AN INTRODUCTION TO TELEMETRY

PART 1: TELEMETRY BASICS

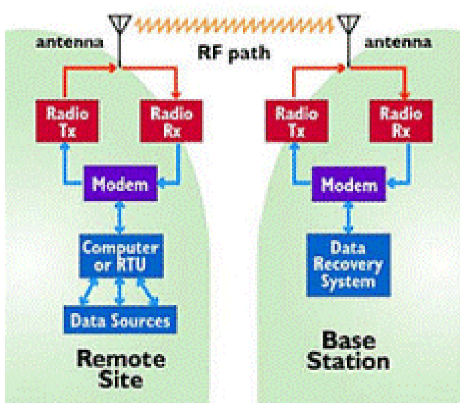
Telemetry is defined as the sensing and measuring of information at some remote location and then transmitting that information to a central or host location. There, it can be monitored and used to control a process at the remote site.

The basic concept of telemetry has been in existence for centuries. Various mediums or methods of transmitting data from one site to another have been used. Dataradio provides a wireless method for transmitting the information. Telemetry using radio waves or wireless offers several distinct advantages over other transmission methods. Some of these advantages are:

- No transmission lines to be cut or broken.
- Faster response time
- Lower cost compared to leased lines
- Ease of use in remote areas where it is not practical or possible to use wire or coaxial cables
- Easy relocation
- Functional over a wide range of operating conditions

Properly designed radio links can provide low cost, effective and flexible data gathering systems that operate for many years with very little maintenance.

COMPONENTS OF A TYPICAL WIRELESS TELEMETRY SYSTEM



At the remote site, a sensor or sensors are typically the data source. The output of the sensor(s) is converted to digital data by a small computer device or RTU (Remote Terminal Unit). The RTU is interfaced to a modem device that converts the digital data into an analog signal that can be transmitted over the air. The radio transmitter then transmits the signal to the host site radio receiver. Now the process is reversed. The modem takes the analog signal received and converts it back to a digital form that can be processed by the data recovery equipment.

In a typical application, the base or host site requests data from the remote site(s). The base transmits a request to the remote unit telling it to send its data. The base reverts to a receive mode and awaits the transmission from the remote site. After the remote sends its data, it goes back to a receive mode waiting for further instructions to come from the base. Once the base receives the remote site information, it may send additional instructions to that site or continue on to request data from the next remote site. This polling process continues until all the remotes in the system have sent their data.

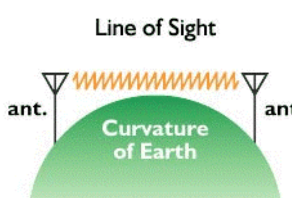
PART 2: RADIO PROPAGATION - SENDING DATA THROUGH THE AIR

Radio waves are propagated when the electrical energy produced by the radio transmitter is converted into magnetic energy by the antenna. Magnetic waves can then travel through space. The receiving antenna then intercepts a very small amount of this magnetic energy and converts it back into electrical energy that is amplified by the radio receiver. Thus, sending information through the air.

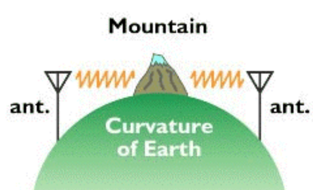
HOW FAR CAN DATA BE TRANSMITTED?

Propagation characteristics of radio waves are subject to many variables that affect the range and performance of a radio system. The main consideration is the loss in the transmission path between the transmitter and receiver. Factors effecting this loss are obstacles and power loss.

The most reliable system will employ a "line-of-sight" design where the radio wave travels directly from the transmitting antenna to the receiving antenna without obstructions as shown below left. However, the curvature of the earth limits the line-of-sight distance. If the transmitting and receiving antennas are too far apart, the earth will block the radio wave. The maximum line-of-sight transmission distance is determined by antenna height and may be limited by other obstacles as shown below.



