Radio Propagation

Introduction

The transmission medium represents the most critical part of a communication link. An ideal medium will only introduce time delay, and a constant attenuation factor. Any deviation either amplitude or time delay results in signal distortion and requires compensation in the design of communication systems.

In wireless communication, the transmission medium can vary depending on the frequency of transmission. In the following sections we study the different mechanisms of radio wave propagation and basic propagation models.

- **Modes of propagation and the uses of the different frequency bands**

The origins of radio-communications go back to the early work of Hertz in the 1880's which showed that electromagnetic wave propagation (at Ultra High Frequency, UHF) was possible in free space which was later practically demonstrated in 1895 by Marconi who established a Low Frequency (LF) radio link over a distance of a few miles using two elevated antennas. Two years later Marconi set-up a link between the Isle of Wight and a tugboat over a distance of 18 miles which can be termed as the first mobile radio link.

To regulate the different services the radio frequencies which extend from 3 kHz-300 GHz are divided by international agreement into 'bands' which are classified as follows:

Frequency bands	frequency range
Extremely Low Frequency (ELF)	< 3 kHz
Very Low Frequency (VLF)	3-30 kHz
Low Frequency	30-300 kHz
Medium Frequency	300 kHz-3 MHz
High Frequency	3-30 MHz
Very High Frequency (VHF)	30-300 MHz
Ultra High Frequency (UHF)	300 MHz-3 GHz
Super High Frequency (SHF)	3-30 GHz
Extra High Frequency (EHF)	30-300 GHz

Electromagnetic waves radiated from a transmitting antenna travel to the receiver in several ways depending on the frequency (see figure 1 for a possible classification of modes of radiowave propagation).

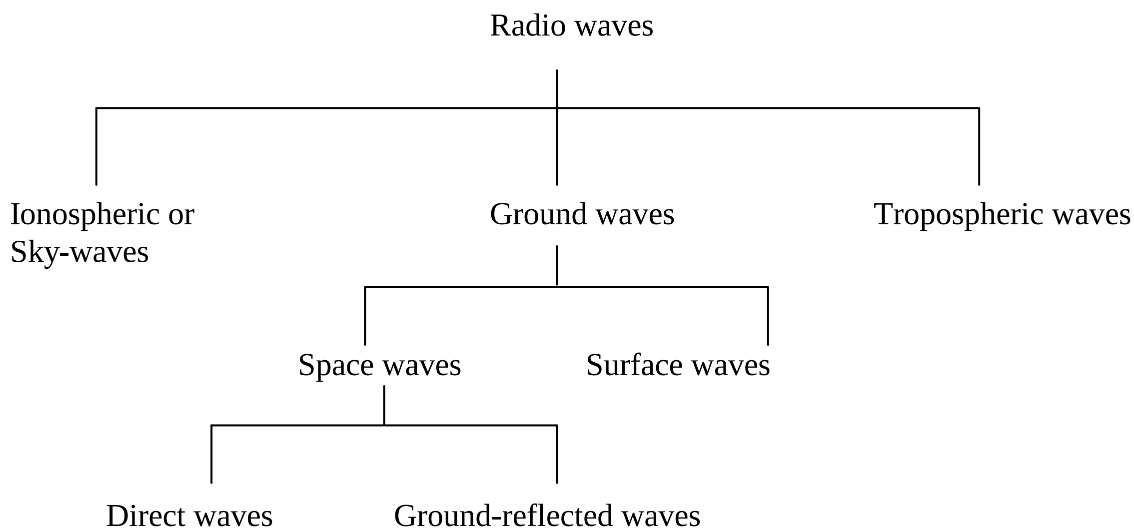

Figure 1. Modes of radiowave propagation (after Parsons)

Waves travelling via the ionosphere which is an ionised region of the atmosphere extending above the earth from about 60 - 500 km are termed sky-wave. Waves travelling via the lower parts of the atmosphere (below 17 km) are termed tropospheric waves and permit long range propagation of waves between about 300 MHz and 10 GHz via forward scatter.

