Introduction

Radio was first postulated in 1873 by Maxwell – who found mathematically that a wave that was both electric and magnetic, and travelled at the speed of light should exist.

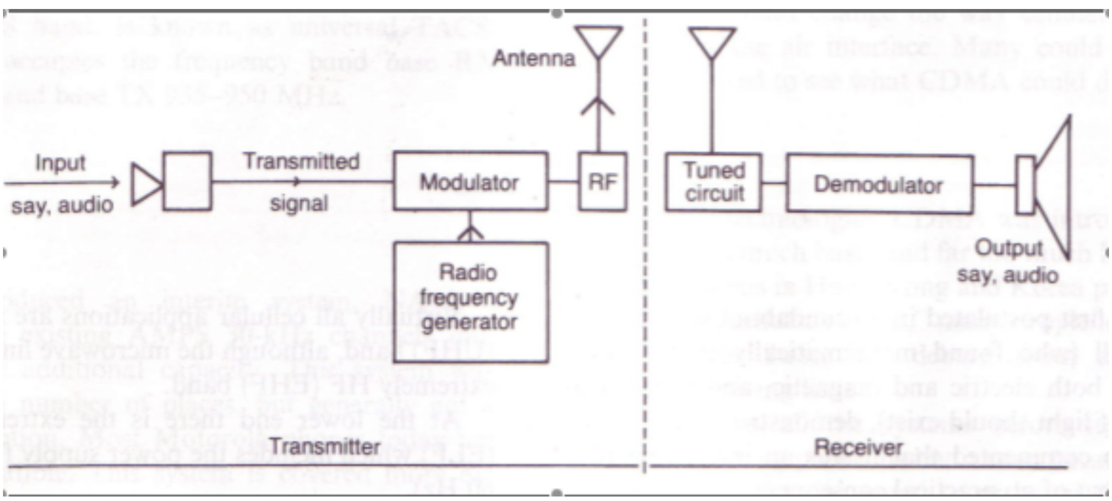
- This was demonstrated in 1888 by Hertz
- Used for practical cause in 1895 by Marconi.

Radio is an electromagnetic phenomenon and radiates as photons. It belongs to the family of radiation that includes X rays, light and infrared waves. Table. 1 below details the different categories of radiation.

Frequency range	*Name/Abbreviation*	*Main Uses*
Less than 300 Hz	Extremely low (ELF)	Submarine
300 Hz – 3 kHz	Infra low (ILF)	Voice band
3 kHz – 30 kHz	Very low (VLF)	Audio band
30 kHz – 300 kHz	Low (LF)	Broadcast/ long range
300 kHz – 3 MHz	Medium (MF)	Broadcast/long range/shortwave
3 MHz – 30 MHz	High (HF)	Shortwave band
30 MHz – 300 MHz	Very high (VHF)	Mobile radio/Paging/VHF TV
300 MHz – 3 GHz	Ultra high (UHF)	Mobile radio/Microwave/TV
3 GHz – 30 GHz	Super high (SHF)	Microwave/Satellite
30 GHz – 300 GHz	Extremely high (EHF)	Microwave
300 GHz – 3000 GHz	Tremendously high (THF)	Experimental

Basic Propagation Model

All practical radio systems can be reduced to the basic scheme shown in Fig. 1. It follows from the Fig.1 that there are three main independent electronics and electromagnetic design tasks related to radio wave communication systems.



- The first task is the specification of the electronic equipment that controls all operations within the transmitter, including the transmitting antenna operation.
- The radio propagation channel plays a separate independent role. Its main output characteristics depend on the conditions of the radio wave propagation in the various operational environments.
- The third task concerns the same operations and signals, but for the receiver, with its own peculiarities. For both kinds of antennas, the transmitting and receiving, an important issue is the influence of different kinds of obstacles located around the antennas and the environmental conditions.

