band	Freq in GHz	Comment
L	1.12 - 2.70	
S	2.60 - 3.95	
G	3.95 - 5.85	
C	4.90 - 7.05	Satellite
J	5.85 - 8.20	
H	7.05 - 10.00	
X	8.20 - 12.40	
M	10.00 - 15.00	
P	12.40 - 18.00	
N	15.00 - 22.00	
K	18.00 - 26.50	
R	26.50 - 40.00	Waveguide size is 0.28 x 0.14 inches

Note: This course is primarily concerned with the unlicensed 12 cm band. The band utilizes 83.5 MHz of spectrum starting at 2.4 GHz. The band is typically divided in half for two channels or two band plans depending upon the equipment manufacture.

<sup>1</sup> Schrödinger was a theoretical physicist with a theoretical cat. See Endnotes. Schrödinger wrote the general equation of particle waves that is used to define RF propagation.

<sup>2</sup> Motorola

<sup>3</sup> There is no one standardized letter designation of Bands.

### 1.1.3 Frequency vs. Wavelength

It can be seen from Table 1-1 that frequency and wavelength are inversely proportional. Add the speed of light and you have . . .

a simple formula:  $\lambda = c / f$

Where:  $\lambda$  : = wavelength in m  
 $c$  : = speed of light in m/s  
 $f$  : = frequency in Hz

The velocity of light is a relative constant that varies with the media, with time, and with gravity. Shifts in relative speed between the source and the observer are manifested in no shift in relative speed? If you can figure this one out . . . .

For the purpose of this document,  $c$  is approximately equal<sup>4</sup> to 300 million m/s.

## 1.2 Radio & RF Basics

### 1.2.1 Discussion on History and Development

Radio was invented by several people including Maxwell, Hertz, Marconi, and Zapalac<sup>5</sup>, (all-American, Texas A&M '36). Some historians credit Nickolai Tesla with the invention. Tesla's experiments were certainly the most spectacular. He was a profuse inventor and even started Mr. Westinghouse in AC. The purchase of Tesla's rights to AC by Westinghouse ignited the struggle between Westinghouse and Edison on AC vs DC for power distribution.

Radio became the cornerstone for long-haul communications but generally at lower frequencies. VHF operation was in its infancy as recently as WWII. Frequencies have migrated higher over the years because of bandwidth issues. Higher frequencies mean higher bandwidths, and that translates to more information. There is a downside to higher frequencies. It is shorter distance. The tradeoff to more information is shorter hops.

You can still hear a few teletype signals on short wave at 75 or 300 baud, but modern data communication starts at VHF and goes up from there.

### 1.2.2 AC and LC circuits

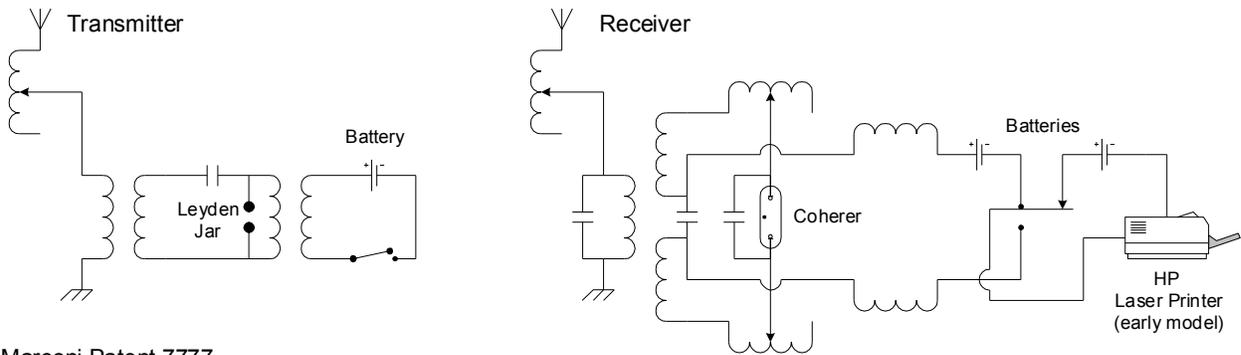
Tesla, in one of his first demonstrations of radio, lit 200 light bulbs from a distance of 25 miles between two mountaintops. He employed AC and a tuned LC, (Inductive-Capacitive) circuit as a driver. A similar LC circuit was used to receive the signal at the light bulbs. This is the same thing you do between mountaintops in Alabama. The only difference is the frequency, the amount of power, and the size of the light bulb.<sup>6</sup>

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<sup>4</sup> Actual is 299,792,500 m/s

<sup>5</sup> Not

<sup>6</sup> Tesla had bragged that he could build a "death ray" that could destroy 10000 airplanes at 250 miles range.



Marconi Patent 7777  
April 1900

**Figure 1-3: Elementary Transmitter/Receiver**

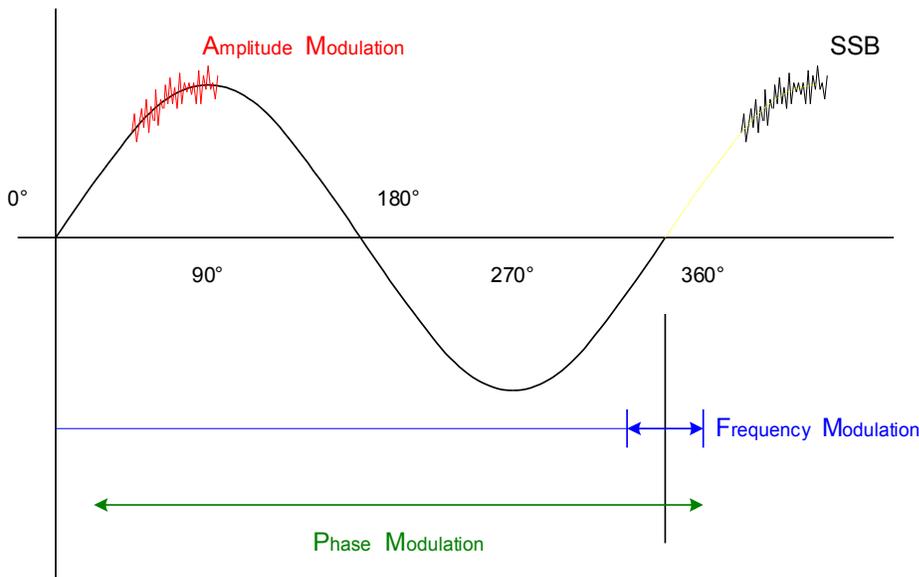
1.2.3 Electromagnetic Radiation

Simply put, electromagnetic radiation is a form of energy released when something is excited. If the "something" is a branding iron just pulled from a hot fire, the electromagnetic radiation is infrared light manifested as heat. If the something is a copper wire strung between two trees excited by an AC oscillator, the electromagnetic radiation is a RF wave. The only difference between these two manifestations of radiation is their frequency. However, one is useful in marking cows, and the other is useful in making telephone calls.

1.2.4 Modulation

To modulate is to inflect or to vary. Radio waves are "inflected" in various ways to transport information. Modulation is accomplished in several ways. Most common are Amplitude Modulation (AM), Frequency Modulation (FM), Phase Modulation, and Pulse Modulation.