VLF waves are transmitted via a waveguide effect formed between the D-layer (the lower part of the ionosphere) and the earth and is used to transmit world wide telegraphy, navigation and communication with submerged submarine since higher frequencies get rapidly attenuated in water. LF and MF propagate via ground wave where LF is mainly a surface wave and is used for navigation, and MF is normally surface wave in the day and skywave via the D-layer at night (AM radio). VHF and UHF propagation is space wave including both ground-reflected and direct waves. SHF usually called microwave also includes frequencies above 1.5 GHz and is mainly line of sight (LOS). This band is used for satellite communication, short range communications and point to point radio links. Finally, the EHF band termed as millimetre band permits the use of very large bandwidths where propagation is mainly by Line Of Sight (LOS) and ground reflection is insignificant due to losses. Only over very smooth grounds or water surfaces does ground reflection become significant. These frequencies are affected by scattering in rain and snow and at certain frequencies absorption by fog, water vapour and other atmospheric gases as illustrated in Figure 2. These frequency bands are mainly used for very short secure communication systems such as the 60 GHz band.

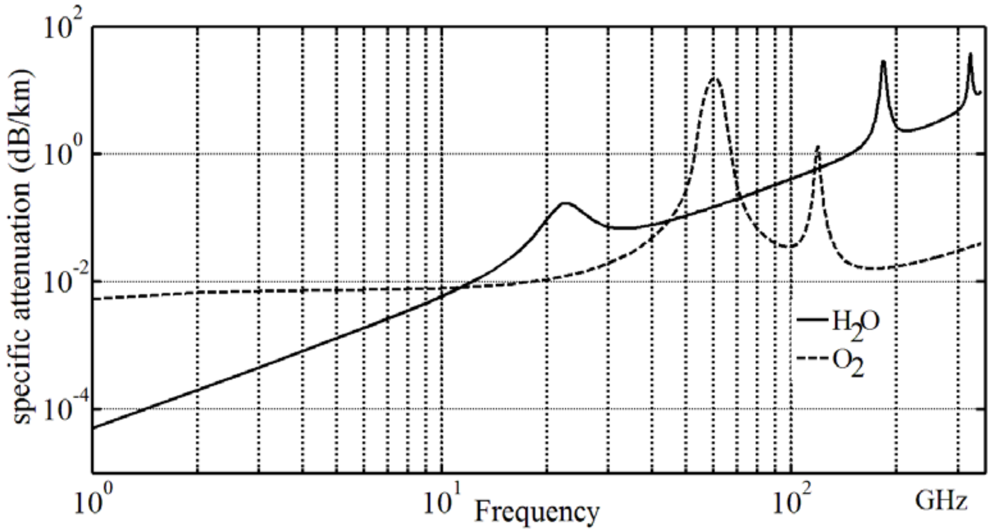

Figure 2. Attenuation by oxygen and water vapour at sea level.

Frequency bands of mobile radio

General considerations

1. Antenna design: efficient transmission requires that the antenna size be directly proportional to the wavelength. Hence, frequencies should be chosen to enable the use of suitable antennas to be mounted on vehicles, base station masts, and on hand-portable equipment.
2. Range: To enable the reuse of allocated frequencies the range covered by the chosen band should not exceed a few km's. If the signal propagates too far it would cause interference to other users. Macrocells 1-35 km (rural area GSM), microcells 100 m-1 km (urban area UMTS) and picocell < 100 m (indoor DECT).
3. Power: it is necessary to use frequencies which permit the generation of the necessary RF power whilst remaining small in physical size.
4. Penetration into buildings: to enable two-way communication in urban areas, signals propagate into and around buildings. Hence, it is necessary to choose frequencies that minimise the losses due to buildings.

For these reasons, mobile radio communications is mainly in the VHF and UHF bands although, covert communication, future 5G cellular networks and short range local area networks are currently being investigated in the mm band. In addition, vertically polarised antennas tend to be more suitable at these frequencies than horizontal polarisation because (i) it produces a higher field strength near the ground, and (ii) vertical antennas are more robust for handheld and vehicle mounting.

The exact frequencies within the VHF and UHF bands that are allocated for various services are agreed by the ITU (International Telecommunication Union) which organises a world administrative radio conference (WARC) every twenty years at which regulations are revised and updated and changes in allocations are agreed. In each country, the use of the spectrum is controlled by a regulatory body such as the Ofcom in the UK and the Federal Communications Commission in the USA.

Table 1 gives a list of major mobile communication systems in Europe

Standard	Frequency	Channel Bandwidth	Access Technique	Duplex Technique
TETRA	400 MHz	25 kHz	TDMA	FDD
GSM	900 MHz	200 kHz	TDMA	FDD
IRIDIUM	1.6 GHz	20-25 kHz	TDMA	TDD
UMTS	2 GHz	Few MHz	CDMA	TDD+FDD

Table 1: Mobile radio systems in Europe

- **Propagation Mechanisms**

The main propagation mechanisms are line of sight (LOS), reflection, refraction, diffraction and scattering. These various mechanisms cause variations in the received signal strength which are characterised either by slow variations known as large scale variations or by fast signal fluctuations known as small scale variations.

