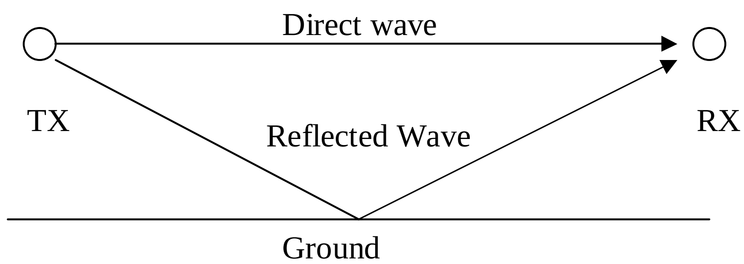
Basics of Radio Wave Propagation

Iulian Rosu, YO3DAC / VA3IUL, http://www.qsl.net/va3iul/

Propagation Modes

- Ground-wave propagation
    - Follows contour of the earth
    - Can Propagate considerable distances



- Ground Wave = Direct Wave + Reflected Wave + Surface Wave
- At MF and in the lower HF bands, aerials tend to be close to the ground (in terms of wavelength). Hence the direct wave and reflected wave tend to cancel each other out (there is a 180 degree phase shift on reflection). This means that only the surface wave remains.
- A surface wave travels along the surface of the earth by virtue of inducing currents in the earth. The imperfectly conducting earth leads to some of its characteristics. Its range depends upon: Frequency, Polarization, Location and Ground Conductivity.
- The surface waves dies more quickly as the frequency increases:

$$Range(km) = \frac{200}{\sqrt{f\,(MHz)}}$$

- Sky-wave propagation
    - Signal reflected from ionized layer of atmosphere back down to earth
    - Signal can travel a number of hops, back and forth between ionosphere and earth's surface
    - Reflection effect caused by refraction
- Line-of-Sight propagation (LOS)
- Non-LOS propagation

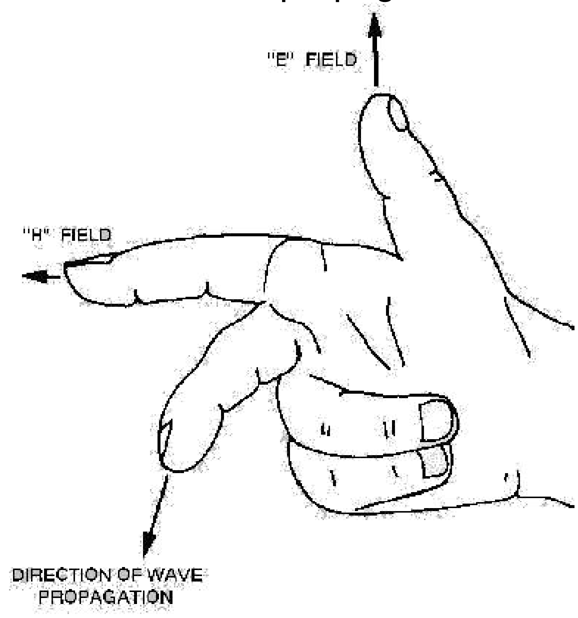
Wave Polarization

- The plane of polarization of a radio wave is the plane in which the E-field propagates with respect to the Earth.
    - If the E-field component of the radiated wave travels in a plane perpendicular to the Earth's surface (vertical), the radiation is said to be VERTICALLY POLARIZED.
    - If the E-field propagates in a plane parallel to the Earth's surface (horizontal), the radiation is said to be HORIZONTALLY POLARIZED.