Line-of-sight transmission



Line-of-sight obstacle

Once a transmission path is determined, signal power comes in to play. In general, signal power decreases in proportion to the square of the distance. For example, if the distance doubles, power decreases by four times. However, in actual practice, power drops off much faster because of attenuation caused by obstructions, trees, foliage, and other factors. This results in the power typically dropping off at a rate to the fourth power of the distance.

Predictions of radio range can be made using a free space isotropic nondirective antenna model where the path loss is 22 dB for one wavelength of separation between antennas and increases 6 dB every time the distance is doubled. However, this model holds true only in free space. Under actual conditions, other factors must be considered. Those other factors will be discussed in detail later on.

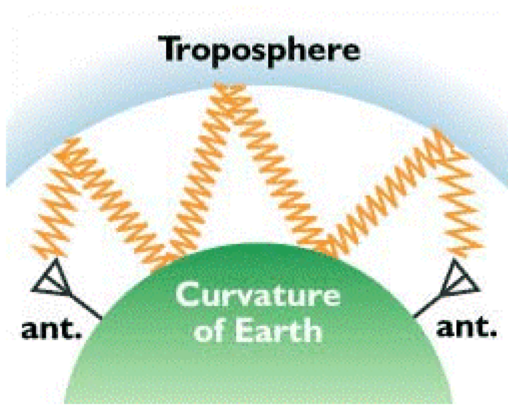
FREQUENCY BANDS

Telemetry radio systems are normally configured as a fixed base station that obtains information from another fixed station at a remote site. The FCC has allocated certain frequencies that can be used for fixed operation. There are certain frequencies available in the VHF band, UHF band and 900 MHz band for this type of operation.

VHF BAND (150-174 MHZ)

Man-made noise such as that from automobiles and power lines, and skip interference caused by radio waves reflecting off the ionosphere back to earth, are much less of a problem at the VHF frequencies.

Under certain atmospheric conditions, long-range transmissions can occur and cause interference. Normally, the dielectric constant of the atmosphere decreases with an increase in altitude. However, with some weather conditions, the opposite occurs. This causes the radio wave to be trapped between the earth and the maximum height of the radio wave path as shown at left. This is called guided propagation, or ducting, and causes the wave to travel much further than line-of-sight. This ducting occurs infrequently and may cause interference with direct wave signals.



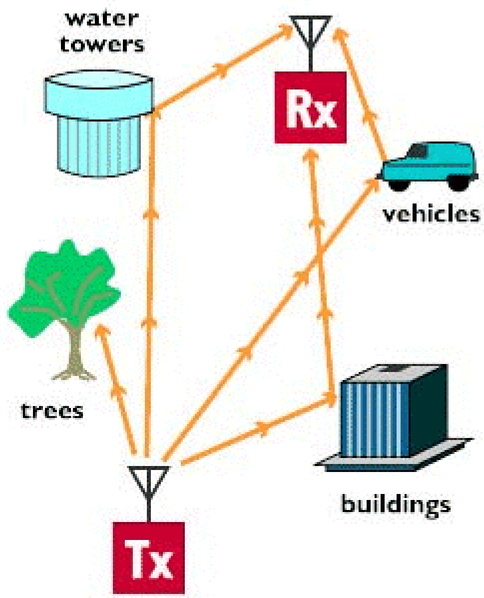
Propagation ducting

UHF BAND (450-470 MHZ)

This band is the one most often used in recent years because of the number of channels available. Range is not quite as good as at VHF, but this band is free of most man-made noise, skip interference and ducting effects. Absorption by trees and foliage causes a greater path loss, but penetration into buildings is better because the short wavelength signal has the ability to reflect off conducting objects.

900 MHZ BAND (928-960)

Skip Interference and ducting are insignificant in this band. However, foliage absorption of the short wavelength is greater which reduces range. In addition, moving objects in the communications path can cause fading due to multipath reception. Multipath reception occurs when the direct wave and a reflected wave arrive at the antenna at different phase angles. (See Below) This phase difference occurs because the reflected wave has to travel further than the direct wave. This causes canceling which weakens the received signal.



