Contents

2.0 Radio Waves

Much of the following information has been gleaned from:

Microwave Radio Primer by McLarnon

Wireless Data Communications by Egan

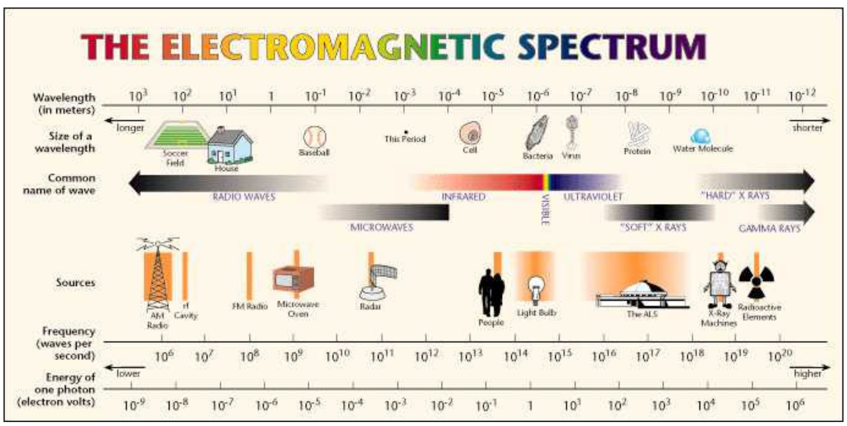
US Frequency Allocation Chart

Spectrum Usage for Fixed Services – NTIA Report 00-378

2.1 Waves

Maxwell first predicted the existence of electromagnetic waves in the 19th century. He came to this conclusion by careful examination of the equations describing electric and magnetic phenomenon. It was left up to Hertz to create these waves, and Marconi to exploit them.

In spite of one hundred years of study, exactly what radio waves are and why they exist, remain somewhat of a mystery.

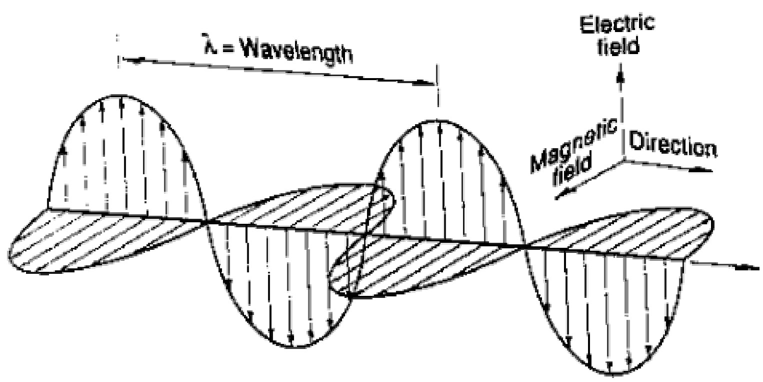


Frequency Band Name	Band Range	Wavelength
ELF – Extremely Low Frequency	30 – 300 Hz	10000 – 1000 Km
VLF – Very Low Frequency	3 – 30 KHz	100 – 10 Km
LF - Low Frequency	30-300 KHz	10-1 Km
MF - Medium Frequency	300-3000 KHz	1000-100 m
HF - High Frequency	3-30 MHz	100-10 m
VHF - Very High Frequency	30-300 MHz	10-1 m
UHF - Ultra High Frequency	300-3000 MHz	100-10 cm
SHF - Super High Frequency	3-30 GHz	10-1 cm
EHF - Extremely High Frequency	30-300 GHz	10-1 mm

Radio Spectrum for various services

Service	Frequency Range
Submarine Communications	ELF
Longwave	Below the AM band (500 KHz) > 60 meter wavelength
Medium Wave	AM Band 540 - 1800 KHz
Shortwave	Above the AM band to 30 MHz
AMPS	824-894 MHz
GSM	890-960 MHz
DECT	1.728 MHz
PCS	1.8-2.0 GHz

Electromagnetic waves in free space, or TEM† waves, consist of electric and magnetic fields, each at right angles to each other and the direction of propagation.



The relationship between wavelength and frequency is given by

$$c = f\lambda$$

where c is the speed of light, approximately 3×10^{8} meters per second.

Radio waves can be reflected and refracted in a manner similar to light. They are affected by the ground terrain, atmosphere and other objects.

Maxwell's equations state that a time varying magnetic field produces an electric field and a time varying electric field produces a magnetic field. This is kind of a chicken and egg situation.