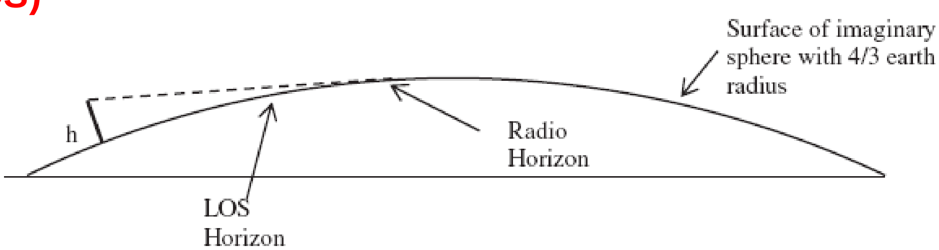
- o CIRCULAR POLARIZATION produces an electric field that rotates as it travels. Circular polarization falls into two categories, depending on the direction of rotation: ‘right-hand circular’ and ‘left-hand circular’.
- The polarization of a radio wave can rotate as it propagates.
  - o If a Linear polarized wave (vertical or horizontal) reflects off a surface that is not vertical or horizontal, its polarization will be changed.
  - o One advantage of Circular polarization is that rotation does not affect it: it remains circular. For this reason, circular polarization is commonly used in links to geostationary satellites at frequencies below 10 GHz.

Direction of Propagation

- If you know the directions of the E and H components, you can use the "right-hand rule" to determine the direction of wave propagation.



Line-of-Sight (LOS)



- Optical line of sight

$$d = 3.57\sqrt{h}$$

- Effective, or radio, line-of-sight

$$d = 3.57\sqrt{\mathrm{K}h}$$

  - o d = distance between antenna and horizon (km)
  - o h = antenna height (m)
  - o K = adjustment factor to account for refraction, rule of thumb K = 4/3
- Maximum distance between two antennas for LOS propagation:

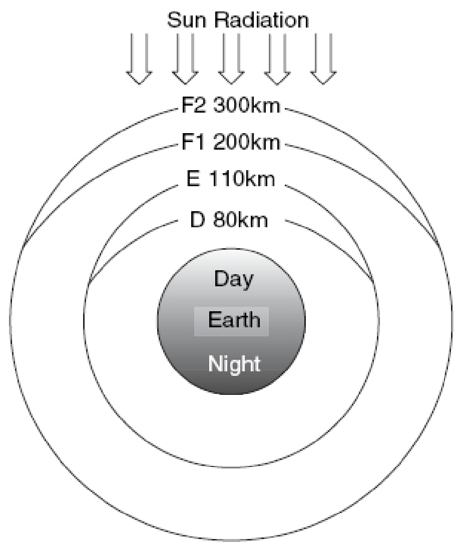
$$3.57\left(\sqrt{\mathrm{K}h_1} + \sqrt{\mathrm{K}h_2}\right)$$

- $h1$ = height of antenna one
- $h2$ = height of antenna two

- LOS Wireless Transmission Impairments
  - Free space loss
  - Attenuation and Scattering
  - Atmospheric absorption
  - Ducting
  - Multipath and Fading
  - Refraction
  - Reflection

Non-LOS Propagation

- Indirect or Obstructed Propagation
  - The efficacy of indirect propagation depends upon the amount of margin in the communication link and the strength of the diffracted or reflected signals.
  - The operating frequency has a significant impact on the viability of indirect propagation, with lower frequencies working the best.
- Tropospheric Propagation
  - consists the reflection or refraction of the RF waves from temperature and moisture layers in the atmosphere.
- Ionospheric Propagation
  - ionosphere is an ionized plasma around the earth that is essential to sky-wave propagation and provides the basis for nearly all HF communications beyond the horizon. These are the ionospheric layers around the Earth:

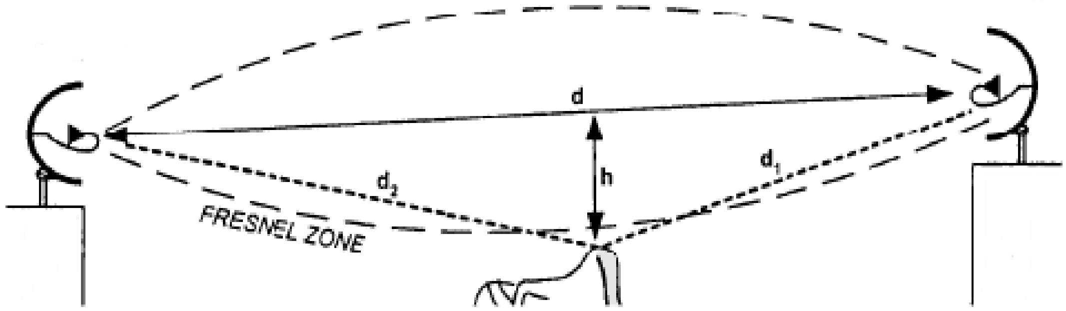


Ionospheric Layers

Fresnel Zone

- Radio waves diffracted by objects can affect the strength of the received signal.

