Wave Propagation

Radio signals are affected in many ways by objects in their path and by the media through which they travel. This means that radio signal propagation is of vital importance to anyone designing or operating a radio system.

The properties of the path by which the radio signals will propagate governs the level and quality of the received signal. Reflection, refraction and diffraction may occur. The resultant signal may also be a combination of several signals that have travelled by different paths. These may add constructively or destructively, and in addition to this the signals travelling via different paths may be delayed causing distorting of the resultant signal. It is therefore very important to know the likely radio propagation characteristics that are likely to prevail.

The distances over which radio signals may propagate varies considerably. For some applications only a short range may be needed. For example a wi-fi link may only need to be established over a distance of a few metres. On the other hand a short wave broadcast station, or a satellite link would need the signals to travel over much greater distances. Even for these last two examples of the short wave broadcast station and the satellite link, the radio propagation characteristics would be completely different, the signals reaching their final destinations having been affected in very different ways by the media through which the signals have travelled.

Radio propagation categories

There are a number of categories into which different types of radio propagation can be placed. These relate to the effects of the media through which the signals propagate.

- ***Free space propagation:*** Here the radio signals travel in free space, or away from other objects which influence the way in which they travel. It is only the distance from the source which affects the way in which the field strength reduces. This type of radio propagation is encountered with signals travelling to and from satellites.
- ***Ground wave propagation:*** When signals travel via the ground wave they are modified by the ground or terrain over which they travel. They also tend to follow the earth's curvature. Signals heard on the medium wave band during the day use this form of propagation. Read more about Ground wave propagation
- ***Ionospheric propagation:*** Here the radio signals are modified and influenced by the action of the free electrons in the upper reaches of the earth's atmosphere called the ionosphere. This form of radio propagation is used by stations on the short wave bands for their signals to be heard around the globe. Read more about Ionospheric propagation
- ***Tropospheric propagation:*** Here the signals are influenced by the variations of refractive index in the troposphere just above the earth's surface. Tropospheric radio propagation is often the means by which signals at VHF and above are heard over extended distances. Read more about Tropospheric propagation

In addition to these categories, many short range radio communications or wireless systems have radio propagation scenarios that do not fit neatly into these categories. Many mobile communications systems along with wi-fi and cellular systems for example need to have their radio propagation models generated for office, or urban situations. Under these circumstances the "free space" propagation is modified by multiple reflections, refractions and diffractions. Despite these complications it is still possible to generate rough guidelines and models for these radio propagation scenarios.

Radio wave Propagation and the Atmosphere

The way that radio signals propagate, or travel from the radio transmitter to the radio receiver is of great importance when planning a radio communications network or system. This is governed to a great degree by the regions of the atmosphere through which they pass. Without the action of the atmosphere it would not be possible for radio communications signals to travel around the globe on the short wave bands, or travel greater than only the line of sight distance at higher frequencies. In fact the way in which the atmosphere affects radio communications is of tremendous importance for anyone associated with radio communications, whether they are for two way radio communications links, mobile radio communications, radio broadcasting, point to point radio communications or any other radio.

Layers of the Atmosphere

The atmosphere can be split up into a variety of different layers according to their properties. As different aspects of science look at different properties there is no single nomenclature for the layers. The system that is most widely used is that associated with. Lowest is the troposphere that extends to a height of 10 km. Above this at altitudes between 10 and 50 km is found the stratosphere. This contains the ozone layer at a height of around 20 km. Above the stratosphere, there is the mesosphere extending from an altitude of 50 km to 80 km, and above this is the thermosphere where temperatures rise dramatically.

There are two main layers that are of interest from a radio communications viewpoint. The first is the troposphere that tends to affect radio frequencies above 30 MHz. The second is the ionosphere. This is a region which crosses over the boundaries of the meteorological layers and extends from around 60 km up to 700 km. Here the air becomes ionised, producing ions and free electrons. The free electrons affect radio communications and radio signals at certain frequencies, typically those radio frequencies below 30 MHz, often bending them back to Earth so that they can be heard over vast distances around the world.