Radio waves propagate outward from an antenna, at the speed of light. The exact nature of these waves is determined by the transmission medium. In free space, they travel in straight lines, whereas in the atmosphere, they generally

† Transverse Electro Magnetic

travel in a curved path. In a confined or guided medium, radio waves do not propagate in the TEM mode, but rather in a TE or TM mode.

Radio waves interact with objects in three principle ways:

Reflection – A radio wave bounces off an object larger than its wavelength.

Diffraction – Waves bend around objects.

Scattering – A radiowave bounces off an object smaller than its wavelength.

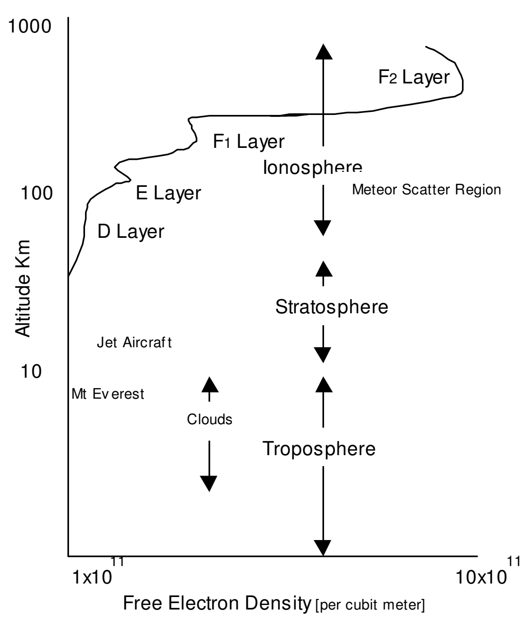
Because of these complex interactions, radio wave propagation is often examined in three distinct regions in order to simplify the analysis:

Surface (or ground) waves are located very near the earth's surface.

Space waves occur in the lower atmosphere (troposphere).

Sky waves occur in the upper atmosphere (ionosphere).

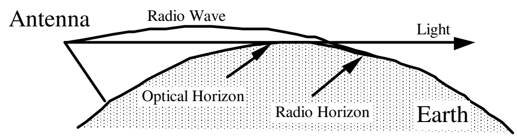
The boundaries between these regions are somewhat fuzzy. In many cases, it is not possible to examine surface waves without considering space waves.



2.1.1 Surface wave

These are the principle waves used in AM, FM and TV broadcast. Objects such as buildings, hills, ground conductivity, etc. have a significant impact on their strength.

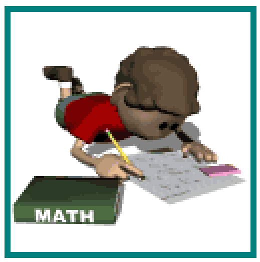
Surface waves are usually vertically polarized with the electric field lines in contact with the earth.



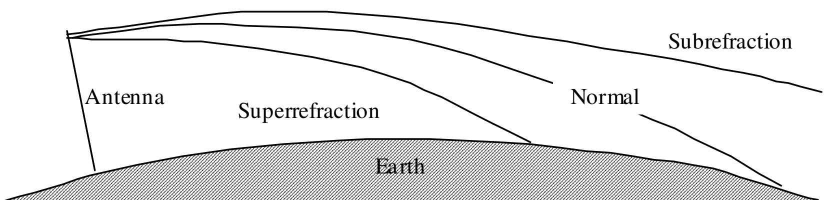
Because of refraction, the radio horizon is larger than the optical horizon by about 4/3. The typical maximum direct wave transmission distance is dependent on the height of the antennas:

$$d_{max} \approx \sqrt{17 h_t} + \sqrt{17 h_r} \quad \text{km}$$

where h_t and h_r are in meters



However, the atmospheric conditions can have a dramatic effect on the amount of refraction.



Super refraction

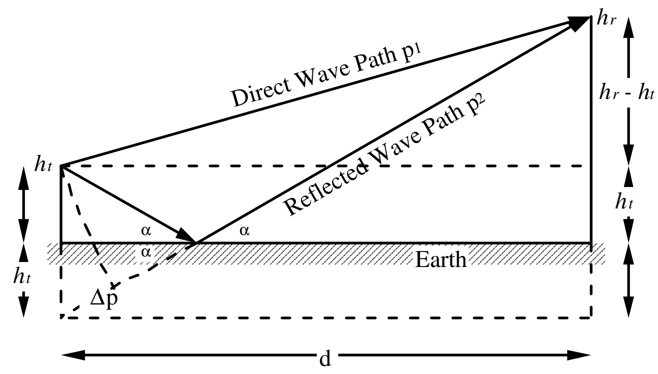
In super refraction, the rays bend more than normal thus shortening the radio horizon. This phenomenon occurs when temperature increases but moisture decreases with height. Paradoxically, in some cases, the radio wave can travel over enormous distances. It can be reflected by the earth, rebroadcast and super refracted again.