This happens even though the obstacle does not directly obscure the direct visual path. This area, known as the "Fresnel Zone", and must be kept clear of all obstructions.



$$h = 17.3\sqrt{\frac{d_1 d_2}{f(d_1 + d_2)}}$$

d_1 and d_2 = km, f = GHz, h = meters

- The 1st Fresnel zone is a spheroid space formed within the trajectory of the path when the path difference when radio wave energy reaches the receiver by the shortest distance, and when it gets there by another route, is within $\lambda/2$.
- Odd-numbered Fresnel zones have relatively intense field strengths, whereas even numbered Fresnel zones are nulls.
- When the radio signal pass from site A to site B, the lack of adequate Fresnel Zone clearance caused signal diffraction, and degradation of the radio signal.
- If the 1st Fresnel zone is not clear, then free-space loss does *not* apply and an adjustment term must be included. To avoid this have to:
    - Use an antenna with a narrower lobe pattern, usually a higher gain antenna will achieve this.
    - Raise the antenna mounting point on Site A and/or Site B.

Free Space Loss

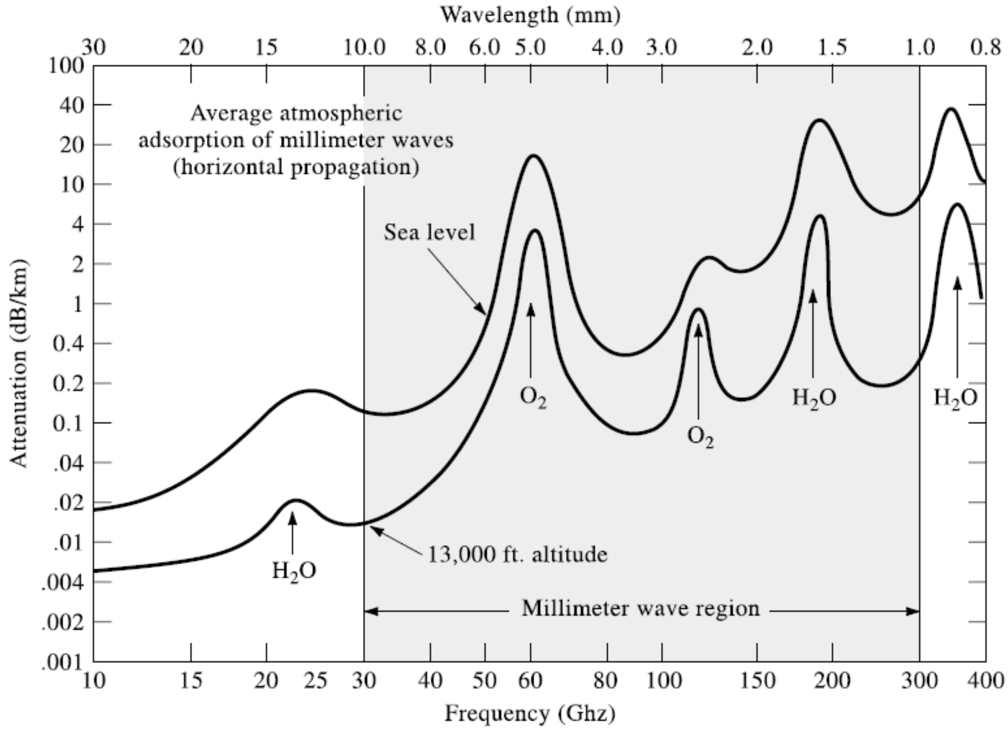
- Radio waves travel from a source into the surrounding space at the “speed of light” (approximately 3.0×10^8 meters per second) when in “free space”. Literally, “free space” should mean a vacuum, but clear air is a good approximation to this.