**Figure 1-4 - Traditional Modulation**



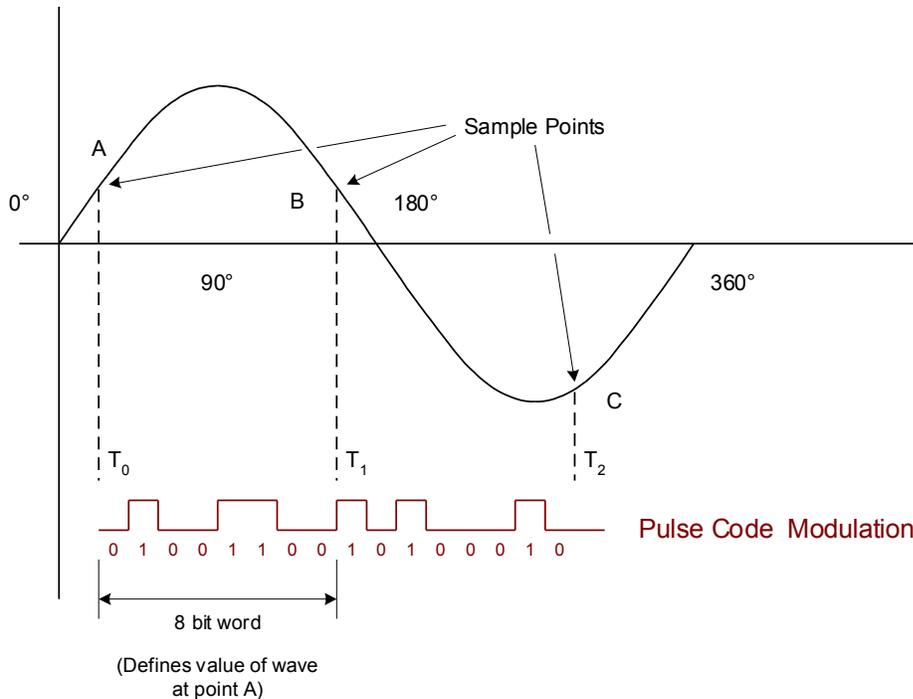
First we must define or describe "unmodulated". It is simply a RF sine wave at the operating frequency. Modulation is how this pure sine wave, or carrier wave, is changed to add information.

In AM, information such as voice is assigned a varying voltage depending upon pitch or frequency. This information is added to the carrier to form a complex sine wave, that is, a sine wave on a sine wave.

In FM, the carrier's center frequency is varied with respect to the amplitude of the input signal. The carrier amplitude remains unchanged.

Phase modulation is very similar to FM. Instead of changing the frequency of the carrier, the phase is shifted.

In Pulse Modulation, a "snapshot" of a waveform is taken at regular intervals. There are a number of pulse modulation schemes; some are Pulse Amplitude Modulation, Pulse Code Modulation (PCM), Pulse Frequency Modulation, Pulse Position Modulation, and Pulse Width Modulation.



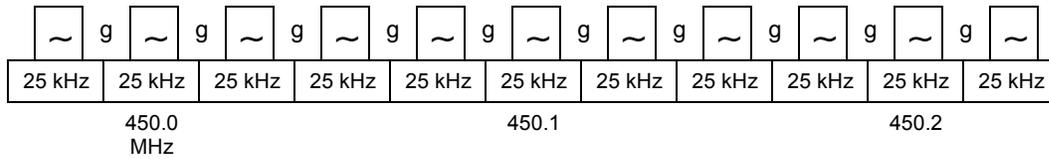
**Figure 1-5: Pulse Code Modulation**

Of these schemes, PCM is of the most interest because it is used in T1 signals. In order to define a sine wave, the wave must be sampled at least twice the rate of the highest supported frequency. A typical voice channel supports a maximum frequency of 4 kHz so the sample rate is 8 kHz.

*Conventional Wisdom*

Classic radio is narrow band. This means the amount of spectrum used is narrow. This was long thought the best way to utilize spectrum. That is, many users on narrow slices of spectrum in an organized "channelized" environment. Unfortunately, adding information to a narrow carrier causes it to get wider. Additionally, harmonics are produced, and harmonics cause intermodulation. As information rates increased, bandwidth between channels became a limiting factor.

**Figure 1-6: Typical Narrow Band Channels**



In the example above, FM deviation is limited to a narrow bandwidth in the center of each channel. The remainder of each channel's bandwidth is required as a buffer or guard band, (represented by the "g"), to prevent interference.

Recent trends in radio have included trunking for data and for voice. Trunking techniques are applied to radio channels via a computer. Each radio channel is like a trunk line. When a user makes a call, he does not know or care what frequency he is using. The talkgroup replaces the channel. DSS and Trunking are a logical match for future communications. For an executive overview of radio trunking see Attachment G.

**1.3 Feedline, Antennas, and Propagation**

**1.3.1 Feedline Basics**

There are several ways to transport power to, (or 'feed'), an antenna. Several popular methods are Twin-lead, Coaxial Cable (Coax), and Waveguide.

Twin lead is simply two conductors held in constant, two-dimensional separation. An example of twin lead is used for TV. Twinlead is typically high impedance, (300 or 600 Ohm). Coaxial cable is probably the most common form of feedline. The characteristic impedance is normally either 50 or 75 Ohm. Several common uses for 75 Ω Coax are Television antenna feedline, cable TV, and PLC data highway. 50 Ω Coax is used more frequently for transmitting RF. Coax is especially suitable for transmitting since it does not tend to radiate spuriously when terminated. Waveguide is used when frequencies get high enough where Coax is lossy and dimensions get practical. A waveguide is nothing more than tubing or pipe, but it is generally rectangular. The 'height' or the diameter of a waveguide must be just over half the wavelength.

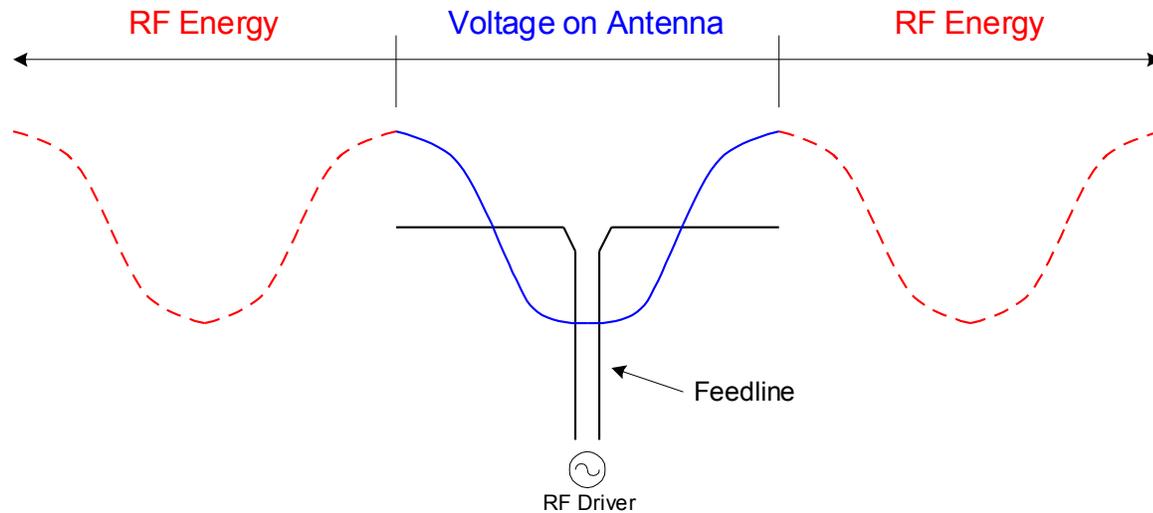
Coaxial cable comes in several types and in varying quality. For lowest loss, a gas filled type such as Heliax<sup>7</sup> is used. Most common is the foam dielectric type. If a gas filled cable is used, it must be filled with dry gas such as helium, nitrogen or air. If air is used, the dryer must be properly maintained.

Coax cable installation is not permanent. Even if the deer hunters miss the tower, lightning will not. Lightning can perforate the cable jacket and allow for the ingress of moisture. Moisture will corrode the braid or corrugated outer conductor. Also, plastics deteriorate with age. Coax in poor condition can rob an installation of critical power. Coax should be checked periodically for damage.

**1.3.2 Antenna Operation and Types**

RF waves are sine waves that leave an electronic circuit and propagate into the atmosphere or free space. The equipment used for the intentional transition between a RF oscillator and RF propagation is called an antenna or aerial. The antenna is actually a tuned circuit working against an earth ground, or equivalent.

<sup>7</sup> Registered trademark of Andrew Corp.



**Figure 1-7: RF Voltage on Antenna**

The end(s) of an antenna are designed or intended to be at the point of maximum RF voltage, (minimum RF current). If RF runs out of metallic conductor at a RF voltage peak, it just keeps going.