Sub refraction

In sub refraction, the rays bend less than normal. This phenomenon occurs when temperature decreases but moisture increases with height. In extreme cases, the radio signal may be refracted out into space.

2.1.2 Space Wave

These waves occur within the lower 20 km of the atmosphere, and are comprised of a direct and reflected wave.



Direct Wave

This is generally a line of sight transmission, however, because of atmospheric refraction the range extends slightly beyond the horizon.

Ground Reflected Wave

Radio waves may strike the earth, and bounce off. The strength of the reflection depends on local conditions. The received radio signal can cancel out if the direct and reflected waves arrive with the same relative strength and 180^o out of phase with each other.

Horizontally polarized waves are reflected with almost the same intensity but with a 180^o phase reversal.

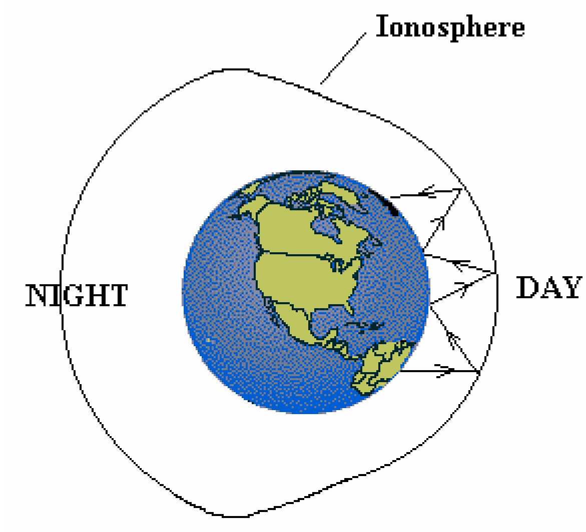
Vertically polarized waves generally reflect less than half of the incident energy. If the angle of incidence is greater than 10^o there is very little change in phase angle.

2.1.3 Sky Wave

These waves head out to space but are reflected or refracted back by the ionosphere. The height of the ionosphere ranges from 50 to 600 km.

Radio waves are refracted by the ionized gas created by solar radiation. The amount of ionization depends on the time of day, season and the position in the 11-year sun spot cycle. The specific radio frequency refracted is a function of electron density and launch angle.

A communication channel thousands of kilometers long can be established by successive reflections at the earth's surface and in the upper atmosphere. This ionospheric propagation takes place mainly in the HF band.



http://ecjones.org/physics.html

The ionosphere is composed of several layers, which vary according to the time of day. Each layer has different propagation characteristics:

D layer – This layer occurs only during the day at altitudes of 60 to 90 km. High absorption takes place at frequencies up to 7 MHz.

E layer – This layer occurs at altitudes of 100 to 125 km. In the summer, dense ionization clouds can form for short periods. These clouds called "sporadic E" can refract radio signals in the VHF spectrum. This phenomenon allows amateur radio operators to communicate over enormous distances.

F layer - This single nighttime layer splits into two layers (F1 and F2) during the day. The F1 layer forms at about 200 km and F2 at about 400 km. The F2 layer propagates most HF short-wave transmissions.

Because radio signals can take many paths to the receiver, multipath fading can occur. If the signals arrive in phase, the result is a stronger signal. If they arrive out of phase with each other, they tend to cancel.

Deep fading, lasting from minutes to hours over a wide frequency range, can occur when solar flares increase the ionization in the D layer.

The useful transmission band ranges between the LUF[†] and MUF[†]. Frequencies above the MUF are refracted into space. Below the LUF, radio frequencies suffer severe absorption. If a signal is near either of these two extremes, it may be subject to fading.

Meteors create ionization trails that reflect radio waves. Although these trails exist for only a few seconds, they have been successfully used in communications systems spanning 1500 Km.

† Lowest Usable Frequency

† Maximum Usable Frequency

The Aurora Borealis or Northern Lights cause random reflection in the 3 - 5 MHz region. Aurora causes signal flutter at 100 Hz to 2000 Hz thus making voice transmission impossible.

2.2 Radiators

2.2.1 Isotropic Radiators

An isotropic source radiates energy equally well in all directions. Stars are isotropic radiators. Our sun is an extremely powerful radiator, broadcasting 64 Megawatts per square meter of surface.