Noise and Signal – Noise Performance

All radio systems are limited in range by noise. When the intrusion of noise is such that an acceptable signal can no longer be obtained, then the system is said to be noise limited. Medium and short wave broadcast operate in a very noisy environment, whilst VHF and UHF operate in quieter environment and most of the noise experienced is generated in the RF preamp of the receiver itself. Regardless of how well the receiver is designed, there is a theoretical noise power level, at a given temperature, cannot be improved upon. This is

- Due to thermal noise which is proportional to operating temperature: antennas and amps will generate thermal noise continuously

Noise is typically separated into additive (or white noise) and multiplicative noise. Additive noise arise from:

- Noise in the receiver antenna
- Noise within the electronic equipment that communicates with antenna
- Background and ambient noise (galvanic, atmospheric, man-made etc

Multiplicative noise arises from:

- Multireflections from ground surfaces, walls and hills
- Multiscaterring from rough surfaces such as the sea, rough terrain, building and trees
- Multidiffraction from edges of walls, building rooftops, and hilltops

Additive noise is mainly due to the random motion of electrons within the various components of equipment. The noise power inside the transmitter-receiver channel at a given system bandwidth B_w is given by:

$$N_F = k_B T_0 B_w \qquad [1]$$

where $k_B = 1.38 \times 10^{-23} WsK^{-1}$ is Boltzmann's constant, $T_0 = 290K(17^\circ C)$. [1] can be written taking into account the noise factor, F, of the receiver:

$$F = 1 + \frac{T_e}{T_0} \qquad [2]$$

where T_e is the effective noise temperature at the receiver.

$$N_F = k_B T_0 B_w F \qquad [3]$$

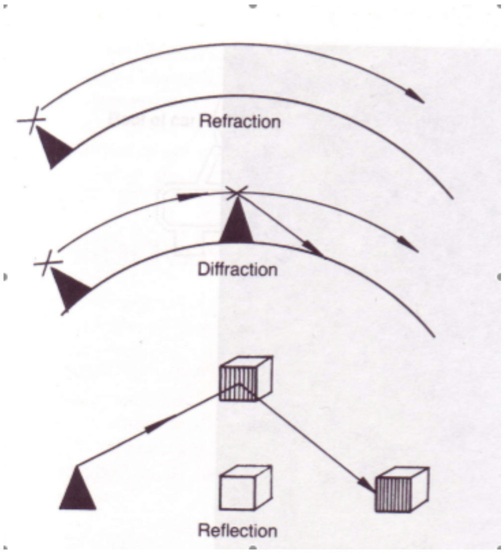
To perceive a relatively noise free signal, the incoming signal must exceed the noise level by a respectable margin – known as the Signal to Noise Ratio (SNR).

- For cellular radio systems, SNR typically is 12 dB for marginal reception and 30 dB for good quality reception

Propagation

Radio waves propagate at the speed of light. They reach the receiver in a multipath situation in which the various waves arrive with different radio paths and time delays. At the receiver, such waves are combined to give an oscillating resultant signal, the variations of which depends on the distribution of phases amongst the incoming component waves.

The signal amplitude variations are known as fading. Fading is basically a spatial phenomenon, but signal variations are experienced as temporal variations by a receiver and/or transmitter moving through the multipath field or due to moving scatters – in essence we are talking about space and time domain variations of electromagnetic fields in land environments. There is also the random fading in the frequency domain, as experienced by mobile comms systems: this otherwise known as the Doppler effects and refers to the complicated interference picture of the received signal caused by receiver/transmitter movements.