Troposphere

The lowest of the layers of the atmosphere is the troposphere. This extends from ground level to an altitude of 10 km. It is within this region that the effects that govern our weather occur. To give an idea of the altitudes involved it is found that low clouds occur at altitudes of up to 2 km whereas medium level clouds extend to about 4 km.

The highest clouds are found at altitudes up to 10 km whereas modern jet airliners fly above this at altitudes of up to 15 km.

Within the troposphere there is generally a steady fall in temperature with height and this has a distinct bearing on some radio propagation modes and radio communications that occur in this region. The fall in temperature continues in the troposphere until the tropo pause is reached. This is the area where the temperature gradient levels out and then the temperature starts to rise. At this point the temperature is around -50° C.

The refractive index of the air in the troposphere plays a dominant role in radio signal propagation and the radio communications applications that use tropospheric radio wave propagation. This depends on the temperature, pressure and humidity. When radio communications signals are affected this often occurs at altitudes up to 2 km.

Ionosphere

The ionosphere is an area where there is a very high level of free electrons and ions. It is found that the free electrons affect radio waves and hence they have a marked effect on radio communications in many instances. Although there are low levels of ions and electrons at all altitudes, the number starts to rise noticeably at an altitude of around 30 km. However it is not until an altitude of approximately 60 km is reached that the it rises to a sufficient degree to have a major effect on radio signals.

The overall way in which the ionosphere is very complicated. It involves radiation from the sun striking the molecules in the upper atmosphere. This radiation is sufficiently intense that when it strikes the gas molecules some electrons are given sufficient energy to leave the molecular structure. This leaves a molecule with a deficit of one electron that is called an ion, and a free electron. As might be expected the most common molecules to be ionised are nitrogen and oxygen.

Most of the ionisation is caused by radiation in the form of ultraviolet light. At very high altitudes the gases are very thin and only low levels of ionisation are created. As the radiation penetrates further into the atmosphere the density of the gases increases and accordingly the numbers of molecules being ionised increase. However when molecules are ionised the energy in the radiation is reduced, and even though the gas density is higher at lower altitudes the degree of ionisation becomes less because of the reduction of the level of ultraviolet light.

At the lower levels of the ionosphere where the intensity of the ultraviolet light has been reduced most of the ionisation is caused by x-rays and cosmic rays which are able to penetrate further into the atmosphere. In this way an area of maximum radiation exists with the level of ionisation falling below and above it.

In terms of its radio communications properties, the ionosphere is often thought of as a number of distinct layers. Whilst it is very convenient to think of the layers as separate, in reality this is not quite true. Each layer overlaps the others with the whole of the ionosphere having some level of ionisation. The layers are best thought of as peaks in the level of ionisation. These layers are given designations D, E, and F1 and F2.

Description of the layers in the ionosphere

1. ***D layer:*** The D layer is the lowest of the layers of the ionosphere. It exists at altitudes around 60 to 90 km. It is present during the day when radiation is received from the sun. However the density of the air at this altitude means that ions and electrons recombine relatively quickly. This means that after sunset, electron levels fall and the layer effectively disappears. This layer is typically produced as the result of X-ray and cosmic ray ionisation. It is found that this layer tends to attenuate signals that pass through it.
2. ***E layer:*** The next layer beyond the D layer is called the E layer. This exists at an altitude of between 100 and 125 km. Instead of acting chiefly as an attenuator, this layer reflects radio signals although they still undergo some attenuation.

   In view of its altitude and the density of the air, electrons and positive ions recombine relatively quickly. This occurs at a rate of about four times that of the F layers that are higher up where the air is less dense. This means that after nightfall the layer virtually disappears although there is still some residual ionisation, especially in the years around the sunspot maximum that will be discussed later.

   There are a number of methods by which the ionisation in this layer is generated. It depends on factors including the altitude within the layer, the state of the sun, and the latitude. However X-rays and ultraviolet produce a large amount of the ionisation light, especially that with very short wavelengths.