Although it is not possible to construct isotropic radio antennas, the concept provides useful analytical tools.

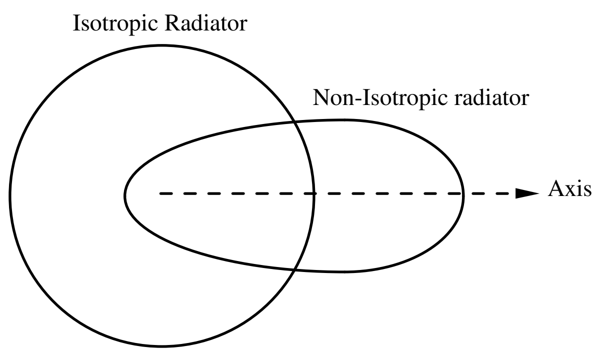
The power density as a function of distance from an isotropic source is easily calculated. It is simply the total energy broadcast, divided by the area it passes through, in this case, a sphere.

$$P_{DI} = \frac{P_t}{4\pi r^2} \qquad \text{watts/m}^2$$

Isotropic gain is also called absolute gain. Antennas gains with respect to isotropic gain are specified in units of *dBi*. Antenna gains can also be specified with respect to a half wave dipole or a short vertical antenna. The gain of a half-wave dipole is 1.64 *dBi*, and that of a dipole is 2.15 *dBi*.

2.2.2 Non-Isotropic Radiators

Virtually all types of antennas are non-isotropic sources. That is that they tend to radiate more energy in a particular direction.



Because of this non-uniform energy distribution, the antenna appears to have a gain [G_t] (if broadcasting the same power) relative to an isotropic radiator along its principle axis and a loss in other most directions. The power density along the antenna axis is given by:

$$P_D = \frac{P_t G_t}{4\pi r^2} \qquad \text{watts/m}^2$$

The receiving antenna attempts to collect this radiated energy through an effective area [A_{eff}]. The received power is therefore:

$$P_r = \frac{P_t G_t}{4\pi r^2} A_{eff} \qquad \text{watts}$$

It would seem reasonable to conclude that the effective area is simply the physical size of the antenna. Fortunately, this is not the case, and very small antennas are possible.

It has been determined that there is a relationship between effective area, transmitted wavelength and antenna gain:

$$\frac{A_{eff}}{G_r} = \frac{\lambda^2}{4\pi}$$

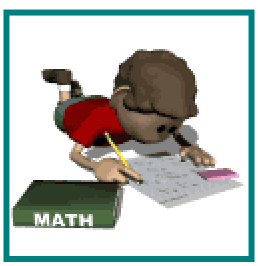
Therefore, the received power can be expressed as:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi r}\right)^2 \qquad \text{watts}$$

Recall that: $\lambda = \frac{c}{f}$

If f is expressed in MHz, c in meters per second, and r in km, then the received power in dB can be expressed as:

$$P_r = P_t + G_t + G_r - (32.45 + 20 \log r + 20 \log f) \qquad \text{dB}$$



Example

Given:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi r}\right)^2 \qquad \text{watts}$$

Make the appropriate substitutions and prove that when distance is specified in km and frequency in GHz, then:

$$P_r = P_t + G_t + G_r - \left(32.45 + 20\log r + 20\log f\right) \qquad \text{dB}$$

Example Deep Space Probe

Find the received signal power, given that:

Frequency = 4 GHz

Satellite antenna gain = 15 dB

Earth station antenna gain = 45 dB

Satellite transmission power = 22 watts

Distance = 3.2 billion km

solution

22 watts = 13.42 dBw

Therefore:

$$\begin{aligned} P_r &= 13.42 + 15 + 45 - \left(32.45 + 20\log 3.2\times10^{9} + 20\log 4000\right) \quad dBw \\ &= -221.174 \quad dBw \qquad or \qquad 7.63\times10^{-23} \quad watts \end{aligned}$$

2.2.3 Electric Field Strength

If the power density of an electromagnetic wave is known, the field strength can be obtained from:

$$E = \sqrt{Z_o P_D}$$

where

$$Z_o = \sqrt{\frac{\mu}{\varepsilon}} = \sqrt{\frac{4\pi\times10^{-7}}{8.854\times10^{-12}}} = 120\pi \text{ (for free space)}$$