Free Space Path Loss$_{(dB)}$ = 27.6$_{(dB)}$ – 20*LOG[Frequency$_{(MHz)}$] – 20*LOG[Distance$_{(m)}$]

- The equations for free-space loss and link-loss can be used between two antennas only for distances greater than the near-field distance of each antenna.

Atmospheric absorption

- The atmosphere, due to the many different gases, water and particles contained therein, absorbs and transmits many different wavelengths of electromagnetic radiation.
- The wavelengths that pass through the atmosphere unabsorbed constitute the "atmospheric windows."
- A significant atmospheric effect is that of attenuation due to rain. Below about 10GHz, rain fading is not very significant, but, at higher microwave frequencies, it becomes the major factor limiting path length, particularly in areas that experience high levels of rainfall. In addition to the attenuation of electromagnetic waves, rain and other precipitation tend to cause depolarization of the wave.



Ducting

- A duct is something that will confine whatever is traveling along it into a narrow 'pipe'.
- The atmosphere can assume a structure that will produce a similar effect on radio waves. When a radio wave enters a duct it can travel with low loss over great distances. The atmosphere will then act in the manner of a giant optical fiber, trapping the radio wave within the layer of high refractive index.
- A wave trapped in a duct can travel beyond the radio horizon with very little loss, producing signal levels within a few dB of the free-space level.

Scattering

- When an electromagnetic wave is incident on a rough surface, the wave is not so much reflected as "scattered".
- Scattering is the process by which small particles suspended in a medium of a different index of refraction diffuse a portion of the incident radiation in all directions.
- Scattering occurs when incoming signal hits an object whose size in the order of the wavelength of the signal or less.

Reflection

- Reflection occurs when signal encounters a surface that is large relative to the wavelength of the signal
- Radio waves may be reflected from various substances or objects they meet during travel between the transmitting and receiving sites.
- The amount of reflection depends on the reflecting material.
  - o Smooth metal surfaces of good electrical conductivity are efficient reflectors of radio waves.
  - o The surface of the Earth itself is a fairly good reflector.
- The radio wave is not reflected from a single point on the reflector but rather from an area on its surface. The size of the area required for reflection to take place depends

on the wavelength of the radio wave and the angle at which the wave strikes the reflecting substance.

- When radio waves are reflected from flat surfaces, a phase shift in the alternations of the wave occurs
- The shifting in the phase relationships of reflected radio waves is one of the major reasons for fading.

Refraction

- Refraction it is the bending of the waves as they move from one medium into another in which the velocity of propagation is different.
- This bending, or change of direction, is always toward the medium that has the lower velocity of propagation.

Difraction

- Diffraction is the name given to the mechanism by which waves enter into the shadow of an obstacle.
- Diffraction occurs at the edge of an impenetrable body that is large compared to wavelength of radio wave.
- A radio wave that meets an obstacle has a natural tendency to bend around the obstacle. The bending, called diffraction, results in a change of direction of part of the wave energy from the normal line-of-sight path. This change makes it possible to receive energy around the edges of an obstacle.
- The ratio of the signal strengths without and with the obstacle is referred to as the diffraction loss. The diffraction loss is affected by the path geometry and the frequency of operation. The signal strength will fall by 6 dB as the receiver approaches the shadow boundary, but before it enters into the shadow region.
- Deep in the shadow of an obstacle, the diffraction loss increases with 10*log(frequency). So, if double the frequency, deep in the shadow of an obstacle the loss will increase by 3 dB. This establishes a general truth, namely that radio waves of longer wavelength will penetrate more deeply into the shadow of an obstacle.