Multipath reception

Multipath reception can also occur at the lower frequencies, but is more of a problem at the higher frequencies because of the ability to reflect off objects increases with frequency. This problem is most common with communication between two moving vehicles or one moving vehicle and a fixed station. However, it can also occur when two fixed stations are communicating, if there are moving vehicles or other types of moving reflective objects in the communications path.

The preceding description highlighted some of the problems encountered in the various bands when radio waves are used to establish a telemetry link. Most of these propagation problems are not common occurrences, and there are usually engineering solutions to overcome them when they do occur.

For example, one thing that minimizes interference when FM (Frequency Modulation) receivers are used is a characteristic of these receivers call "capture effect". Unlike AM or SSB receivers, if the desired signal is only a few dB greater in strength than the interfering signal, the desired signal completely captures the receiver. Therefore, it is important that losses between the transmitter and receiver be minimized to take advantage of this effect.

PART 3: ANTENNA SYSTEM DESIGN

The design of the transmit and receive antenna system is important because it determines how well energy is transferred from one antenna to the other. Some of these factors are gain, directivity, polarization and height above the ground.

Antenna height is simply a matter of the higher the better. Increasing the height extends the line-of-sight distance and reduces the effects of objects on the ground.

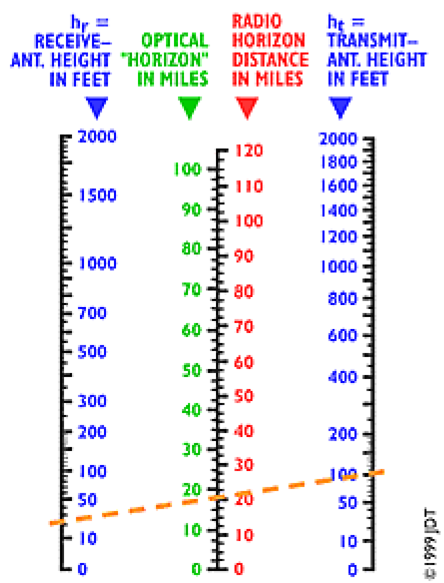
The distance to the horizon is dependent on the height above the surface of the earth. It can be seen that because of the curvature of the earth, the distance to the horizon is longer when viewed from an elevated position.

Radio waves are somewhat like light waves in that they tend to travel in a straight line. However, radio waves also tend to refract or bend as they follow the curvature of the earth. This extends the radio horizon beyond the optical horizon. This bending is caused by the tendency of a radio wave to travel slower as the density of the air increases. Since part of the radio wave travels near the earth where the air is denser, this bending occurs.

When studying the behavior of radio waves in space, it is more convenient to use a path that is a straight line instead of a curve. This requires that the radius of earth curvature be simultaneously readjusted to preserve the correct relationship. For the standard atmosphere, the equivalent radius is 4/3 or 1.3 times the actual radius of the earth as shown by experience. As previously stated the optical and radio wave paths differ. The distance in miles from antenna to the optical and radio wave horizon is determined as follows:

Optical Horizon Distance = Square Root of 2h
Radio Horizon Distance = 1.33 x Square Root of 2h

Where, "h" is height in feet. The maximum possible distance at which direct-wave transmission is possible between transmitting and receiving antennas at given heights (the line-of-sight distance) is equal to the sum of the horizon distances calculated separately for the individual antenna heights. When the distance involved is less than line-of-sight, the path is sometimes referred to as the optical path. The nomogram below shows this relationship.



Radio and optical horizon nomogram

As the distance between the transmitting and receiving antennas increases, the energy concentration for a given area decreases. Therefore, the distance from the transmitting antenna also determines how much energy an antenna intercepts. This loss of signal strength due to increased distance is known as path attenuation and is expressed in decibels or dB.

The amount of power available at the receiving antenna is dependent on the amount of energy it intercepts. An electrically large antenna will intercept more energy than an electrically small antenna. The actual dimensions of an antenna are related to wavelength. The higher the frequency, the smaller the antenna for a given wavelength. Because a smaller antenna intercepts less energy, there is a decrease in usable range as frequency increases. It is possible to increase the size (in terms of wavelength) of higher frequency antennas so that they intercept more power. These antennas are referred to as "gain" antennas.