Therefore the field strength at one meter is:

$$E_0 = \sqrt{120\pi\frac{P_t G_t}{4\pi r^2}} = \sqrt{30 P_t G_t} \text{ v/m}$$

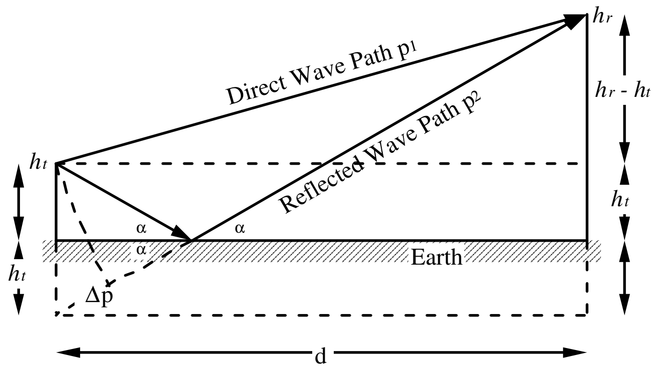
2.3 Fading and Interference

Radio signals may vary in intensity for many reasons.

Notes

2.3.1 Flat Earth Reflections (Horizontal Polarization)

There are at least two possible paths for radio waves to travel when the antennas are near the earth: direct path and reflected path. These two signals interact in a very complex manner. However, ignoring polarization and assuming a flat earth can produce some interesting mathematical descriptions.



$p_1 =$ direct wave path length

$p_2 =$ reflected wave path length

$\Delta p = p_2 - p_1 =$ difference in path lengths

$d =$ distance

From the geometry we can observe:

$$p_1^2 = (h_r - h_t)^2 + d^2$$

$$p_2^2 = (h_r + h_t)^2 + d^2$$

$$p_2^2 - p_1^2 = (h_r + h_t)^2 + d^2 - (h_r + h_t)^2 - d^2 = 4h_r h_t$$

$$(p_2 - p_1)(p_2 + p_1) = 4h_r h_t$$

But: $\Delta p = (p_2 - p_1)$ and $d \approx p_1 \approx p_2$

Therefore:

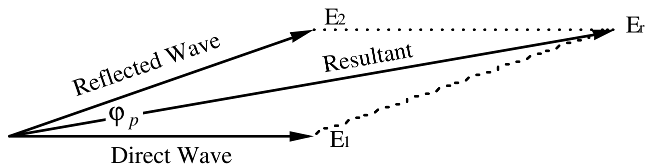
$$\Delta p \, 2d \approx 4h_r h_t$$

$$\Delta p \approx \frac{2h_r h_t}{d}$$

If the difference in the two paths Δp, is 1/2 λ long, the two signals tend to cancel. If Δp is equal to λ, the two signals tend to reinforce. The path difference Δp therefore corresponds to a phase angle change of: $\varphi_p = \frac{2\pi}{\lambda}\Delta p = \frac{4\pi h_t h_r}{\lambda d}$

The resultant received signal is the sum of the two components. The situation is unfortunately made more complex by the fact that the phase integrity of the reflected wave is not maintained at the point of reflection.

If we limit the examination of reflected waves to the horizontally polarized situation, we obtain the following geometry:

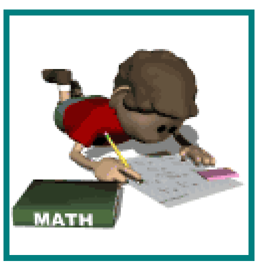


Applying the cosine rule to this diagram, we obtain a resultant signal of:

$$E_r = E_1\sqrt{2\left(1-\cos\varphi_p\right)} = 2E_1\sin\left(\frac{\varphi_p}{2}\right)$$

The signal strength of the direct wave is the unit distance value divided by the distance: $E_r = \frac{E_o}{d}$ Therefore, the received signal can be written as:

$$E_r = \frac{2E_o}{d}\sin\left(\frac{2\pi h_t h_r}{\lambda d}\right)$$



For small angles this can be approximated by:

$$E_r \approx \frac{2E_o}{d}\frac{2\pi h_t h_r}{\lambda d} = E_o\frac{4\pi h_t h_r}{\lambda d^2}$$

Example

A mobile radio transmitter broadcasts 150 watts at a carrier frequency of 250 MHz. The transmit antenna is a half wave dipole located 15 meters above the ground. Assuming a flat earth, calculate the signal strength at a receiving antenna located 2.5 meters above the ground, at a distance of 35 km.