Multipath

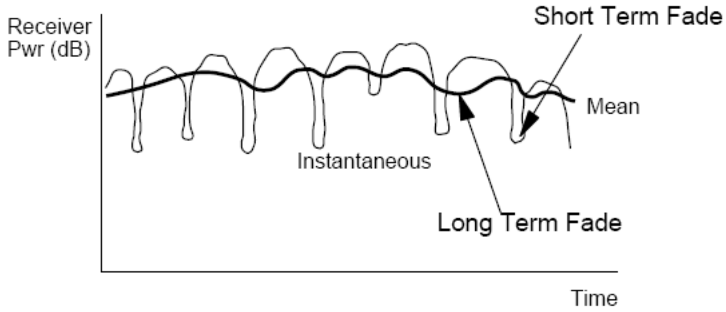
- Multipath is a term used to describe the multiple paths a radio wave may follow between transmitter and receiver. Such propagation paths include the ground wave, ionospheric refraction, reradiation by the ionospheric layers, reflection from the Earth's surface or from more than one ionospheric layer, etc.
- If the two signals reach the receiver in-phase (both signals are at the same point in the wave cycle when they reach the receiver), then the signal is amplified. This is known as an “upfade.” If the two waves reach the receiver out-of-phase (the two signals are at opposite points in the wave cycle when they reach the receiver), they weaken the overall received signal. If the two waves are 180º apart when they reach the receiver, they can completely cancel each other out so that a radio does not receive a signal at all. A location where a signal is canceled out by multipath is called a “null” or “downfade.”

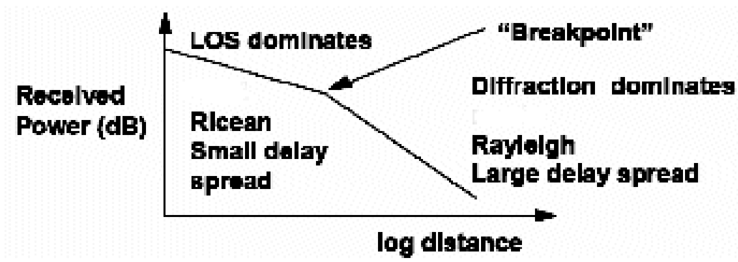
- If the reflecting surfaces that cause the multipath situation do not move, the locations of the maxima and minima will not move, hence the name ‘standing wave’.
- The depth of the null in a standing wave pattern is dependent upon the magnitude of the reflection coefficient of any reflecting surface.
- The Effects of Multipath Propagation
    - Multiple copies of a signal may arrive at different phases
    - If phases add destructively, the signal level relative to noise declines, making detection more difficult.
    - Dealy Spread resulting in Intersymbol interference (ISI) - one or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit

Fading

- There is a large dependence of fading on distance.
    - The probability of a fade of a particular depth increases with the cube of distance. Thus, as the distance is doubled, the probability of a particular fade depth increases by a factor of eight. Or, alternatively, the fade for a given probability increases by 9 dB. So, doubling the distance will increase the free-space loss by 6 dB, and increase the probability of fading by 9 dB, thus increasing the overall link-budget loss by 15 dB.
- There is a slight dependence of fading on frequency. Increasing the frequency by 1GHz will decrease the probability of a fade by a factor of 1.08.
- There is a fairly strong dependence of fading on the height of the path above sea level.
    - There is simply less atmosphere at higher altitudes and therefore the effect of atmospheric fading is smaller.
    - For every 1000 meter increase in altitude the required fade margin reduces by 10 dB.
- Types of Fading
    - Fast fading - occurs when the coherence time of the channel is small relative to the delay constraint of the channel. Fast fading causes rapid fluctuations in phase and amplitude of a signal if a transmitter or receiver is moving or there are changes in the radio environment (e.g. car passing by). If a transmitter or receiver is moving, the fluctuations occur within a few wave lengths. Because of its short distance fast fading is considered as small-scale fading.
    - Slow fading - arises when the coherence time of the channel is large relative to the delay constraint of the channel. Slow fading occurs due to the geometry of the path profile. This leads to the situation in which the signal gradually gets weaker or stronger.
    - Flat fading – occurs when the coherence bandwidth of the channel is larger than the bandwidth of the signal.
    - Selective fading – occurs when the coherence bandwidth of the channel is smaller than the bandwidth of the signal.
    - Rayleigh fading - assume that the magnitude of a signal that has passed through a communications channel will vary randomly.