DIRECTIONAL "GAIN" ANTENNAS

Communication range is calculated by determining the path attenuation and relating it to the power output of the transmitting antenna. Path attenuation places a practical limit on maximum usable range because a point is reached where it is impractical to radiate sufficient power to overcome path loss. While antenna height establishes the maximum possible range, the radiated power determines the practical limit since that determines the signal level at the receiving antenna. Even though base station power could be increased to several thousand watts (regulations permitting); the system "talk back" range would still be limited by the power output capability of the remote units.

If the radio link consists of two fixed stations communicating only with each other, the use of directional (gain) antennas can offer an advantage. A directional antenna normally provides several dB of gain by concentrating the RF energy in only one direction. This minimizes potential interference with other stations on other azimuths. If communication is required with stations on different azimuths, an omnidirectional antenna is probably required. Some gain can also be built into that type of antenna.

There are several ways of adding gain to antenna such as using 5/8 wavelength, yagi, corner reflector, or colinear designs. At VHF frequencies, gain antennas are rather large and cumbersome. However, at the higher frequencies, they become practical and may make up for some of the higher path loss at those frequencies.

Directional (gain) antenna

Gain antennas usually perform very well in line-of-sight applications. However, when the radiation pattern of a gain antenna is compared to that of a standard quarter-wave unity gain antenna, the gain antenna radiates at a smaller vertical angle. It is possible to be under the radiation pattern and operate at a signal loss with this type of antenna. Therefore, if the received signal is the result of a reflected wave, a gain antenna may not enhance performance.

The transmission line that connects the antenna to the receiver or transmitter is also a source of power loss. Typically, this loss is specified in dB per 100 feet of transmission line. For example, 100 feet of RG-8U coaxial cable has a 5.0 dB loss at 400 MHz. However, RG-19U coaxial cable has only a 1.85 dB loss at the same frequency, and 7/8" heliax cable has only a 0.9 dB loss at 450 MHz. Although transmission lines with a lower loss cost more and are larger in diameter, they offer an advantage if the antenna is a considerable distance from the receiver or transmitter.

Antennas generally are horizontally or vertically polarized. If radio link performance is to be maximized, it is important that both the transmitter and receiver antennas be of the same polarization. Opposite polarization results in additional path loss.

Polarization cross coupling can occur when a transmitted signal is reflected off an object. There is less chance of cross coupling a vertical wave to a horizontal wave than vice versa. This is because most buildings, electrical poles, and similar reflectors are parallel to the vertical polarized wave. Therefore, there is less chance of depolarizing a vertical wave by such a reflection. At higher frequencies that are more subject to reflection, vertical antennas may be preferred because less ground reflections will be produced.

PART 4: TELEMETRY RADIO RANGE

Determination of radio range is a complex matter that has many variables, some of which were discussed in Radio Propagation and Antenna System Design. It is not within the scope of this paper to cover all the variables. Instead, an outline will be given of a basic approach that can be used to determine the distance at which a telemetry link will operate and provide reliable communication. The following are the steps that can be taken:

1. Determine the line-of-sight transmission distance.
2. Select the antenna height above the average terrain.
3. Calculate the transmitter and receiver transmission line losses at the operating frequency.
4. Determine transmitter power output and receiver sensitivity in dBm.
5. Determine transmitter and receiver antenna gain.
6. Calculate the path loss at the operating frequency.

Once these parameters have been determined, an estimate of the RF link range can be done over smooth earth. Obviously, if there are major obstacles to overcome, designing a useable radio link may be difficult. An example of this would be if there were a 10,000 foot mountain between a base station and remote site that are only 100 feet above average terrain. The following information describes the calculations for each of the steps listed above.