In built up areas, the urban propagation channel is approximately stationary in time, but the spatial variations of signal level have a triple nature:

- Path Loss – defined as an overall decrease in the signal strength with distance between two terminals – the transmitter and receiver – when the signal is expressed in dB.
    - The physical processes, which cause this phenomenon are the spreading of electromagnetic wave radiated outwards in space by the transmitter antenna and the obstructing effects of any natural and man-made object surrounding this antenna. The spatial and temporal variations of the signal path loss are large and slow.
- Shadow (or Slow) Fading: This is a large scale (in the space domain) and long term (in the time domain) fading. It is caused by diffraction from buildings' corners ad their rooftops, or from hill's top located along the radio link surrounding the terminal antennas. The spatial scale of the large-scale variations is of the order of the obstructions'' dimensions.
- Fast Fading: Small scale fading in the space domain and short term (or fast) signal variations in the time domain, which are caused by the mutual interference of the wave components of the multi ray field. The characteristic scale of such waves in the space domain is changed from half wavelength to three wavelength

Path Loss, Slow Fading and Fast Fading

Path loss determines the effectiveness of the propagation channel in various kinds of environments. It defines variations of the signal amplitude or field intensity along the propagation path from point to point within the communication channel.

Let's assume that the signal wave amplitude at the point r_1 along the propagation path is $A_1(r_1)$ or the signal wave intensity is $J(r_1) = A_1^2(r_1)$. In the process of propagation along the path, at any next point r_2, the signal wave amplitude is $A_2(r_2)$ or the intensity $J(r_2) = A_2^2(r_2)$.

Path loss is defined as the logarithmic difference between the amplitude or the intensity at the points r_1 and r_2 along the propagation path in the medium.

$$L = 10\log\frac{A^2(r_2)}{A^2(r_1)} \qquad [4]$$

Slow Fading: Slow spatial signal variations tend to normal or Gaussian distributions, the average signal power variations, as a result of their averaging within some individual small area, tend to the log-normal distribution with the standard deviation that depends on the relief of the terrain and on the type of built up area.

Fast Fading: observed over distances of about half or one wavelength. Two main situations can be discussed:

- Subscribers' antennas are stationary with respect to the base station: this situation is referred to as static multipath situation.
  - Narrowband signals travel along different paths of varying lengths due to multiple reflections and scattering
- Subscribers' antennas are in motion relative to the base station: this situation is referred to as dynamic multipath situation.
  - The spatial variations of resultant signal at the receiver can be seen as temporal variations at the receiver as it moves through the multipath field
  - Signal fading occurs in the time domain
  - Doppler effects

Radio Survey is the process of measuring the propagated radio field strength over an area of interest. It is an essential part of cellular radio site selection process. It is a design aid and also a maintenance tool. As a design aid, it helps determine the potential coverage of a proposed base station site. As a maintenance tool, it confirms the continual satisfactory coverage.

A radio survey is usually performed using a field strength-measuring receiver located in a vehicle. Sometimes the reciprocal path – that is the path from the mobile to base station – is measured instead.

- Both measurements are mathematically equivalent – except in satellite mobile links
- It is important to note that field strength is a statistical variable parameter and thus the measurement method needs to allow for this
- Three factors contribute to the field strength value measured
  - Path Loss (free space)
  - Log Normal Fading
  - Rayleigh (or Multipath) Fading

Path Loss Prediction Models in Various Outdoor Comm Links

Free Space Path Loss

If we consider a non-isotropic antenna placed in free space as a transmitter of P_T watts and with a directivity gain G_T, then at an arbitrary large distance from the source (i.e. $r > r_F$), the radiated power is uniformly distributed over the surface area of a sphere of radius r. If P_R is the power of the receiver antenna, located at a distance r from the transmitting antenna and has a directivity gain G_R, then the path loss is defined as (refer to [4]):

$$L = 10\log\frac{P_T}{P_R} \qquad [5]$$

$$L = 32.5 + 20\log f_{MHz} + 20\log r_{km}\ dB \qquad [6]$$

[6] is derived by inserting the expression for Friis formula in [5].

Path Loss over a Flat Terrain

This represents the simplest case of radio wave propagation over terrain – where the ground surface is assumed flat. This assumption is valid for radio links between subscribers up to 10 15 km apart. The main process is a reflection from the flat terrain, which is described by the reflection coefficient.