Antennas come in many types and forms. The type and form depends upon the application and other practical matters. The main practical matter is wavelength.

A RF sine wave has two components; electric and magnetic. These components are physically 90 degrees apart. The orientation of the electric portion of the wave determines the polarization. The two most common polarizations are vertical and horizontal.

Generally speaking, the separation between vertical and horizontal polarization is at least a factor of 1/20 the power. That is, transmitting vertical and receiving horizontal does not work well.

### 1.3.3 Propagation

As previously stated, propagation is RF energy leaving the antenna. We shape and direct the propagated beam to suit our purposes. Our purpose is point-to-point communications. Simply put, we want narrow RF beams that are aimed accurately and have no obstacles in or near the path.

In radio bands typically down from 30 MHz, propagation is affected by the ionosphere. The ionosphere reflects these wavelengths back to the earth and provides long distance communications. The ionosphere is affected by the Sun's eleven year cycle. As sunspots increase, the ionosphere becomes "stronger", (various layers materialize or strengthen). A "stronger" ionosphere reflects even higher frequencies. The shortest wavelength that is reflected by the ionosphere during a solar activity maximum is around 2 meters or 150 MHz. This is a long way from microwave so it can be assumed that point-to-point microwave communications will not normally be affected indirectly by the Sun's activity.

Microwave propagation is affected by other natural phenomenon. These include temperature inversions, reflections, rain, fog, and clouds. 2.4 GHz DSS has several advantages over other microwave frequencies and techniques; it is reflection, (multi-path), resistant and raindrops are the wrong size, (see the paragraph on Rain Fade in 1.5.2). There is one additional possibility for interference, and it does come from the Sun. See the paragraph on Noise in 1.5.2.

**1.4 The Decibel**

Any prelude to a discussion of Path and Budget must start with an understanding of the decibel. Refer to the definition; in short, dB is a logarithmic way of representing a relative level. If something is relative, it has to relate to something else. For this reason, several standard references have been developed.

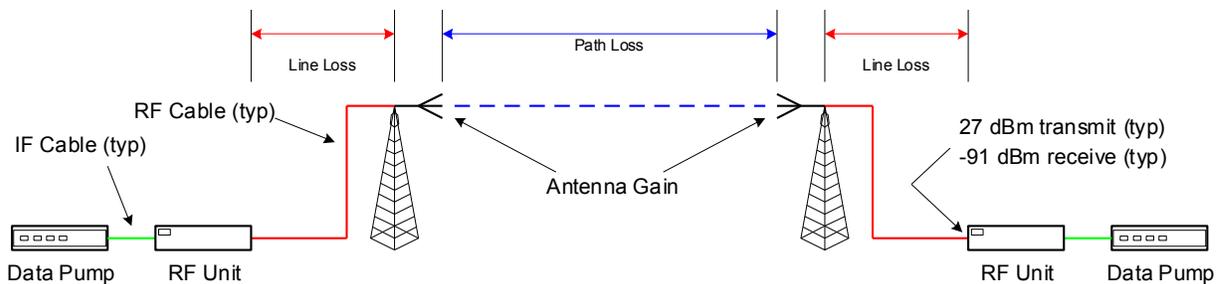
A dBa for instance is a dBa(djusted) for those frequencies most readily perceived by a human<sup>8</sup>. The reference level in this case is  $10^{-12}$  W/m<sup>2</sup>, which is considered to be the minimum sound level perceptible.

This discussion on the decibel is limited to Power.

There are some dB shortcuts. Examples: 10 dB down is 1/10<sup>th</sup> the power. 3 dB up is twice the power and vice-versa.

**1.5 Path and Budget**

Anything is a sum of its parts. A radio system must be able to receive a usable signal to operate. A radio system path is equal to the sum of its parts, and the bottom line must be usable. This minimum usable signal is called the budget. The sum of gains and losses in the path must be greater than the budget.



**Figure 1-8: Typical DSS Path**

**1.5.1 Gains**

Gain is power. There are three places where you can get power in a radio system. You add it up front, you back into it at the receiver, and you borrow, (re-direct), power at the antenna(s). The limitations are equipment and FCC related. For 2.4 GHz, the FCC limits the transmitter output to 1 Watt into the antenna, and the receiver is state-of-the-art. Antenna size, gain, and dollars are directly proportional, but they are not linear. With regard to cost, a 24 dBi gain antenna can be purchased for under \$200; an 8 foot dish can cost \$1400 in shipping charges alone.

Since transmitter gain is set by the FCC, and the receiver is doing its best, where do we get more power? The antenna cannot manufacture power so what do we mean by gain in an antenna?

Think of a theoretical, (isotropic), antenna as a light bulb sitting in the middle of a room. It radiates equally in all directions and illuminates all areas equally in Watts/unit area. If we put a mirror on one side of the light bulb, we immediately get more light on one side of the room and a shadow on the other. The amount of power output from the bulb is the same, but it has been re-directed. The effective power on one wall is greater than that on the other wall. You can bend the mirror into a

<sup>8</sup> Telephone systems and dBa measurements were not designed for females. The female ear has a different frequency response range.

parabola and concentrate a large portion of the light into one small area. The concentrated light on one point is effectively the same as cranking up the power to the light bulb. This concept is known as Effective Radiated Power, (ERP). In this example, the ratio between the Watts/unit area of the concentrated beam compared to the no mirror situation is the gain. We simply borrowed power going in the wrong direction and sent it in the right direction.