Solution

The isotropic gain of a half wave dipole is 1.64.

$$\lambda = \frac{3\times10^8}{250\times10^6} = 1.2 \quad \text{meters}$$

$$E_o = \sqrt{30 P_t G_t} = \sqrt{30 \times 150 \times 1.64} = 85.9 \quad \text{v/m}$$

$$E_r = \frac{2 \times 85.9}{35 \times 10^3} \sin\left(\frac{2\pi \times 15 \times 2.5}{1.2 \times 35 \times 10^3}\right) = 27.54 \quad \mu\text{V/m}$$

2.3.2 Multipath Fading

http://users.ece.gatech.edu/~mai/tutorial_multipath.htm

The received signal is generally a combination of many signals, each coming over a different path. The phase and amplitude of each component are related to the nature of the path. These signals combine in a very complex manner.

Some multipath fading effects are characterized by delay spread, Rayleigh and Ricean fading, doppler shifting, etc. Fading is the most significant phenomenon causing signal degradation. There are several different categories of fading:

Flat fading: the entire pass band of interest is affected equally (also known as narrow or amplitude varying channels).

Frequency selective fading: certain frequency components are affected more than others (also known as wideband channels). This phenomenon tends to introduce inter-symbol interference.

Slow fading: the channel characteristics vary at less than the baud rate.

Fast fading: the channel characteristics vary faster than the baud rate.

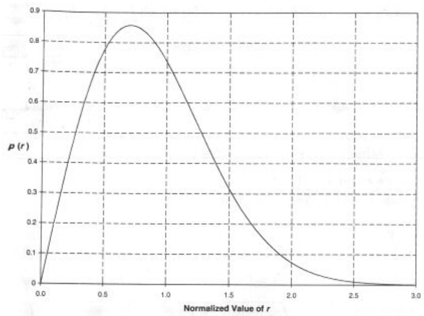
Time dispersion

Time dispersion occurs when signals arrive at different times. Signals traveling at the speed of light move about 1 foot in 1 nSec. This spreading tends to limit the bit rate over RF links.

Rayleigh fading

The Rayleigh distribution can be used to describe the statistical variations of a flat fading channel.

Generally, the strength of the received signal falls off as the inverse square of the distance between the transmitter and receiver. However, in cellular systems, the antennas are pointed slightly down and the signal falls of more quickly.

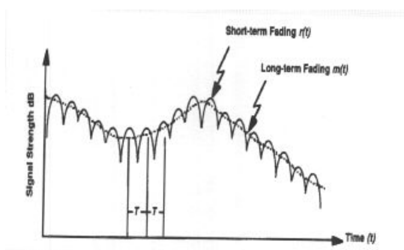


Rayleigh Distribution—Short-Term Fading

Ricean fading

The Ricean distribution is used to describe the statistical variations of signals with a strong direct or line-of-sight component and numerous weaker reflected ones. This can happen in any multipath environment such as inside buildings or in an urban center.

A received signal is generally comprised of several signals, each taking a slightly different path. Since some may add constructively in-phase and others out of phase, the overall signal strength may vary by 40 dB or more if the receiver is moved even a very short distance.



Doppler Shift

A frequency shift is caused by the relative motion of the transmitter and receiver, or any object that reflects/refracts signal. This movement creates random frequency modulation. Doppler frequency shift is either positive or negative depending on whether the transmitter is moving towards or away from the receiver.

This Doppler frequency shift is given by:

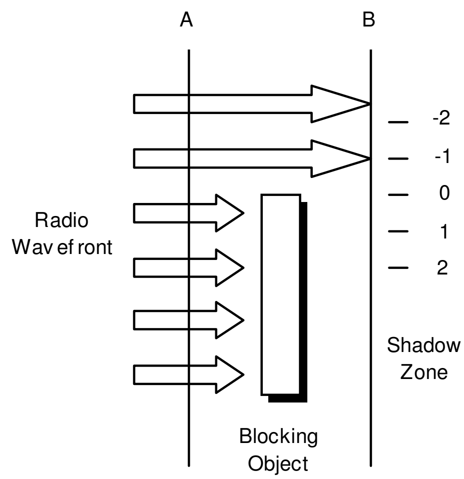
$$f_d = \frac{v_m}{c} f_c$$

v_m is the relative motion of the transmitter with respect to the receiver, c is the speed of light and f_c is the transmitted frequency.

In the multipath environment, the relative movement of each path is generally different. Thus, the signal is spread over a band of frequencies. This is known as the Doppler spread.