- Ricean fading - occurs when one of the paths, typically a line of sight signal, is much stronger than the others.
- Nakagami fading - occurs for multipath scattering with relatively larger time-delay spreads, with different clusters of reflected waves.
- Weibull fading - considers a signal composed of clusters of one multipath wave, each propagating in a non-homogeneous environment.





Diversity Techniques

Fade margin on the transmitter path is not an efficient solution at all, and one alternate solution is to take the advantage of the statistical behavior of the fading channel.

This is the basic concept of Diversity, where two or more inputs at the receiver are used to get uncorrelated signals.

- Frequency Diversity
  - Different frequencies means different wavelengths. The hope when using frequency diversity is that the same physical multipath routes will not produce simultaneous deep fades at two separate wavelengths.
- Space Diversity
  - Deep multipath fade have unlucky occurrence when the receiving antenna is in exactly in the 'wrong' place. One method of reducing the likelihood of multipath fading is by using two receive antennas and using a switch to select the better signal. If these are physically separated then the probability of a deep fade occurring simultaneously at both of these antennas is significantly reduced.
- Angle Diversity
  - In this case the receiving antennas are co-located but have different principal directions.
- Polarization Diversity
  - This involves simultaneously transmitting and receiving on two orthogonal polarizations (e.g. horizontal and vertical). The hope is that one polarization will be less severely affected when the other experiences a deep fade.
- Time Diversity
  - This will transmit the desired signal in different periods of time.
  - The intervals between transmissions of the same symbol should be at least the coherence time so that different copies of the same symbol undergo independent fading.

Propagation within a building

- The energy present in an incident radiowave that does not reflect from a surface must penetrate that surface.
  - The reflection coefficient of the material affects the amount that penetrates into the material.
  - Once inside the material, the wave will travel through the material. In most materials, the strength will decay as it travels.
  - Good insulators tend to allow the wave to propagate through them with only low loss.
  - Good conductors tend to reflect the radio wave at its surface and very little signal passes through
- Signal propagation within a building is strongly dependent upon the topology, construction and content of the building and is influenced by the following:
  - Reflection from flat conducting surfaces such as metal cladding, galvanized roofing, foil backed plasterboard, metal coated anti-reflection glazing or any surfaces greater than a wavelength in size.
  - Re-radiation from thin conductors such as pipe work, electrical wiring, steel frame works and any conductor of greater than a half wave in length.
  - Absorption by lossy materials such as damp concrete, stonework and people.
  - People moving around: Additional multipath induced attenuation of 10 dB
  - Buildings with few metal and hard partitions: RMS delay spread of 30 to 60 ns
  - Buildings with metal/open aisles: RMS delay spread of up to 300 ns
  - Between floors:
    - Concrete/steel flooring yields less attenuation than steel plate flooring
    - Metallic tinted windows yield greater attenuation 15 dB for first floor separation, 6 - 10 dB for next four floors, 1 - 2 dB for each additional floor of separation
- A building with an open-plan structure whose walls contain large glass windows will introduce little extra path loss (less than 5 dB), whereas a building with thick stone walls and small windows and an internal structure consisting of many solid walls can introduce extra path loss amounting to several tens of dB.
- Physical Effects of Indoor Propagation:
  - Signal decays much faster
  - Coverage contained by walls, etc.
  - Walls, floors, furniture attenuate/scatter radio signals
- Indoor Propagation Path Loss formula:

$$Path\_Loss_{[dB]} = Unit\_Loss_{[dB]} + n*10*\log(d) = k*F + N*W_{[dB]}$$

  where:
  Unit loss = power loss (dB) at 1m distance
  n = power-delay index
  d = distance between transmitter and receiver
  k = number of floors the signal traverses
  F = loss per floor
  N = number of walls the signal traverses
  W = loss per wall

Refrences:

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