- ***Line of sight*** propagation occurs when there is an unobstructed clear propagation path between the transmitter and the receiver such as that shown in Figure 3 at location 1. In this case the signal strength can be predicted by what is known as 'free space loss' which is mainly a function of frequency and distance.

- ***Reflection*** occurs when an electromagnetic wave impinges upon a smooth surface with very large dimensions with respect to the wavelength of the propagating wave. The earth surface, buildings and walls are common reflecting sources (locations 2 and 3 in Figure 3).

- ***Diffraction*** occurs when the transmission path between the receiver and the transmitter is obstructed by a dense body with large dimensions compared to the wavelength or by a surface with large irregularities. The diffraction phenomenon induces formation of secondary waves behind the obstructing body (Huygens' principle). It is relevant to take this effect into account when there is no LOS component in the radio path. Diffraction is usually referred to as shadowing since the diffracted field can reach the receiver even when shadowed by an impenetrable obstacle such as a hill top or a building (location 5-7 in Figure 3).

- ***Scattering*** occurs when the radio wave impinges on large surfaces or small objects (dimensions on the order of a wavelength or less). It may also be produced by irregularities in the channel such as in tropospheric scatter. The scattering mechanism causes the energy to spread out in all directions. Buildings, windows, foliage, and street signs are potential scatterers.

- ***Refraction*** occurs due to variations of the refractive index in the atmosphere such as in the troposphere and in the ionosphere. This phenomenon is similar to the propagation of light in a prism where different frequencies travel over different paths. Refraction is important for HF frequencies and affects VHF and UHF when variations in the refractive index occur over a large scale resulting in radiowaves being diffracted beyond the horizon.

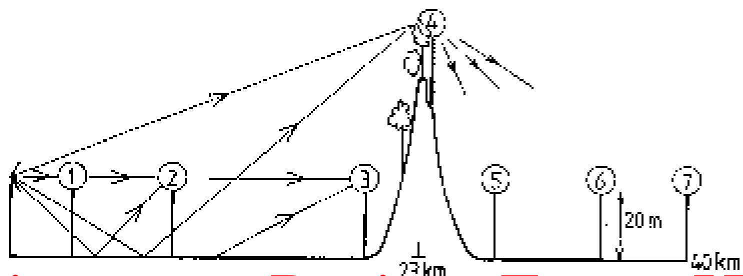

Figure 3 Path Loss Prediction Models

- **Large scale variations**

These are variations in the mean of the received signal strength for an arbitrary transmitter-receiver separation. Various models are available to predict the path loss. This is a very important step in planning a mobile radio system that will provide efficient and reliable coverage of a specified area. Path loss models describe the signal attenuation between the transmitter and receiver as a function of the propagation distance and other parameters. Some models can include many details of the terrain profile to estimate the signal attenuation.

In the example of Figure 3, the most appropriate path loss model depends on the location:

- <u>At location 1</u>, "*free space loss"* is likely to give an accurate estimate of path loss.

- <u>At locations 2 and 3</u>, a strong line-of-sight is present, but ground reflections can significantly influence path loss. The "*plane earth loss model"* appears appropriate,

- <u>At location 4</u>, free space loss needs to be corrected for significant *diffraction losses*, caused by trees cutting into the direct line of sight.

- <u>At locations 5-7</u>, path loss prediction is more difficult than at the other locations. *Ground reflection* and *diffraction losses* interact.

- **Free Space Propagation**

For propagation distances *d* much larger than the antenna size, the far field of the generated electromagnetic wave dominates all other components. In free space, the energy radiated by an omni-directional antenna is spread over the surface of a sphere.

The power density W (Watts/m^2) at distance d from a transmitter with power P_T (Watts) and antenna gain G_T (dimensionless) is:

$$W = P_T G_T / \left(4\pi d^2\right)$$

where $4\pi d^2$ is the surface area of a sphere of radius d. The available power P_R at a receive antenna with gain G_R and effective area (or aperture) A is

$$P_R = \frac{P_T G_T}{4\pi d^2} A = \frac{\lambda^2}{(4\pi d)^2} G_T P_T G_R \qquad (1)$$

with $G_R = 4\pi A/\lambda^2$. The product $G_T P_T$ is called *the effectively radiated power (ERP).*

Equation 1 can be rewritten as:

$$\frac{P_R}{P_T} = G_T G_R \left[\frac{\lambda}{4\pi d}\right]^2 \qquad (2)$$

which is known as the "*Free Space*" equation or *Friis* equation.