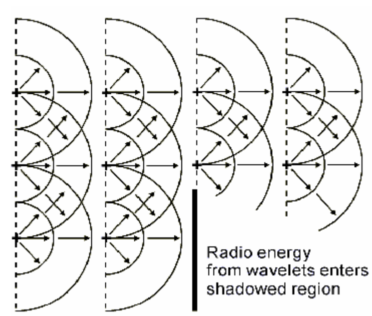
2.3.3 Atmospheric Diffraction

Radio waves cannot penetrate very far into most objects. Consequently, there is often a shadow zone behind objects such as buildings, hills, etc.

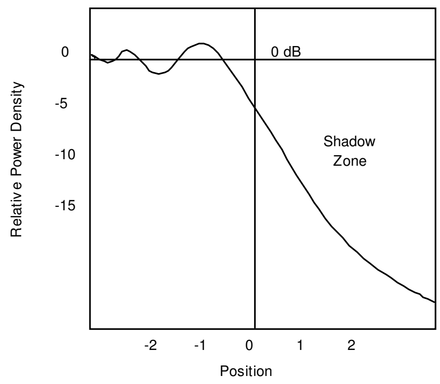


The radio shadow zone does not have a very sharp cutoff due to spherical spreading, also called Huygens' principle.

Each point on a wavefront acts as it were a point source radiating along the propagation path. The overall wavefront is the vector sum of all the point sources or wavelets. The wavelet magnitude is proportional to $1+\cos\theta$ where θ is measured from the direction of propagation. The amplitude is a maximum in the direction of propagation and zero in the reverse direction.

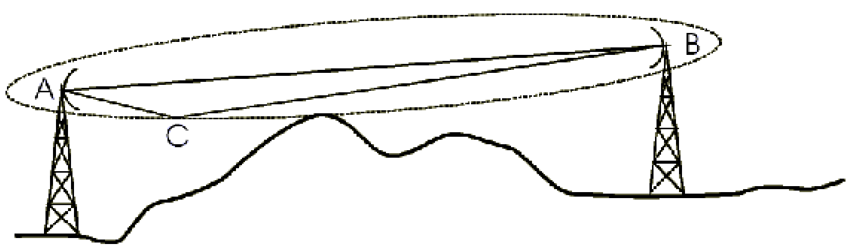


The net result is that the radio intensity at the shadow boundary does not cutoff sharply.



2.3.4 Fresnel Zone

Fresnel zones are a series of ellipsoids centered on the direct path. The first zone is the ellipse whose chords (ACB) are λ/2 longer than the direct path. This geometry can be used to locate positions of objects that could have a drastic effect on the received signal.



A radio signal reflecting off an object tangent to the first Fresnel zone will experience a shift of λ/2 because of the increased path length. It will also experience an additional phase shift of λ/2 due to the reflection. The reflected wave therefore will add constructively with the direct line of sight signal. This is true of any signal reflecting off an object located tangent to any odd integer Fresnel zone.

Consequently, any signal traveling along even Fresnel paths cancel the direct signal. For this reason, the first zone is generally kept free from objects that could create a multipath signal.

2.4 Propagation Models

There have been numerous attempts to create an analytical model, which accurately predicts the characteristics of a radio channel in an urban environment[1]. This is an extremely difficult thing to do. Consequently, many models resort to imperial methods.

1 Wireless Communications Principles & Practice by Theodore S. Rappaport

Notes

Longley-Rice Model

This model is used to predict the characteristics of a simple point-to-point link for frequencies between 20 MHz and 10 GHz. It incorporates 2-ray reflection, diffraction around knife-edge objects, and tropospheric refraction. It does not consider multipath fading or any effects caused by buildings or foliage.

Durkin Model

This technique uses elevation data to predict the point-to-point path loss. It takes into account multiple diffraction edges and Fresnel zone effects. It does not consider ground effects or multipath propagation.

Okumura Model

Unlike other models, this one uses empirical data rather than calculated values. Although the data is based on measurements from 150 MHz to 1.92 GHz, it is often extrapolated to 3 GHz.

A series of curves providing the mean attenuation as a function of distance and height, are used to predict path loss. Various topographical correction factors can be applied to provide a better estimate.

This model is considered one of the simplest and most accurate.

Hata Model

This is a mathematical representation of the graphs used in the Okumura model. It has been extended and is used to predict the path loss in European PCS systems.