3. ***F layer:*** The F layer is the most important region for long distance HF communications. During the day it splits into two separate layers. These are called the F_1 and F_2 layers, the F_1 layer being the lower of the two. At night these two layers merge to give one layer called the F layer. The altitudes of the layers vary considerably with the time of day, season and the state of the sun. Typically in summer the F_1 layer may be around 300 km with the F_2 layer at about 400 km or even higher. In winter these figures may be reduced to about 300 km and 200 km. Then at night the F layer is generally around 250 to 300 km. Like the D and E layers, the level of ionisation falls at night, but in view of the much lower air density, the ions and electrons combine much more slowly and the F layer decays much less. Accordingly it is able to support radio communications, although changes are experienced because of the lessening of the ionisation levels. The figures for the altitude of the F layers are far more variable than those for the lower layers. They change greatly with the time of day, the season and the state of the Sun. As a result the figures which are given must only be taken as an approximate guide. Most of the ionisation in this region of the ionosphere is caused by ultraviolet light, both in the middle of the UV spectrum and those portions with very short wavelengths.

The way in which the various regions in the atmosphere affect radiowave propagation and radio communications is a fascinating study. There are very many factors that influence radio propagation and the resulting radio communications links that can be established. Predicting the ways in which this occurs is complicated and difficult, however it is possible to gain a good idea of the likely radio communications conditions using some simple indicators. Further pages in this section of the website detail many of these aspects.

Radio Signal Path Loss

Radio signal path loss is a particularly important element in the design of any radio communications system or wireless system. The radio signal path loss will determine many elements of the radio communications system in particular the transmitter power, and the antennas, especially their gain, height and general location. The radio path loss will also affect other elements such as the required receiver sensitivity, the form of transmission used and several other factors.

As a result, it is necessary to understand the reasons for radio path loss, and to be able to determine the levels of the signal loss for a give radio path.

The signal path loss can often be determined mathematically and these calculations are often undertaken when preparing coverage or system design activities. These depend on a knowledge of the signal propagation properties.

Accordingly, path loss calculations are used in many radio and wireless survey tools for determining signal strength at various locations. These wireless survey tools are being increasingly used to help determine what radio signal strengths will be, before installing the equipment. For cellular operators radio coverage surveys are important because the investment in a macrocell base station is high. Also, wireless survey tools provide a very valuable service for applications such as installing wireless LAN systems in large offices and other centres because they enable problems to be solved before installation, enabling costs to be considerably reduced. Accordingly there is an increasing importance being placed onto wireless survey tools and software.

Signal path loss basics

The signal path loss is essentially the reduction in power density of an electromagnetic wave or signal as it propagates through the environment in which it is travelling.

There are many reasons for the radio path loss that may occur:

- ***Free space loss:*** The free space loss occurs as the signal travels through space without any other effects attenuating the signal it will still diminish as it spreads out. This can be thought of as the radio communications signal spreading out as an ever increasing sphere. As the signal has to cover a wider area, conservation of energy tells us that the energy in any given area will reduce as the area covered becomes larger.
- ***Absorption losses:*** Absorption losses occur if the radio signal passes into a medium which is not totally transparent to radio signals. This can be likened to a light signal passing through transparent glass.