Using the well known relationship between the wavelength λ, frequency f, and velocity of propagation c, ($c = \lambda f$) Friis' equation can be rewritten as

$$\frac{P_R}{P_T} = G_T G_R \left[\frac{c}{4\pi f d}\right]^2 \qquad (3.a)$$

The propagation loss (or path loss) is conveniently expressed in dB

$$L_f = 10\log_{10}\frac{P_T}{P_R} = -10\log_{10} G_T - 10\log_{10} G_R + 20\log_{10} f + 20\log_{10} d - k \qquad (3.b)$$

where f is in Hz, d in meters and:

$$k = 20\log_{10}\frac{c}{4\pi} = 147.6$$

For isotropic antennas (antennas which radiate uniformly in all directions and hence their gain is equal to 1) equation 3.b. can also be expressed as

$$L_f\,(\text{dB}) = 10\log_{10}(P_T/P_R) = 32.44 + 20\log_{10} f_{\text{MHz}} + 20\log_{10} d_{\text{km}} \qquad (4)$$

Equation 3.a shows that free-space propagation obeys an inverse square law with range d, so that the received power falls by 6 dB when the range is doubled (or reduced by 20 dB when the range is multiplied by 10) i.e. 6 dB/octave or 20 dB/decade. Similarly, the path loss also increases with the square of the transmission frequency, so that losses also increase by 6 dB if the frequency is doubled. High gain antennas can be used to compensate for this loss and such antennas are relatively easy to design at frequencies in and above the VHF band.

NOTE: Friis free space equation is only valid for values of d which are in the far-field of the transmitting antenna which is defined as the region beyond the distance d_f

$$d_f = \frac{2D^2}{\lambda} \qquad (5)$$

where D is the largest physical linear dimension of the antenna and $d_f >> \lambda$ and $>> D$. Consequently, Friis equation cannot be used for d=0 and usually a reference distance $d_o \geq d_f$ is used for the close-in power.

Eqn. 3.a can also be written in terms of the power received at two different distances as

$$\frac{P_R(d_2)}{P_R(d_1)} = \left(\frac{d_1}{d_2}\right)^2 \qquad (6)$$

Setting $d_1 = d_o$ equation 6 can be used to find the power at distances greater than d_o.

For practical systems in the 1-2 GHz range d_o is typically 1 m in indoor environments and 100 m or 1 km in outdoor environments.

Example

A transmitter produces 50 W of power applied to unity gain antenna at a 900 MHz carrier frequency. (a) Express the transmitter power in dBm and dBW. (b) Find the received power in dBm at a free space distance of 100 m and 10 km from the transmit antenna. Assume unity gain for the receive antenna.

Answer:

(a) P_R =50 W

dBW refers to power relative to 1 W and dBm refers to power relative to 1 mW.

P_T (dBW) = 10log$_{10}$ (50W / 1W) = 17 dBW
P_T (dBm) = 10log$_{10}$ (50x1000 /1 mW) = 47 dBm.

(b) Using equation 4, the loss can be found to be 71.52 dB.

Hence, P_R=10log$_{10}$$P_T$ - 71.52 dB = -54.5 dBW or –24.5 dBm.

(c) Using equation 6, the received power at 10 km is

P_R (10 km) = P_R (100 m) + 20 log$_{10}$ (100/10,000) = -24.5 – 40 = -64.5 dBm.

Relating power to electric field

While cellular telephone operators mostly calculate in received power in the planning of the coverage area of broadcast transmitters, it is recommended to use the *electric field strength E* at the location of the receiver.

$$W = \frac{E^2}{\eta} \qquad 7$$

$$\frac{E^2}{120\pi} = \frac{P_T G_T}{4\pi d^2} \Rightarrow E = \frac{\sqrt{30 P_T G_T}}{d} \qquad 8$$

where η =120 π Ω = 377Ω is the characteristic wave impedance of free space:

The *maximum useful power* delivered to the terminals of a matched receiver is:

$$P = \frac{E^2 A}{\eta} = \frac{E^2}{120\pi}\frac{\lambda^2 G_R}{4\pi} = \left(\frac{E\lambda}{2\pi}\right)^2 \frac{G_R}{120} \qquad 9$$

For an antenna matched to the receiver impedance, the power delivered to the load is

$$P_R = i^2 R_{ant} = \frac{v_{rms}^2}{(2R_{ant})^2} \times R_{ant} = \frac{v_{rms}^2}{4R_{ant}} \qquad (10)$$

Example

Assume a receiver is located 10 km from a 50 W transmitter. The carrier frequency is 900 MHz and the gain of the transmitter and receiver antennas is 1 and 2, respectively. Find (a) the power at the receiver, (b) the magnitude of the electric field at the receive antenna, and (c) the rms voltage applied to the receiver input assuming the receiver antenna has a purely real impedance of 50 Ω and is matched to the receiver.