Figure 1-9: Concept of Gain

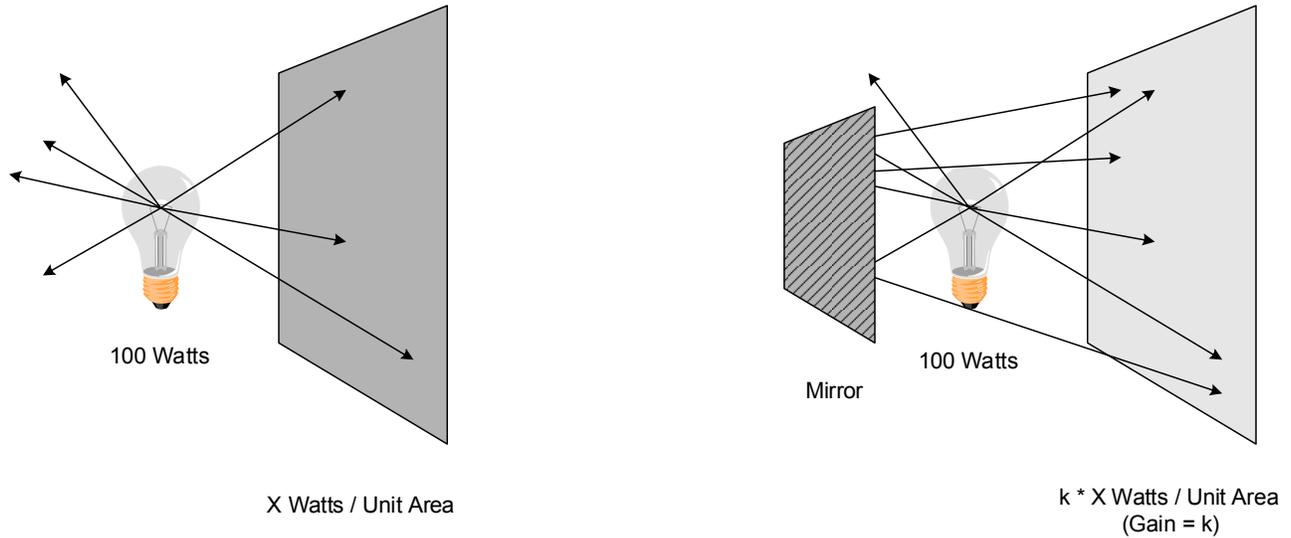


Figure 1-10: Parabolic Reflector and Gain

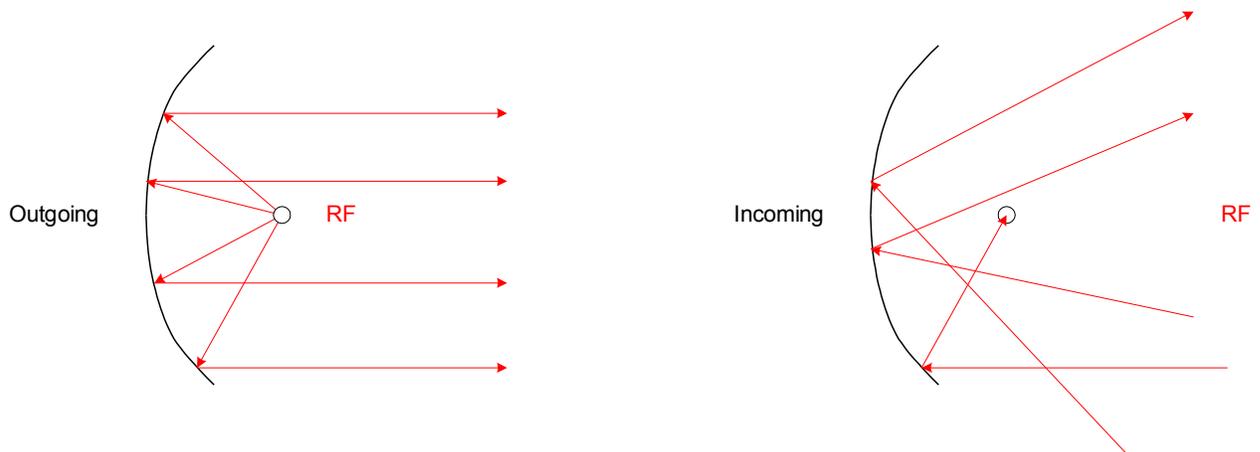
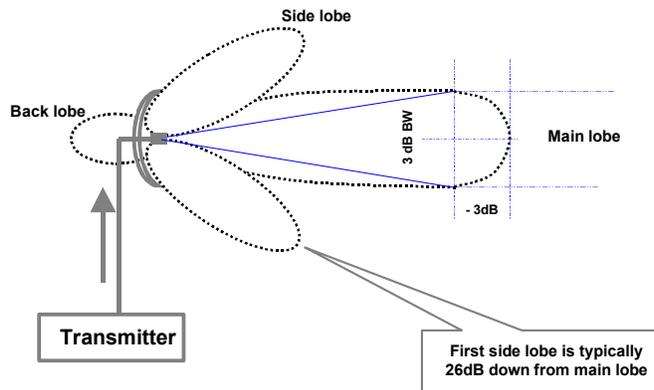


Figure 1-11: Parabolic Antenna Pattern



### 1.5.2 Losses

#### *Transmission Line*

In general, the higher the frequency, the more loss per unit length of transmission line. For our purposes, this is always the case. The transmission line should be a significant concern, and its design and maintenance is within our control.

Coaxial cable does not last forever. The environment, (lightning, moisture, birds, and bullets), cause deterioration. Regular testing is prudent.

Each transmission line connector represents a loss. A good rule-of-thumb is 1 dB per connector. Connectors must be made up properly, and the number should be kept to a minimum.

#### *Reflection and Mismatch*

If impedances in the radio, transmission line, and the antenna do not match, some transmitter power will be reflected back down to the radio. The energy is lost as heat. Also, if the antenna's resonant frequency does not match the operating frequency, power cannot be transferred efficiently. These are potential losses we can prevent.

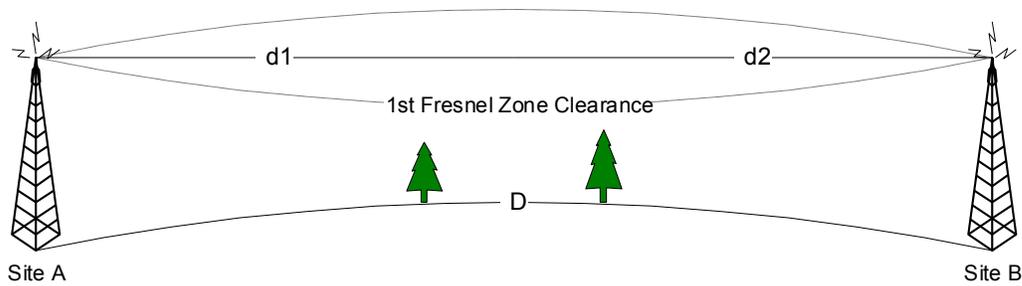
#### *Free Space*

The workable path for VHF frequencies up through microwave is essentially line-of-sight. Unlike longer waves that can bounce off layers in the ionosphere and return to earth at great distances, higher frequency waves tend to get dissipate quickly. Also, the higher the frequency, the more likely objects in or close to the path will affect communications.

The path is often set or fixed by factors outside our control. The calculation of free space path loss is straight-forward.

#### *Fresnel Zone*

The Fresnel Zone is a series of imaginary ellipsoid surfaces that surround the straight line path between two antennas. See the definition in Attachment A. It is important to design a path such that objects are outside the first Fresnel Zone. As a practical matter, it is sufficient to have 60% of the first Fresnel Zone clearance for a path to approximate free space loss. If the required 60% clearance is not obtained, path losses can be significant but difficult to quantify.



**Figure 1-12: Fresnel Zone**

Even if a path is designed properly, new construction and tree growth can enter the 60% clearance zone and cause a good hop to go bad.

Note: 1st Fresnel Zone clearance can be approximated at any point<sup>9</sup> along a path by use of the following formula:  $h = 72.1 (d_1 * d_2 / f * (d_1 + d_2))^{1/2}$  where h is in feet,  $d_1$  and  $d_2$  are the distances in miles from any point along the path to each end respectively, and f is the frequency in GHz. In Figure 1-12, h is the distance from the solid line between the tower tops to the lower (or upper) clearance line.

### Noise Level

The sensitivity of a receiver is referenced against a noise level. If a noise level at the receiver's frequency, (or intermediate frequencies), is increased, the receiver's performance is degraded.

Noise is caused by a myriad of sources, manmade and natural. Manmade noise can be from electric motors, microwave ovens, and other transmitters. Natural noise comes from the earth's changing magnetic field, lighting, static electricity, and space, (especially the sun). Noise is typically AM in nature and vertically polarized.

### Rain Fade

Rain Fade is absorption or refraction of a signal due to rain. It is generally not specifically considered for systems below around 6 GHz. The amount of loss increases significantly with frequency through 20 GHz and then decreases.

For example, if we assume a 20 mile hop and a 4 in/hr rain, the Rain Fade losses are approximately:

- 2.4 GHz 1.25 dB
- 6.0 GHz 3.2 dB
- 20 GHz 300+ dB
- 30 GHz 190 dB

### 1.5.3 Fade Margin and Path Availability

Fade Margin is the allowance you are left with after considering all the factors in the path including what the receiver can faithfully recover without error, (receiver sensitivity). Fade Margin is equal to the absolute value of the receiver sensitivity<sup>10</sup> less the Received Signal Level, (RSL). Since we can only deal with factors we are aware of, Fade Margin should be kept as high as possible by design to compensate for unknown factors and transient anomalies. For a reliable, available path, Fade Margin should be at least 30 dB.

<sup>9</sup> Not accurate at the ends of the path.

<sup>10</sup> We take the absolute value of the receiver sensitivity because it is expressed as a negative by custom. It is actually a gain.

Fade Margin is tied directly to path availability. This course will not go into the details of path and system availability but the following is presented for information in understanding the main factors that determine the availability of the path.<sup>11</sup>

$$\text{Availability} := 1 - (C * T * 2.5 * 10^{-6} * f * D^3 * (10^{-F/10})) * 100\%$$

Where

- C := Climate Factor (0.125 for very dry, 0.25 for temperate, and 0.5 for humid)
- T := Terrain Factor (4.0 for smooth, 1.0 for average, and 0.25 for mountainous)
- f := frequency (GHz)
- D := path Length in miles
- F := Fade Margin (actual excess path margin)

It can be seen that availability decreases as C, T, f, and D increase. In general, we cannot change these factors. Therefore, the only way to increase availability is to increase Fade Margin.