The line-of-sight distance can be determined by the following equation:

D (optical) = $\sqrt{2\, h_r} + \sqrt{2\, h_t}$
D1 (radio) = 1.3 x D

Where,

D = Distance in miles to optical horizon
D1 = Distance in miles to radio horizon
H_t = Transmitter antenna height
H_r = Receiver antenna height
For example, assume that the antenna heights above the spherical earth are 25 feet for the receiver and 100 feet for the transmitter. Line-of-sight distance would then be:

D = $\sqrt{2\,(25)} + \sqrt{2\,(100)}$ = 21.2 miles
D1 = 1.3 (21.2) = 27.5 miles

Determining the line-of-sight distance does not guarantee that much range. The transmitter power, receiver sensitivity, transmission line loss, antenna loss or gain, and operating frequency must also be considered. The line-of-sight distance only means that the curvature of the earth does not block the signal. To determine path loss with these factors, assume that the RF system has the following fixed parameters:

Transmitter RF Power Output	2.0 watts (33 dB)
Operating Frequency	450 MHz
Total Tx Trans Line Loss (Heliax, 100 ft.)	0.85 dB
Total Rx Trans Line Loss (RG/U, 25 ft)	1.25 dB
Receiver 12 dB SINAD Sensitivity	116 dB
Transmit and Receive Antennas	0 dB gain, 7-element yagi

Determine the path loss at radio line-of-sight using 100 and 25 foot antennas at 450 MHz by using the following general equation:

PL = 117 + 20 $\log_{10}$ f MHz - 20 $\log_{10} h_t h_r$ + 40 $\log_{10}$ D

Where,

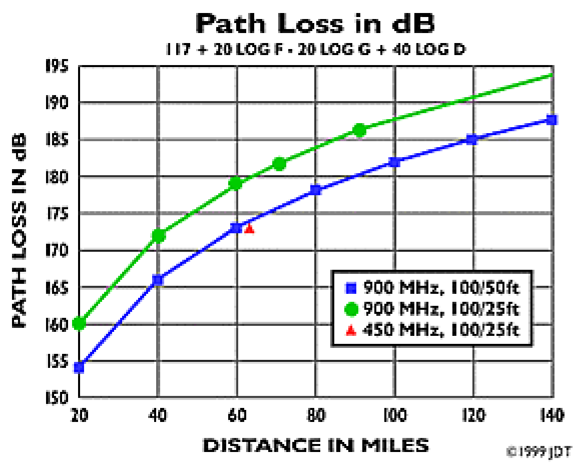
PL = Path loss in dBm
117 is a constant
f = Operating frequency
h_t = Transmitter antenna height
h_r = Receiver antenna height
D = Distance between antennas

Plugging in the data gives the calculation:

PL = 117 + 20 $\log_{10}$ f MHz - 20 $\log_{10}$ (100') (25') + 40 $\log_{10}$ 27.5 miles

PL = 117 + 53.06 - 67.9 + 57.5 = 159.6 dB

Therefore, path loss at radio line-of-sight is 159.6 dB at 450 MHz with a receiving antenna height of 25 feet and a transmitting antenna height of 100 feet. The figure below shows the relationship between path loss and radio range in miles over smooth earth with the above listed conditions.



Path loss chart

Transmitter power output is +33 dB or 2.0 watts. With 159.6 dB path loss, the signal at the receiver site is +33 dB-159.6 dB = -126.6 dB which is 10.6 dB below the receiver 12 dB SINAD sensitivity of -116 dB which was arbitrarily chosen.

A calculated receiver power exactly equal to the receiver threshold yields a useful circuit only 50% of the time. This is because the received carrier levels in a communication system fluctuate constantly about an average value. This is caused by continuously changing atmospheric conditions.

In order to provide path reliability greater than 50%, it is customary to design a communication system so that the receiver threshold is exceeded by a fading cushion called a fade margin. The statistical relationship between fade margin and the expected path reliability is based on a mass of correlated field data.

Fading is a random increase in path loss caused by abnormal propagation conditions. When these conditions occur, path loss may increase 10-30 dB or more for very short periods of time. Therefore, it is important to design the system to compensate for fading.