Answer:

(a) The received power can be found using either equation 4 or equation 9. Using equation 4, the loss can be found to be equal to 111.46 dB.

$P_R = 10\log_{10}(50) + 10\log_{10}(2) - 111.46 = -91.46$ dBW = -61.46 dBm

(b) Using equation 8 the electric field $= \dfrac{\sqrt{30 P_t G_t}}{d} = \dfrac{\sqrt{30 \times 50}}{10{,}000} = 0.0039 \quad V/m$

(c) Using equation 10, the voltage at the receiver input V= $\sqrt{7.133 \times 10^{-10} \times 4 \times 50}$ =0.374 mV

Propagation over a Plane Earth (or over a plane reflecting surface)

The free space equation applies only under very restricted conditions. In practical situations there are almost always obstructions in or near the propagation path or surfaces from which the radio waves can be reflected. A very simple case is of propagation between two elevated antennas within line of sight of each other, above the surface of the earth as shown in Figure 4. To derive expressions for the received signal, Figure 5 shows the graphical representation over a flat earth where $d >> h_T, h_R$. Note that for short links where d is less than a few tens of kilometers, the flat curvature can be neglected permitting the flat earth assumption of Figure 5.

Figure 4. Propagation over a Plane Earth

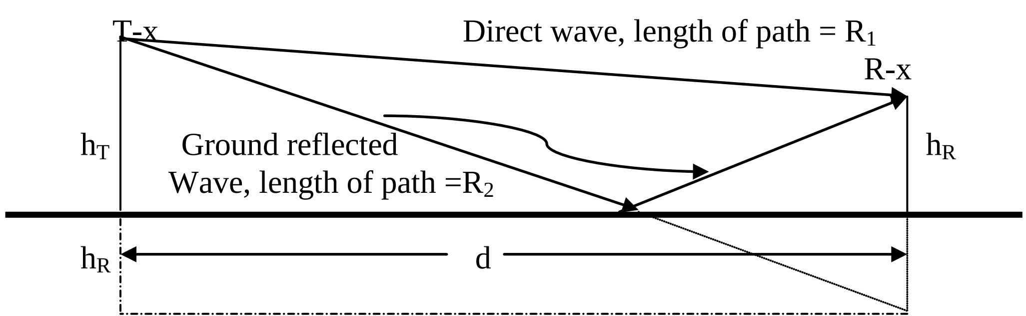

Figure 5. Graphical representation of propagation over a flat earth

For (theoretical) isotropic antennas above a plane earth as in Figure 5, the received electric field strength consists of two components: the direct wave and the reflected wave. The reflected component electric field strength depends on the reflection coefficient of the earth, ρ. The resultant received electric field is given by equation 11 below

$$E = E_O\left(1 + \rho \ \exp(-j\Delta)\right) \qquad 11$$

where E_o is the field strength for propagation in free space, and Δ is the phase difference between the waves. This expression can be interpreted as the complex sum of a direct line-of-sight wave, and a ground-reflected wave.

The p*hase difference* between the direct and the ground-reflected wave can be found considering Figure 5. The phase difference is proportional to the difference in propagation time between the two paths i.e. R_2-R_1. From Figure 5 and using the approximation $\sqrt{1+\varepsilon} \cong 1+\frac{\varepsilon}{2}$, expressions for R_1 and R_2 can be found to be

$$R_1 = d\left[1+\frac{(h_T - h_R)^2}{d^2}\right]^{1/2} \cong d\left[1+\frac{1}{2}\left(\frac{h_T - h_R}{d}\right)^2\right]$$

and

$$R_2 = d\left[1+\frac{(h_T + h_R)^2}{d^2}\right]^{1/2} \cong d\left[1+\frac{1}{2}\left(\frac{h_T + h_R}{d}\right)^2\right]$$

The difference $\Delta R = R_2 - R_1$ reduces to

$$\Delta R = \frac{2h_T h_R}{d}$$

giving a phase difference which can be expressed as:

$$\Delta \cong \frac{4\pi}{\lambda}\frac{h_T h_R}{d} \qquad 12$$

For grazing incidence i.e. when the angle of incidence on earth is very small, the reflection coefficient, ρ tends to -1, so the received signal electric field becomes:

$$E = E_o\left(1 - \exp(-j\Delta)\right) = E_o\left[1 - \cos\Delta + j\sin\Delta\right]$$