To illustrate the effect of Fade Margin on availability, see the following:

**Table 1-13: Path Availability**

Fade Margin	Availability	Loss Time	
		sec/yr	min/yr
40	99.9998	47	0.78
30	99.9989	405	6.75
20	99.987	3972	66.2
15	99.96	12542	209
10	99.87	39641	661 (11 hours)

<sup>11</sup> AdTran

## 2 Spread Spectrum

### 2.1 Introduction

Actress Hedy Lamarr invented spread Spectrum Radio in 1940<sup>12</sup>. Miss Lamarr and composer George Antheil refined their idea, based on a player piano, and submitted it for patent. A patent was granted, but the US Government, due to military implications, immediately classified it. Military spread spectrum techniques were de-classified in 1985.

Today, Spread Spectrum is used for GPS, Wireless LANs, PCS, cordless phones, and point-to-point communications.

### 2.2 Basics

The more information applied to a carrier wave, the wider the bandwidth of the carrier. In a "channelized" world, this is bad. With spread spectrum, the bandwidth is intentionally increased, and the amplitude is decreased. The spreading is accomplished by multiplying the information signal with a higher rate bit-sequence.

In Spread Spectrum systems, users can transmit in the same spectrum simultaneously. The frequency of the data-signal is spread using a code, (bit-sequence), unrelated, (not correlated), to the signal. Because the codes used for spreading have low cross-correlation values and are unique to each user, the bandwidth occupancy factor is greatly increased. A spread spectrum receiver hearing another spread spectrum transmitter on the same frequency but using another spreading code hears nothing but noise.

There are several advantages to Spread Spectrum.

- Low spectrum power density
- Privacy/Security due to coding
- Reduced multi-path effect
- High jamming and interference rejection

### 2.3 Techniques

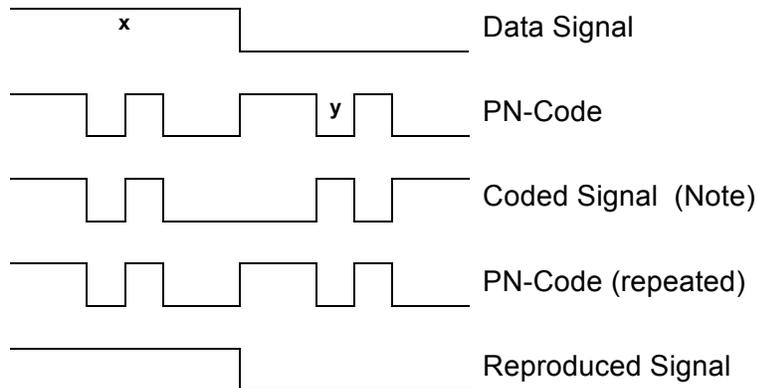
There are several techniques or protocols used to "spread" a signal. Some of these techniques are Direct Sequence, Frequency Hopping, and Time Hopping. Direct Sequence is currently the best known technique and the only technique currently allowed in the 2.4 GHz ISM band.

In Direct Sequence, the data signal is multiplied by a Pseudo Random Noise Code or PN-code. A PN-code is a spreading sequence of "chips" that have noise-like properties. The PN-code has a fixed length; after a given number of bits, the PN-code repeats itself exactly.

Figure 2-1 gives an example of Direct Sequence coding.

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<sup>12</sup> See Endnotes: Hedy Lamarr Inventor

**Figure 2-1: Direct Sequence Spreading**

x = 1 bit period

y = 1 chip period

Note: There is no correlation to the Data signal.

In Boolean<sup>13</sup> mathematics, if an information bearing bit-stream is multiplied by another bit-sequence and the resulting product is again multiplied by the same bit-sequence, the original bit-stream is reproduced. In Figure 2-1 above, the PN-Code is multiplied with the Data Signal producing the Coded Signal. A second multiplication using the same PN-Code produces a duplicate of the original Data Signal. This is how a Data Signal is reproduced at a receiver.

A typical modulation technique for Direct Sequence DSS radio is DQPSK or Differential Quadrature Phase Shift Keying or  $\Pi/4$  offset PSK. Refer to paragraph 2.2.4 on Phase Modulation. In DQPSK, the phase is shifted by 90 degrees giving four possibilities, (quadrature). The advantages of this type of modulation are spectral efficiency, fast access time, and ease of demodulation without a reference timer.

Note: The Frequency Hopping technique is self-describing, but it has several disadvantages:

- It does not lend itself to high Processing Gain.
- It has a slower access time.

## 2.4 Processing Gain

An important factor in DSS systems is the Processing Gain. This is the received signal fidelity gained at the cost of bandwidth. It is defined<sup>14</sup> as:

$$C = W \log_2 (1+S/N)$$

where

C := capacity in bps      and      W := bandwidth in Hz

S/N := Signal to Noise ratio

<sup>13</sup> George Boole, 1815 - 1864. His contemporaries could not see a use for his binary math.

<sup>14</sup> Virginia Polytechnic Institute

It can be readily seen from this formula that capacity will increase with bandwidth and the signal to noise ratio has little effect. Therefore, S/N can be reduced with little or no effect on BER. Viola, low power.

In summary, Processing Gain is the ratio of transmission bandwidth in Hz and information capacity in bps. Also, Processing Gain is essentially the Spreading Factor. The higher the ratio the better, but, the FCC places limits on certain applications. For a comparison of specs on several manufacturers, see Attachment C.

## 2.5 Guidelines, Troubleshooting, and Testing

### 2.5.1 RF Unit Location

Manufacturers make a RF unit designed for outdoor use. The recommended placement is as close as possible to the antenna, (tower mount). Note: some manufacturers make a rack mount RF unit for special cases where there is a short distance from the communications equipment room to the antenna.

### 2.5.2 Polarization

Use horizontal as default whenever possible.

### 2.5.3 Co-location

1. If two systems in the same band are operating at the same site, the antenna polarity of one system should be set to horizontal and the other to vertical. This can provide 20 to 30 dB of isolation.
2. Use a minimum of 10 feet of vertical separation between the antenna grids.
3. If the two systems are of the same manufacturer, set the **transmitters** to the same band plan or frequency and set each to a separate spreading code.
4. If the two systems are from different manufactures, set the transmit frequencies as close as possible and use different spreading codes.
5. Note: In accordance with CFR 47, Part 15.247, you cannot co-locate two systems transmitting **identical** information.

### 2.5.4 Dealing with Interference

1. Identify the interference with a spectrum analyzer.
2. Change the frequency plan (A to B or B to A)
3. Change polarization
4. Change the spreading code
5. Beam offset. A 2 to 3 degree offset can reduce interference and can still provide a reliable path.
6. Narrow the beam-width by using a larger antenna.
7. Shorten the path.

### 2.5.5 Weatherproofing Connectors

1. Insure fittings are hand tightened.
2. Wrap securely with electrical tape.
3. Wrap with weatherproofing compound.
4. Wrap again with electrical tape.

## 2.6 FCC issues

### 2.6.1 General

In 1934, a Communications Act was passed by Congress. The implementation of this Act took into consideration international standards and requirements. Regularly scheduled international conferences are held to amend the agreements on spectrum usage and other communications issues. The Communications Act of 1934, as amended, is still the basis of FCC regulation. Violation of FCC Rules and Regulations carry punishments ranging from loss of license through fines to a run at the tennis courts in a federal facility or all of the above.

The 1959 Geneva Convention defined harmful emission as "any emission which endangers the functioning of a radio navigation service or other safety service or degrades or obstructs or interrupts a radio communication service" and makes such harmful interference "subject to legal action".

### 2.6.2 DSS

The FCC has established three frequency bands for unlicensed services. These are 902-928 MHz, 2400-2483 MHz, and 5725-5850 MHz. The most popular band is 2.4 GHz because of the bandwidth/dollar ratio.