Most fading problems occurring at frequencies below 10 GHz are caused by multipath reception. These problems tend to increase with frequency and path distance. Multipath fading has been proven to follow a Rayleigh probability distribution. To avoid complex calculations, the following rule of thumb assumption can be used to determine what fade margin should be designed into the system for the desired reliability (assuming single-hop links below 10 GHz).

Reliability	Fade Margin
90%	8 dB
99%	18 dB
99.9%	28 dB
99.99%	38 dB
99.999%	48 dB

Referring back to the hypothetical RF link parameters, 10 dB gain antennas were included in the loss of the transmitter and receiver transmission lines. These parameters must be added or subtracted from path loss.

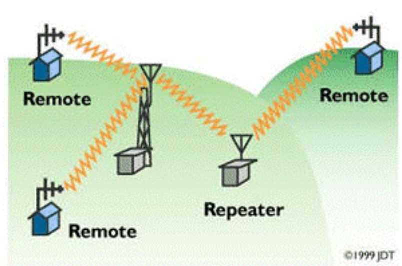
The 2-watt (+33 dB) power output of the transmitter is attenuated 0.85 dB by the transmission line so the actual power supplied to the antenna now becomes 32.15 dB or 1.6 watts. However, with a 10 dB gain antenna, the effective radiated power (ERP) becomes 42.15 dB or 15.6 watts. This effectively reduces the path loss by 9.15 dB, so the signal level at the receiver antenna is now -117.4 dB.

The receiver antenna also has a 10 dB gain, so the signal input to the receiver is -107.4 dB. This level is equal to 0.95 µV. Loss in the receiver transmission line is 1.25 dB which brings the signal level at the receiver antenna jack to -108.6 dB or .83 mV. The fade margin is 7.4 dB when the base is transmitting to the remote site receiver at the edge of the radio line-of-sight distance or slightly under a 90% link reliability over smooth earth.

Careful selection of antenna height, antenna gain, and low transmission line loss can greatly enhance the fade margin of a radio link. Increasing transmitter power output or lowering the receiver sensitivity can also increase fade margin. Lowering the receiver sensitivity can also be done by using a receiver with a lower noise figure or adding an amplifier between the receiver antenna and the transmission line which makes up for transmission line losses.

However, adding an extra RF amplifier can make the receiver more susceptible to interference from unwanted signals. In addition, increasing the transmitter power output could have legal implications because some radio channels are limited to certain power outputs as well as antenna heights by the FCC.

Another method that can be used to increase radio range is to add a repeater to the system. A repeater receives the signal from the base and retransmits it at a different frequency to the remote site. This can effectively double the range of the system as shown at left. At the UHF frequencies, the input and output frequencies of the repeater are normally separated by 5 MHz.



The base interrogates the remote site through the repeater and then returns to the receive mode. The remote site transmits back via the repeater to the base station. Either an omnidirectional or directional antenna is required at the repeater site depending on how remote sites at different azimuths are being interrogated and monitored.

Repeaters are useful tools for extending radio range. However, the repeater rebroadcasts exactly what it receives. Therefore, the link between the repeater receiver and the base or remote station transmitter should be as free of noise and distortion as possible.

Some systems may require more than one repeater to obtain the required range. However, whenever more repeaters are inserted in the radio link, the problem of noise and distortion multiplies with the number of repeaters, particularly in bands where occupied channel bandwidth is restricted.

PART 5: SUMMARY AND BIBLIOGRAPHY

There are many phenomena affecting radio signals that are beyond the scope of this paper. If you would like additional information, consult the following bibliography.

This paper established the effects of various factors on radio wave propagation. These factors included optical and radio line-of-sight distance, antenna height, antenna gain, transmission line loss, transmitter power, receiver sensitivity, operating frequency, and path loss over smooth terrain. Mention was also made of problems relating to skip, ducting, multipath, and interference. This information gives you a basic understanding of the factors that must be considered to build a reliable telemetry system. However, further adjustments may be required to overcome specific problems.

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