Thus the magnitude of the Electric field is

$$|E| = |E_o|\left[1+\cos^2\Delta - 2\cos\Delta + \sin^2\Delta\right]^{1/2} = 2|E_o|\sin\frac{\Delta}{2}$$

The received power is proportional to $|E|^2$, hence

$$P_R = \frac{\lambda^2}{(4\pi d)^2} 4\sin^2\left[\frac{2\pi}{\lambda}\frac{h_T h_R}{d}\right] P_T G_T G_R \text{ since } |E_o|^2 = P_T\left(\frac{\lambda}{4\pi d}\right)^2 G_t G_R \qquad 13$$

The above equation indicates an oscillatory nature for the received power. However, for values of $d >> h_T$, h_R, i.e. for propagation distances which substantially extend beyond the turnover point $d = \frac{2}{\lambda} h_T h_R$, sin (θ) ≅ θ equation 13 tends to the *fourth power distance law*:

$$P_R \to \frac{(h_T h_R)^2}{d^4} P_T G_T G_R \qquad 14$$

which is known as the *Plane -Earth Propagation Equation*. Equation 13 is shown in figure 6.

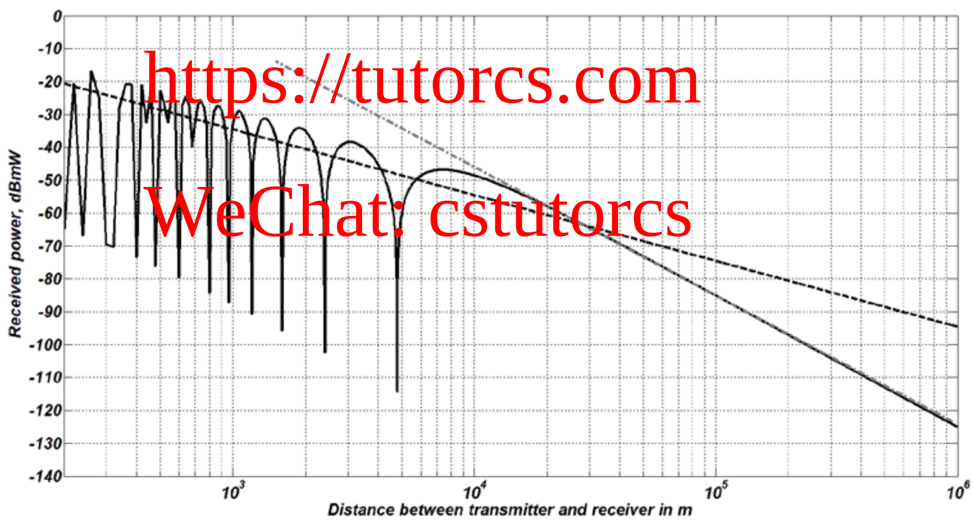

Figure 6. Variation of signal strength with distance in the presence of a specular reflection

Equation 14 differs in two important ways from the free-space equation. First, it is frequency independent and secondly it obeys a fourth order power law with range. That is the received power decreases more rapidly with range, 12 dB for each doubling of distance instead of 6 dB for the free space case.

In convenient logarithmic form, Equation 14 can be written as:

$$L_p = -10\log_{10} G_T - 10\log_{10} G_R - 20\log_{10} h_T - 20\log_{10} h_R + 40\log_{10} d$$

For isotropic antennas, equation 15 reduces to (15)

$$L_P = -20\log_{10} h_T - 20\log_{10} h_R + 40\log_{10} d$$

Note that the above analysis assumed specular reflection where the earth surface was assumed to be smooth. When the surface is rough the incident wave is presented with many facets giving a diffuse reflection and the mechanism is more akin to scattering. In this case only a small fraction of the incident energy can travel in the direction of the receiving antenna and the 'ground reflected' wave may therefore make a negligible contribution to the received signal. A measure of roughness is given by the Rayleigh criterion expressed as

$C \cong \dfrac{4\pi\sigma\psi}{\lambda}$ where σ is the standard deviation of the ground undulations relative to the mean height and ψ is the angle of incidence of the wave on the ground. For C <0.1, there is a specular reflection and the surface can be considered smooth. For C > 10, there is highly diffuse reflection and the reflected wave is small enough to be neglected.