With regard to power and ERP, the FCC has several requirements. First<sup>15</sup>, maximum peak output power of the "intentional radiator" shall not exceed 1 W. Second<sup>16</sup>, for fixed, point-to-point systems with over 6 dBi of directional gain, the maximum peak output power of the intentional radiator must be reduced by 1 dB for every 3 dB of directional gain in excess of 6 dBi. Under the first requirement the limitation is 30 dB, (1 W), into a 6 dBi antenna or 36 dB. The first requirement is superceded and relaxed by the second requirement.

To illustrate the second FCC rule referenced above, assume an installation has an 8 ft grid dish with 33 dBi of gain and 6 dB of transmission line loss. This antenna has 27 dBi of gain in excess of the rule's 6 dBi. For every 3 dB of this 27 dBi we must reduce the power by 1 dBm. We must therefore reduce the power at the intentional radiator by 9 dBm. 9 dBm down from the maximum allowed of 30 is 21 dBm. The maximum allowable EIRP of the installation is therefore 21 dB + 33 dB or 54 dB.

#### Notes:

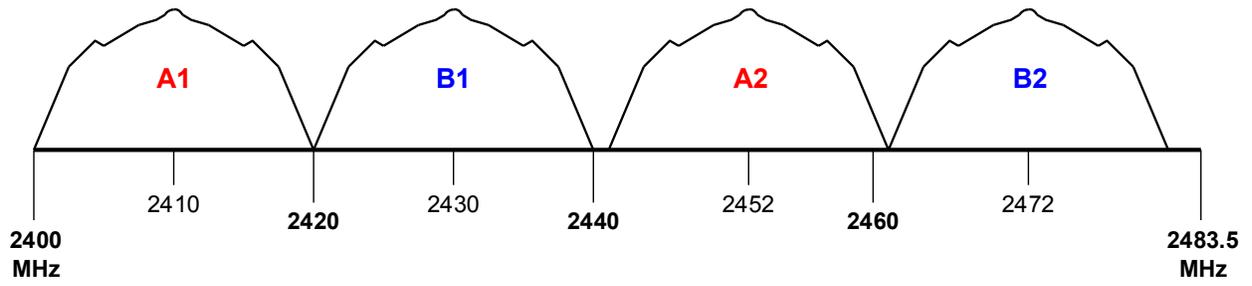
- The FCC code for digital spread spectrum equipment is DSS.
- 2.4 GHz is a part of the ISM band.
- The 2.4 GHz band is unlicensed but regulated under Title 47, Section 15.247 of the CFR. Refer to Attachment E.
- As stated above, you cannot co-locate two systems transmitting **identical** information.

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<sup>15</sup> Title 47 CFR, Ch 1, Section 15.247 (b)(1), Edition 10/1/97

<sup>16</sup> 15.247 (b)(3)(i)

Figure 2-2: 2.4 GHz Bandplan



## 3 Grounding & Lightning Protection

### 3.1 Overview

**DANGER**  
**50,000  $\Omega$**

This warning may seem ridiculous at first glance, but not with regard to grounding. Personnel safety, equipment protection, and equipment operation are tied to grounding<sup>17</sup>.

Improper grounding manifests operational problems. These problems include damaged equipment and anomalous errors. These errors may be very difficult to track, so, if you find yourself in a data-error situation that you can't explain, go back to basics and check your system grounding. **A good single-point grounding system is also a noise reduction and EMI/RFI reduction system.**

### 3.2 Lightning Protection

#### 3.2.1 General

A properly designed lightning protection and grounding system should take into account the probability of a large lightning strike. There are numerous ways a strike can damage equipment. Unwanted voltages can enter a communications building via conduction or induction. Conduction via voltage splits comes in on copper or other metal entering the building. For induction, a strike will cause a tower, (or other object), to radiate RF energy. The near field, (magnetic field), produced from the strike will be cut by equipment interconnecting wiring, and voltages will be induced. By using the right installation techniques, the right ancillary equipment and proper grounding, lightning damage can be prevented.

Note: For a lightning protection and grounding system to work, IT MUST BE MAINTAINED. Maintenance includes testing protectors, measuring the ground system, pulling on ground rods, and inspection/cleaning of connections.

#### 3.2.2 Equipment Protection and Techniques

##### *Coaxial Cable*

Refer to paragraph 8.2.3. Coaxial cable grounding kits should be installed where the coax leaves the tower, at the 150 foot level, and every 100 feet up the tower.

Coaxial cable lightning protectors are available but care must be taken in selection and placement. Coax cable between the data pump and the RF Unit (IF cable) carries a DC voltage to the RF unit. Some lightning protectors do not pass DC. A typical lightning protector for the RF coax would be a PolyPhasor Model IS-ML50LN. And for the IF coax, use a Huber Suhner Model 3401.17A or equal.

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<sup>17</sup> Pardon the pun.

### *Tower Grounding*

All radials associated with tower grounding should be run away from the equipment shelter. The more radials there are, the more the voltage is divided, (and the less the voltage will reach the equipment shelter ground). The equipment shelter ground should have only one connection to the tower base, and that should be just below the coax cable runs. Re-bar in the concrete should have been used to augment the grounding system.

### *Other Suggestions*

- For a new installation, don't place the communications shelter too close to the tower.
- Use a copper bulkhead plate for shelter cable entrance. Run the coax through the plate with a grounding kit and add a protector (when possible). The connection from the bulkhead plate to the ground should have as large a surface area as the combined surface areas of the coax cables.
- Protect all metallic inputs and outputs to the shelter at the shelter entry or exit point.
- Use the best quality in-line protectors available. They pay for themselves.
- If it looks metallic, ground it.

### *Things that don't Work, don't Help, and can be Counterproductive*

The following list is controversial and arguable, but this author feels the position against the use of these devices is technically sound.

- Lightning rods on the tower
- No-concrete tower bases
- Copper ground wires run up the tower
- "Whisker brushes" and other dissipation devices

Just follow sound grounding and protection practice and these 'snake-oil' remedies are not required.

## **3.3 Grounding Standards**

Grounding is described in several reference documents<sup>18</sup>. Following are some grounding quips and quotes.

- Section 810 of NFPA 70 (NEC) covers radio grounding.
- Compliance with the NEC "does not imply that adequate grounding will be provided to ensure continued performance of electronic equipment and systems without mutual interference; or that a quiet ground structure will be provided to allow equipment to be isolated from external interference, either conducted or radiated".<sup>19</sup>
- TIA/EIA 607 specifies the requirements for a uniform telecommunications grounding and bonding infrastructure that shall be followed within commercial buildings where telecommunications equipment is intended to be installed. See Attachment D.
- UL 1459

The following is derived and paraphrased from the Underwriter's Laboratory Standard 1459 for Telephone Safety.

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<sup>18</sup> EIA/TIA 222 (Section 12, Protective Grounding), NEC, EIA/TIA 607

<sup>19</sup> EIA/TIA 569

An equipment grounding conductor that is no smaller in size than the ungrounded branch-circuit supply conductor(s) must be installed as part of the circuit that supplies the product or system, (T1 Radio).

The attachment-plug receptacles in the vicinity of the product or system must be of the grounding type, and the equipment grounding conductors servicing these receptacles must be connected to earth ground at the service equipment.

A supplementary equipment grounding conductor must be installed between the product or system and ground that is in addition to the equipment grounding conductor in the power supply wiring.

The supplementary equipment grounding conductors must not be smaller in size than the ungrounded branch-circuit supply conductors. The supplementary equipment grounding conductor must be connected to the product at the terminal provided, and shall be connected to ground in a manner that will retain the ground connection when the product is unplugged from the receptacle. The connection to ground of the supplementary equipment grounding conductor shall be in compliance with the rules for terminating bonding jumpers at Part K or Article 250 of the NEC, NFPA-70.

A good single-point grounding system is also a noise reduction and EMI/RFI reduction system.