The proposed path loss expression in dB is:

$$L_{50}(urban) = 46.3 + 33.9\log f_c - 13.82\log h_{te} - a(h_{re}) + (44.9 - 6.55\log h_{te})\log d + C_M$$

Where:

f= frequency in MHz(1500 to 2000)

h_{te} *= transmitter antenna height in meters (30 – 200)*

h_{re} *= receiver antenna height in meters(1 – 10)*

d = distance in Km (1 – 20)

$a(h_{re})$ *= mobile antenna correction factor*

C_M *= urban correction factor (0 dB for suburbs or small cities, 3 dB for large cities)*

The mobile correction factor for suburbs or small cities is:

$$a(h_{re}) = (1.1\log f_c - 0.7)h_{re} - (1.56\log f_c - 0.8)$$

Notes

The mobile correction factor for large cities is:

$$a(h_{re}) = 8.29(\log 1.54 h_{re})^2 - 1.1 \qquad f_c \leq 300MHz$$

$$a(h_{re}) = 3.2(\log 11.75 h_{re})^2 - 4.97 \qquad f_c \geq 300MHz$$

Walfisch and Bertoni Model

This complex model calculates the received signal strength at the street level by taking into account the effect of all the surrounding buildings. It is currently being considered for the IMT-2000 standard.

2.5 Modulation

Modulation by US Navy

http://www.dxing.com/modesand.htm

http://www.williamson-labs.com/480_mod.htm

Assignment Questions

Quick Quiz

1. [Maxwell, Hertz] was the first to predict mathematically the existence of electromagnetic waves.
2. The UHF band runs from 0.3 to 3 GHz. [True, False]
3. The speed of light in free space is approximately 3×10^{8} km per second. [True, False]
4. A time varying electric field produces a time varying magnetic field, but the converse is not true. [True, False]
5. TEM waves can propagate in a guided medium. [True, False]
6. The troposphere is [higher, lower] in altitude than the stratosphere.
7. If a wave is [refracted, reflected] it is no longer considered a direct wave.
8. [Vertically, Horizontally] polarized waves are not likely to be reflected without significant loss.
9. Surface waves are generally [horizontally, vertically] polarized.
10. The electric field of horizontally polarized radio waves [are, are not] short-circuited when they reflect from the ground.
11. Doppler shifting occurs if the observed object is moving but not if the observer is moving. [True, False]
12. The radio horizon is [longer, shorter] than the optical horizon.
13. The ionosphere is [higher, lower] during the daytime than nighttime.
14. Radio shadow zones have very sharp cut-off due to Huygens' principle. [True, False]
15. Radio propagation methods for predicting cellular phone performance in urban areas are essentially [analytical, empirical].
16. Rayleigh fading is also known as flat fading. [True, False]
17. The impedance of a vacuum to an electromagnetic field is [0, 377, ∞] Ω.
18. Reflected waves may cause constructive and destructive interference with direct waves. [True, False]
19. Multipath fading can be easily corrected. [True, False]
20. [Rayleigh, Ricean] fading is characterized by having a strong direct signal.
21. Spherical spreading is also known as Newton's principle. [True, False]

Analytical Questions

1. A mobile radio transmitter has the following characteristics:

    Operating frequency = 250 MHz

    Radiated power = 150 watts

    Transmit antenna is a 1/2 λ dipole

    Antenna height = 15 meters

    The receiving antenna has the following characteristics:

    Is a 1/2 λ dipole

    Antenna height = 15 meters

    Distance = 35 km

    Assuming a flat earth:

    a) Calculate the received signal strength

    b) What would be the expected increase in field strength if the transmitting antenna were changed to a 4-element broadside array?

    c) Make a sketch of the transmitting antenna showing its correct orientation

Composition Questions

1. Explain what causes and affects super and sub refraction of radio waves in the atmosphere.

_____ Notes _____

For Further Research

VLF

http://www.vlf.it/

Longwave

http://www.lwca.org/

http://www.anarc.org/lwca/

Shortwave

http://www.shortwave.org/

http://www.anarc.org/naswa/

Radio Wave Propagation

http://www.ips.gov.au/Main.php?CatID=8&SecID=5&SecName=Other%20Topics&SubSecID=3&SubSecName=Radio%20Communication

Antennas

http://www.andrew.com/

http://www.antenna.com/

http://www.comtelco.net/index.html

http://www.csawrls.com/

http://www.sinctech.com/

http://www.radiowavesinc.com/

http://www.lingoinc.com/antenna.htm

http://www.afcsat.com/

http://www.smartantennas.com/

http://www.webproforum.com/arraycomm/

Astronomical Observatory

http://www.astro.ku.dk/

_____ Notes _____

Wireless Networking Products

http://www.solectek.com/techlib/index.html

http://www.greamerica.com/

http://www.micropath.com/