- ***Diffraction:*** Diffraction losses occur when an object appears in the path. The signal can diffract around the object, but losses occur. The loss is higher the more rounded the object. Radio signals tend to diffract better around sharp edges.
- ***Multipath:*** In a real terrestrial environment, signals will be reflected and they will reach the receiver via a number of different paths. These signals may add or subtract from each other depending upon the relative phases of the signals. If the receiver is moved the scenario will change and the overall received signal will be found vary with position. Mobile receivers will be subject to this effect which is known as Rayleigh fading.
- ***Terrain:*** The terrain over which signals travel will have a significant effect on the signal. Obviously hills which obstruct the path will considerably attenuate the signal, often making reception impossible. Additionally at low frequencies the composition of the earth will have a marked effect. For example on the Long Wave band, it is found that signals travel best over more conductive terrain, e.g. sea paths or over areas that are marshy or damp. Dry sandy terrain gives higher levels of attenuation.
- ***Buildings and vegetation:*** For mobile applications, buildings and other obstructions including vegetation have a marked effect. Not only will buildings reflect radio signals, they will also absorb them. Cellular communications are often significantly impaired within buildings. Trees and foliage can attenuate radio signals, particularly when wet.
- ***Atmosphere:*** The atmosphere can affect radio signal paths. At lower frequencies, especially below 30 - 50MHz, the ionosphere has a significant effect, reflecting (or more correctly refracting) them back to Earth. At frequencies above 50 MHz and more the troposphere has a major effect, refracting the signals back to earth as a result of changing refractive index. For UHF broadcast this can extend coverage to approximately a third beyond the horizon.

These reasons represent some of the major elements causing signal path loss for any radio system.

Free Space Path Loss and Formula or Equation

The free space path loss is used in many areas for predicting radio signal strengths that may be expected in a radio system. Although it does not hold for most terrestrial situations as there are several situations in which it can be used and it is also useful as the basis for understanding many real life radio propagation situations. Despite this, the free space path loss is an essential basic parameter for many RF calculations. It can often be used as a first approximation for many short range calculations. Alternatively it can be used as a first approximation for a number of areas where there are few obstructions. As such it is a valuable tool for many people dealing with radio communications systems.

Free space loss formula frequency dependency

Although the free space loss equation given above seems to indicate that the loss is frequency dependent. The attenuation provided by the distance travelled in space is not dependent upon the frequency. This is constant.

The reason for the frequency dependence is that the equation contains two effects:

1. The first results from the spreading out of the energy as the sphere over which the energy is spread increases in area. This is described by the inverse square law.
2. The second effect results from the antenna aperture change. This affects the way in which any antenna can pick up signals and this term is frequency dependent.

As one constituent of the path loss equation is frequency dependent, this means that there is a frequency dependency within the complete equation.

Decibel version of free space path loss equation

Most RF comparisons and measurements are performed in decibels. This gives an easy and consistent method to compare the signal levels present at various points. Accordingly it is very convenient to express the free space path loss formula, FSPL, in terms of decibels. It is easy to take the basic free space path loss equation and manipulate into a form that can be expressed in a logarithmic format.

$$\mathbf{FSPL\ (dB) = 20\ log_{10}\ (d) + 20\ log_{10}\ (f) + 32.44}$$

Where:
d is the distance of the receiver from the transmitter (km)
f is the signal frequency (MHz)

Affect of antenna gain on path loss equation

The equation above does not include any component for antenna gains. It is assumed that the antenna gain is unity for both the transmitter. In reality, though, all antennas will have a certain amount of gain and this will affect the overall affect. Any antenna gain will reduce the "loss" when compared to a unity gain system. The figures for antenna gain are relative to an isotropic source, i.e. an antenna that radiates equally in all directions.

$$\mathbf{FSPL\ (dB) = 20\ log_{10}\ (d) + 20\ log_{10}\ (f) + 32.44 - Gtx - Grx}$$

Where:
Gtx is the gain of the transmitter antenna relative to an isotropic source (dBi)
Grx is the gain of the receiver antenna relative to an isotropic source (dBi)

The free space path loss equation or formula given above, is an essential tool that is required when making calculations for radio and wireless systems either manually or within applications such as wireless survey tools, etc. By using the free space path loss equation, it is possible to determine the signal strengths that may be expected in many scenarios. While the free space path loss formula is not fully applicable where there are other interactions, e.g. reflection, refraction, etc as are present in most real life applications, the equation can nevertheless be used to give an indication of what may be expected. It is obviously fully applicable to satellite systems where the paths conform closely to the totally free space scenarios. ....