## 4 Notes

### 4.1 Reference Information and Data

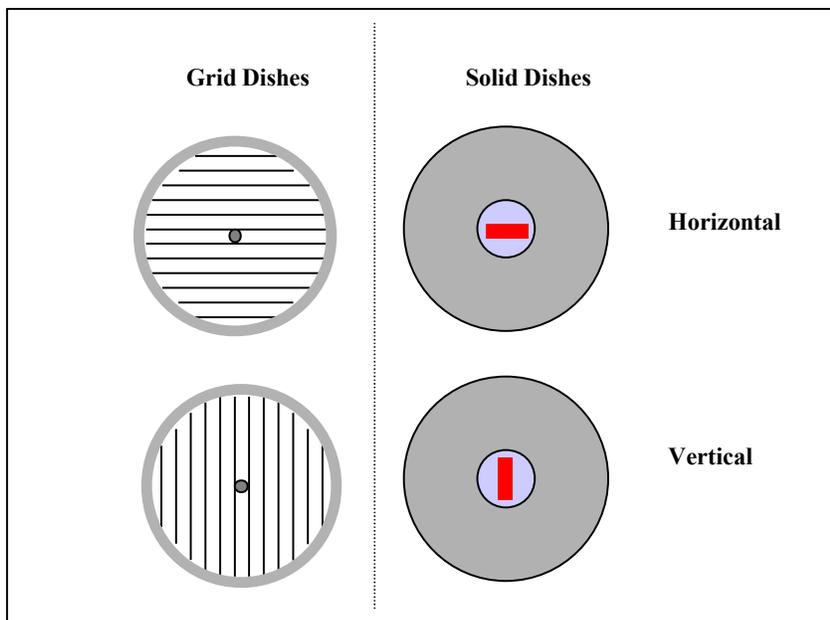
#### 4.1.1 Typical Dish Antenna Information

Table 4-1

Diameter	Gain (dBi)	3 dB beamwidth
18 inch	18.08	19 deg
4 foot	27.32	7.17 deg
6 foot	30.84	4.76 deg
8 foot	33.34	3.57 deg
10 foot	35.28	2.85 deg
12 foot	36.86	2.38 deg
30 meter	54.999	0.309 deg

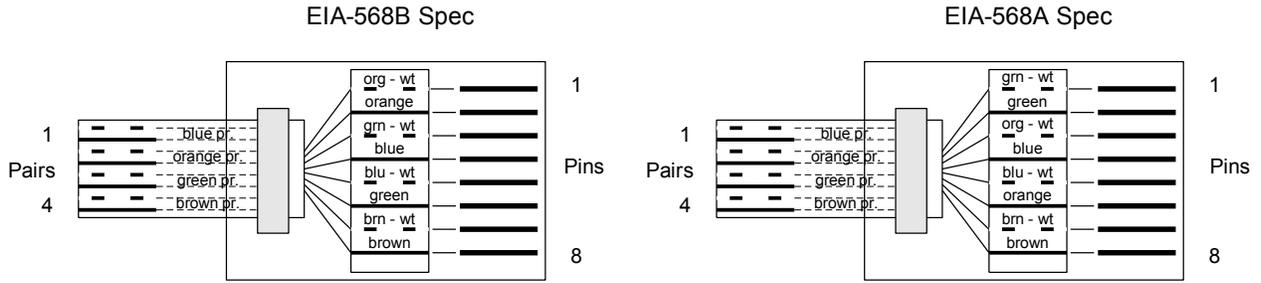
#### 4.1.2 Dish Polarization

Figure 4-2



4.1.3 Cat-5 & RJ-45 Wiring

Figure 4-3



"B" Spec is most common.

4.1.4 Approximate Free Space Path Loss for 2.4 GHz

Table 4-4

Distance in Miles	Loss in dB
1	104.2
5	118.2
10	124.2
15	127.7
20	130.2
25	132.2
30	133.7
35	135.1
40	136.2

Formula:  $L_{fs} \text{ (dB)} = 96.6 + 20 \text{ Log}_{10} D \text{ (miles)} + 20 \text{ log}_{10} f \text{ (GHz)}$

## 4.1.5 Metric Numerical Symbols

Table 4-5

Multiples & Sub's	Prefix Name	Symbol
1,000,000,000,000 ( $10^{12}$ )	tera	T
1,000,000,000 ( $10^9$ )	giga	G
1,000,000 ( $10^6$ )	mega	M
1,000 ( $10^3$ )	kilo	K
100 ( $10^2$ )	deka	dk
0.1 ( $10^{-1}$ )	deci	d
0.01 ( $10^{-2}$ )	centi	c
0.001 ( $10^{-3}$ )	milli	m
0.000001 ( $10^{-6}$ )	micro	u
0.000000001 ( $10^{-9}$ )	nano	n
0.000000000001 ( $10^{-12}$ )	pico	p

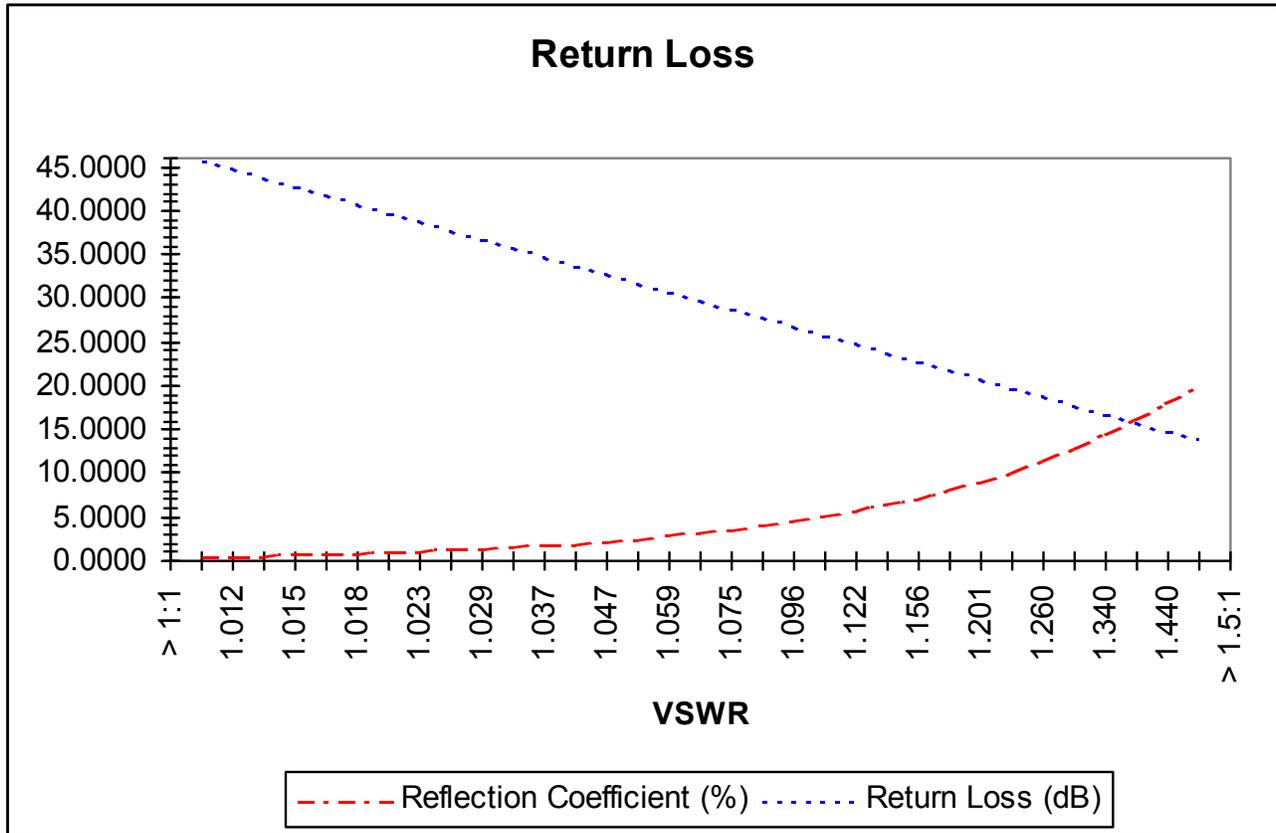
## 4.1.6 Power Relationships

Table 4-6

dBm	mW (W)	dB	mW
<b>50</b>	<b>100,000 (100)</b>		
<b>40</b>	<b>10,000 (10)</b>		
<b>36</b>	<b>3,981</b>		
<b>30</b>	<b>1000 (1)</b>		
29	794.3	19	79.43
28	630.96	18	63.096
27	501.2	17	50.12
<b>26</b>	<b>398.1</b>	<b>16</b>	<b>39.81</b>
25	316.2	15	31.62
24	251.2	14	25.12
23	199.5	13	19.95
22	158.5	12	15.85
21	125.9	11	12.59
<b>20</b>	<b>100</b>	<b>10</b>	<b>10</b>