Propagation over irregular terrain

The previous models of free space loss and reflection from a smooth ground do not accurately model the actual path loss experienced in mobile radio environments such as over irregular terrain or built up areas. In this section, the effect of irregular terrain is first considered.

- **Diffraction loss**

If the direct line-of-sight is obstructed by a mountain, a hill or a building, some of the electric filed still reaches the receiver. This is due to the Huygen principle which states that 'each point on a wavefront acts as the source of a secondary wavelet and that these wavelets combine to produce a new wavefront in the direction of propagation' as shown in figure 7.

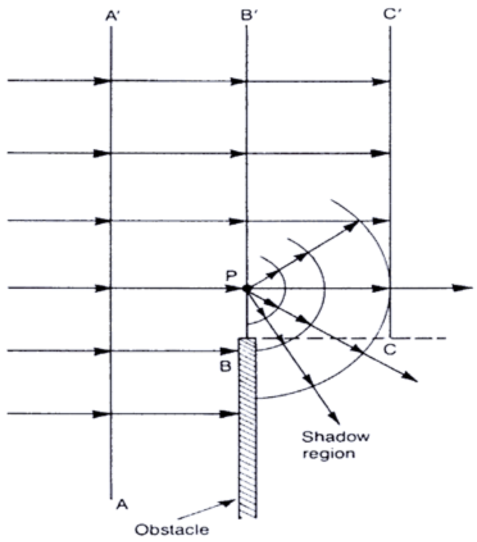

Figure 7. Diffraction at the edge of an obstacle (after Parsons)

To find the path loss due to diffraction, the case of a single obstacle as shown in fig.(8), is usually considered. In this case, the transmitter and the receiver are considered to be at the same level with an obstruction in the LOS path with height h_m.

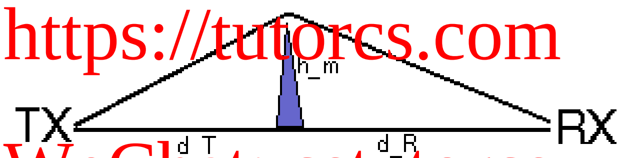

Figure 8 Path profile model for (single) knife-edge diffraction

Considering the geometry of figure 8, the difference in path length between the diffracted path and the LOS path ($d=d_T+d_R$) can be found as follows:

$$\Delta R = \sqrt{h_m^2 + d_T^2} + \sqrt{h_m^2 + d_R^2} - d$$

assuming that $h_m << d_T$, d_R, the above equation can be simplified to

$$\Delta R \cong \frac{1}{2} h_m^2 \left(\frac{d_T + d_R}{d_T d_R} \right) \qquad 16$$

The range difference can be converted to a phase difference i.e.

$$\Delta\phi = \frac{2\pi\Delta R}{\lambda} = \frac{\pi}{2} v^2$$

where v is known as the Fresnel-Kirchhoff diffraction parameter given by equation 17.

$$\nu = h_m\left(\sqrt{\frac{2}{\lambda}\left(\frac{d_T + d_R}{d_T d_R}\right)}\right) \qquad 17$$

The diffraction loss is defined as the ratio of the received electric field with the obstruction to the LOS electric field. This can be determined as the sum of all the secondary Huygens sources in the plane above the obstruction which is expressed in terms of a complex Fresnel integral as given by equation 18 below.

$$\frac{E}{E_o} = \frac{1+j}{2}\left\{\left(\frac{1}{2} - C(\nu) - j\left(\frac{1}{2} - S(\nu)\right)\right)\right\} \qquad 18$$

where C and S are the real and imaginary parts of the Fresnel integral.

Figure 9 shows the diffraction loss in dB relative to the free space loss as given by equation 18. In the shadow zone below the LOS the loss increases smoothly; whereas above the LOS the loss oscillates about its free space value with the amplitude of the oscillation decreasing as ν becomes more negative. This corresponds to the case when the obstruction is lower than the LOS. When there is grazing incidence over the obstacle there is 6 dB loss i.e. the field strength is $E_o/2$.