Multipath Propagation

Multipath propagation is a fact of life in any terrestrial radio scenario. While the direct or line of sight path is normally the main wanted signal, a radio receiver will receive many signals resulting from the signal taking a large number of different paths. These paths may be the result of reflections from buildings, mountains or other reflective surfaces including water, etc. that may be adjacent to the main path. Additionally other effects such as ionospheric reflections give rise to multipath propagation as does tropospheric ducting.

The multipath propagation resulting from the variety of signal paths that may exist between the transmitter and receiver can give rise to interference in a variety of ways including distortion of the signal, loss of data and multipath fading. At other times, the variety of signal paths arising from the multipath propagation can be used to advantage. Schemes such as MIMO use multipath propagation to increase the capacity of the channels they use. With increasing requirements for spectrum efficiency, the use of multipath propagation for technologies such as MIMO are able to provide significant improvements in channel capacity that are much needed.

Multipath propagation basics

Multipath radio signal propagation occurs on all terrestrial radio links. The radio signals not only travel by the direct line of sight path, but as the transmitted signal does not leave the transmitting antenna in only the direction of the receiver, but over a range of angles even when a directive antenna is used. As a result, the transmitted signals spread out from the transmitter and they will reach other objects: hills, buildings reflective surfaces such as the ground, water, etc. The signals may reflect of a variety of surfaces and reach the receiving antenna via paths other than the direct line of sight path.

Multipath fading

Signals are received in a terrestrial environment, i.e. where reflections are present and signals arrive at the receiver from the transmitter via a variety of paths. The overall signal received is the sum of all the signals appearing at the antenna. Sometimes these will be in phase with the main signal and will add to it, increasing its strength. At other times they will interfere with each other. This will result in the overall signal strength being reduced. At times there will be changes in the relative path lengths. This could result from either the transmitter or receiver moving, or any of the objects that provides a reflective surface moving. This will result in the phases of the signals arriving at the receiver changing, and in turn this will result in the signal strength varying. It is this that causes the fading that is present on many signals.

It can also be found that the interference may be flat, i.e. applied to all frequencies equally across a given channel, or it may be selective, i.e. applying to more to some frequencies across a channel than others.A more in depth description of multipath fading is given in a page referenced in the "Related Articles" section on the left hand side of this page below the main menu.

Interference caused by multipath propagation

Multipath propagation can give rise to interference that can reduce the signal to noise ratio and reduce bit error rates for digital signals. One cause of a degradation of the signal quality is the multipath fading already described. However there are other ways in which multipath propagation can degrade the signal and affect its integrity.

One of the ways which is particularly obvious when driving in a car and listening to an FM radio. At certain points the signal will become distorted and appear to break up. This arises from the fact that the signal is frequency modulated and at any given time, the frequency of the received signal provides the instantaneous voltage for the audio output. If multipath propagation occurs, then two or more signals will appear at the receiver. One is the direct or line of sight signal, and another is a reflected signal. As these will arrive at different times because of the different path lengths, they will have different frequencies, caused by the fact that the two signals have been transmitted by the transmitter at slightly different times. Accordingly when the two signals are received together, distortion can arise if they have similar signal strength levels.

Another form of multipath propagation interference that arises when digital transmissions are used is known as Inter Symbol Interference, ISI. This arises when the delay caused by the extended path length of the reflected signal. If the delay is significant proportion of a symbol, then the receiver may receive the direct signal which indicates one part of the symbol or one state, and another signal which is indicating another logical state. If this occurs, then the data can be corrupted.

One way of overcoming this is to transmit the data at a rate the signal is sampled, only when all the reflections have arrived and the data is stable. This naturally limits the rate at which data can be transmitted, but ensures that data is not corrupted and the bit error rate is minimised. To calculate this the delay time needs to be calculated using estimates of the maximum delays that are likely to be encountered from reflections. Using the latest signal processing techniques, a variety of methods can be used to overcome the problems with multipath propagation and the possibilities of interference.