4.1.7 Return Loss

Figure 4-7



Definitions<sup>20</sup>

Return Loss, (RL), is the decibel power ratio of the incident power to the reflected power.

$$RL = -20 \log_{10} (\Gamma) \quad \text{dB}$$

Reflection Coefficient, ( $\Gamma$  for Rho), is the numerical ratio of the reflected voltage to the incident voltage.

$$\Gamma = \frac{VSWR - 1}{VSWR + 1} \quad \%$$

or

$$\Gamma = \text{antilog}_{10} ((-RL) / 20) \quad \%$$

Voltage Standing Wave Ratio, (VSWR), is the numerical ratio of the maximum Voltage to the minimum Voltage that would exist on a uniform reference transmission line.

$$VSWR = \frac{1 + \Gamma}{1 - \Gamma}$$

4.1.8 Corrosion

When dissimilar metals are brought in contact, care must be given to the types of metals used in order to minimize or prevent bimetallic corrosion. Corrosion is formed when the metallic contact is subjected to moisture; it can be enhanced when current flows. The results can be high resistance grounding and intermittent connection problems. Care should be taken to ensure that metals of similar galvanic

<sup>20</sup> Andrew Corp.

activity are placed in contact. See the following list of metals rated from anode (lower numbers) to cathode (higher numbers). If possible, avoid contact between metals not adjacent to each other in the list. If this is not possible, protect from moisture or mitigate by plating or coating.

**Table 4-8: Electrical Activity of Metals**

1)	Magnesium	-1.75
2)	Zinc	-1.10
3)	Aluminum (pure)	-0.80
4)	Aluminum Alloy	-1.05
5)	Cadmium	
6)	Iron or Steel	-0.2 to -0.8
7)	Stainless Steel	
8)	Lead-Tin Solders	
9)	Lead	-0.50
10)	Tin	
11)	Nickel	
12)	Brass	-0.20
13)	Copper	-0.20
14)	Monel	
15)	Silver	
16)	Gold	
17)	Platinum	
18)	Carbon	+0.30

If you choose two substances in Figure 4-8, electrically bond them, and place them in electrolyte, you can observe a produced voltage equal to the difference in the substance potential. The potentials for several are listed. For example, A carbon graphite rod and a magnesium rod immersed in electrolyte will produce a measure voltage of 2.05 Volts.

Note that Revision F changes to EIA/TIA 222 address corrosion. See the following points

- Copper ground rods are changed to Galvanized Steel.
- Buried ground wire is changed from 'bare' to 'tinned' copper.
- Language is added to alert tower purchasers of their responsibilities toward specifying corrosion control when required.
- Change in tower inspection criteria to include questions addressing existing corrosion on tower anchors as well as corrosion control measures on tower anchors.
- Changes relating to soil investigation specifying the inclusion of analysis of soil for corrosivity.
- Appendix J entitled "Corrosion Control Options for Guy Anchors in Direct Contact with Soil". This appendix addresses cathodic protection.

#### 4.1.9 Lightning Information

<sup>21</sup>A lightning strike begins with a local breakdown of the atmosphere. It 'steps' about 150 feet in 1  $\mu$ s increments every 49  $\mu$ s. During each 49  $\mu$ s 'dormant' stage, an imaginary hemisphere of 150 foot radius can be used to determine the next jumping distance. Any object, such as a tower or side-mounted antenna, that penetrates this hemisphere, can be chosen as the point of attachment for the return stroke, (lightning strike).

<sup>21</sup> Paragraph Paraphrased from PolyPhasor.

Lightning is an electrical and a mechanical phenomenon. The creation of the lightning path, (local breakdown of the atmosphere), has a mechanical component. Physical forces are exerted in the path. Momentum is developed. Lightning does not like to turn corners; there is too much momentum. There is momentum in gas molecules being displaced and there is momentum in the current.<sup>22</sup> Luckily, we do not have to deal with the “main bolt”, we have to deal with its consequences. That is, when lightning hits a tower for instance, it splits into various paths depending upon resistance. We design systems so we only have deal with the smallest 'splinter'.

Lightning facts:

- Lightning can produce a potential of 100,000 Volts
- Lightning can cause a current of 40,000 Amps
- Lightning can generate temperatures of 50,000 °C
- Lightning can travel 40 miles

100,000,000 Volts at 40,000 Amps =  $4 \times 10^{12}$  Watts or 4,000,000,000 kW. Assuming a 1 second strike at this power level, we have 1,110,000 kWh. At \$0.17 per kWh we have \$188,700 of sales potential.

Remember when we discussed the creation of RF by excitation. Lightning produces electromagnetic radiation across the entire spectrum (DC to Daylight).

#### 4.1.10 Hedy Lamarr, Inventor<sup>23</sup>

“Actress devises ‘red-hot’ apparatus for use in Defense. Hedy Lamarr, screen actress was revealed today in a new role, that of an inventor. So vital is her discovery to national defense that government officials will not allow publication of its details. Colonel L. B. Lent, chief engineer of the National Inventors Council, classed Miss Lamarr’s invention as in the ‘red hot’ category. The only inkling of what it might be was the announcement that it was related to remote control of apparatus employed in warfare.”

#### 4.1.11 The Infamous Zimmermann Telegram

Before U. S. entered the war, German Foreign Minister Zimmermann sent a telegram to the German Ambassador in Washington, via three routes: via radio-telegram direct to North America, via Sweden, and by the American embassy in Berlin via the U. S. embassy in Copenhagen and thence to Washington. The message was in a German diplomatic code. British cryptanalysts had received copies from all three routes, and had cracked the code in their legendary Room 40 in the Admiralty. While they knew the provocative contents of the telegraph, they needed a way to reveal it to the U.S. government without letting the Germans know that they had the ability to read essentially all of their diplomatic cable traffic. With the help of an employee in the Mexican Telegraph Office, a British agent in Mexico had obtained a copy of the telegram which had been forwarded from Washington to Mexico City, with minor changes from the original cable. This they handed over to the U.S. Government, and the Germans believed that they intercept had taken place in North America, not in Europe. In it, the Germans attempted to incite the Mexican government to enter the war against the U. S., promising them Texas, New Mexico, and Arizona as their prize. The telegram's existence helped to bring the U.S. into the war.

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<sup>22</sup> Electrons have mass, and they drift through a conductor at a velocity of approximately 17 feet/second. This drift is not to be confused with the charge that travels at the speed of light.

<sup>23</sup> New York Times, dateline Hollywood, September 30<sup>th</sup>, 1940

## 4.1.12 Schrödinger's Cat

Many barroom disagreements have revolved around whether the theoretical cat is 1-dead, 2-alive, or 3-neither/both. The Internet is recommended for further reading on this subject. Keep in mind however that physicists at the National Institute of Standards and Technology, (NIST), trapped a single beryllium ion in an electromagnetic cage, excited it into a superposition of internal electronic quantum states, and then eased those two states apart so that the atom appeared to be in two distinct physical locations simultaneously. This lends credence to the possible dual state of the cat's well being, but, as a practical matter, the theoretical cat is theoretically dead.

Ω