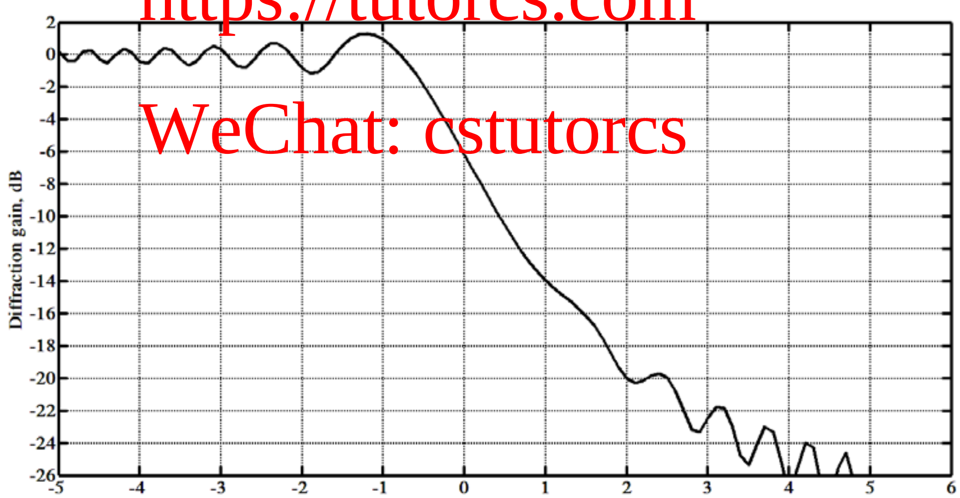

Figure 9. Diffraction loss over a single knife-edge as a function of the parameter ν

The diffraction loss can be either computed from figure 9 or by using approximate formulae such as equation 19 which gives the modified expressions given by Lee for additional to free space loss expressed in dB:

$$
L(\nu) = \begin{cases} 20\log(0.5 - 0.62\nu) & -0.8 < \nu < 0 \\ 20\log[0.5\exp(-0.95\nu)] & 0 < \nu < 1 \\ 20\log[0.4 - \sqrt{0.1184 - (0.38 - 0.1\nu)^2}\,] & 1 < \nu < 2.4 \\ 20\log[0.225/\nu] & \nu > 2.4 \end{cases} \qquad 19
$$

The attenuation over rounded obstacles (example a hill top) is usually higher than $L(\nu)$ in the above formula but this will not be treated here.

- **Multiple edge diffraction**

Diffraction due to multiple edges is a complicated mathematical problem which has been solved using a computer program. Approximate techniques to compute the diffraction loss over multiple knife-edges have been proposed. In this section a number of these techniques will be presented.

- Bullington Method

In this method, the terrain is replaced by a single 'equivalent' knife-edge at the point of intersection of the horizon ray from each of the terminals as shown in figure 9. The diffraction loss is then computed using equation 19 with the parameters for distance and height are those of the equivalent obstacle.

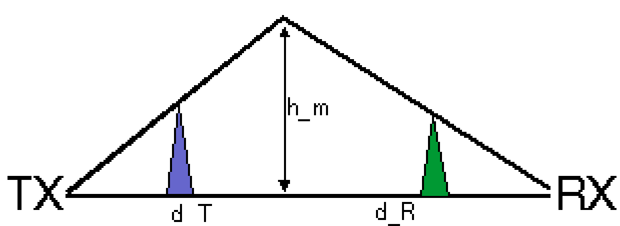

Figure 9. The Bullington 'equivalent' knife-edge

This method has the advantage of simplicity but it generally underestimates path loss.

- <u>Epstein-Peterson Method</u>

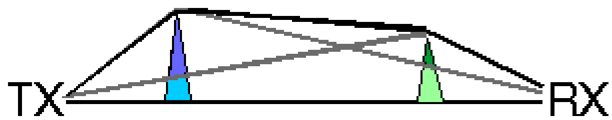

Figure 10. The Epstein-Peterson diffraction construction

In this method the diffraction loss is the sum of all losses due to each obstacle where starting at the transmitter, the loss due to the first obstacle is found by assuming that obstacle two is the receiver. Loss due to obstacle two is then found by assuming obstacle three as the receiver and obstacle one as the transmitter and so on. The total loss is the sum of all the losses.

Comparison of this method with Millington's rigorous solution has revealed that large errors occur when the two obstacles are closely spaced.

- <u>Deygout Method</u>

Figure 11. The Deygout diffraction construction

Deygout suggested searching the `main' obstacle, i.e., the point with the highest value of *v* along the path. This is done by calculating the value of the diffraction parameter for each obstacle in the absence of all other obstacles i.e. assuming that each obstruction is present alone. The diffraction loss due to the main obstacle is first found. This is followed by adding the loss due to the `secondary' obstacles by drawing lines between the 'main edge' and the transmitter and the receiver. For several obstacles, it is usual to only consider three components only, the main edge and the subsidiary main edges on either side.

The Deygout method is very good in most cases. However, it overestimates the path loss when the obstructions are close together.