Reflection Coefficients

The expressions for the complex coefficients of reflections (Γ) for wave with vertical and horizontal polarizations is given below respectively:

$$\Gamma_V = |\Gamma_V| e^{-j\varphi_V} = \frac{\varepsilon_r \sin\psi - \left(\varepsilon_r - \cos^2\psi\right)^{1/2}}{\varepsilon_r \sin\psi + \left(\varepsilon_r - \cos^2\psi\right)^{1/2}} \qquad [7]$$

$$\Gamma_H = |\Gamma_H| e^{-j\varphi_H} = \frac{\sin\psi - \left(\varepsilon_r - \cos^2\psi\right)^{1/2}}{\sin\psi + \left(\varepsilon_r - \cos^2\psi\right)^{1/2}} \qquad [8]$$

where ψ is the grazing angle defined as $\pi/2 - \theta_0$, θ_0 is the angle of wave incidence. The knowledge of reflection coeff amplitude and phase variations is a very important factor in the prediction of path loss for different situations in the land propagation channels.

- Ground properties are determined by the conductivity and absolute dielectric permittivity of the subsoil medium

Note: The Fresnel reflection coeff, Γ, accounts for the electrical properties of the earth surface. Since the earth is a lossy medium, the value of the reflection coeff depends on the complex relative permittivity of the surface, the grazing angle and wave polarisation

Line of Sight (LOS) Two Ray Model

First proposed for describing the process of radio wave propagation over flat terrain. It is based on the superposition of a direct ray from the source and a ray reflected from the flat ground surface (Fig.)

Starting from the relation between the field strength and power at the transmitter:

$$E = \sqrt{\frac{30 G_T G_R P_T}{r_1}} \qquad [9]$$

The total field at the receiver is the sum of direct and received waves:

$$E_R = E_T \left(1 + \frac{r}{r_1} |\Gamma| e^{-jk\Delta r} \right) \qquad [10]$$

$k\Delta r = \Delta\varphi$ is the phase difference between the reflected and direct waves which can be presented as:

$$\Delta\varphi = \frac{2\pi}{\lambda} r \left\{ \left[1 + \left(\frac{h_R + h_T}{r} \right)^2 \right] - \left[1 + \left(\frac{h_R - h_T}{r} \right)^2 \right] \right\} \qquad [11]$$

We can simplify [11] by making some assumptions. For $r_1 \gg (h_T \pm h_R)$ and $r \gg (h_T \pm h_R)$, with the assumption that $r_1 \approx r_2 \approx r$, [11] becomes

$$\Delta\varphi = \frac{4\pi h_R h_T}{\lambda r} \qquad [12]$$

If we assume that the antennas are omnidirectional such that $G_R \approx G_T = 1$ and that the reflection coeff, $\Gamma(\psi) \approx -1$ for the farthest ranges from transmitter (when the grazing angle is small), then we can write an expression for the absolute value of power at the receiver:

$$|P_R| = |P_T| \left(\frac{\lambda}{4\pi r} \right)^2 \left| 1 + \cos^2 \Delta\varphi - 2\cos\Delta\varphi + \sin^2 \Delta\varphi \right| \qquad [13]$$

$$= |P_T| \left(\frac{\lambda}{4\pi r} \right)^2 \sin^2 \frac{\Delta\varphi}{2} \qquad [14]$$

[14] Implies that a maximum (received powered) is obtained when $\sin x \approx 1$, this distance is known as the critical range, r_b:

$$r_b \approx \frac{4 h_R h_T}{\lambda} \qquad [15]$$

For small incident angles, that is, when $\sin^2\frac{\Delta\varphi}{2} \approx \left(\frac{\Delta\varphi}{2}\right)^2$, $\Delta r = \frac{2h_T h_R}{r}$. This is valid for large distances between antennas relative to antenna heights. We can now write an approximate expression for path loss:

$$L_{FT} = 10\log\frac{|P_T|}{|P_R|} = 10\log\frac{r^4}{h_R^2 h_T^2} = 40\log r_m - 20\log\left(h_{Tm}h_{Rm}\right) \qquad [16]$$

[16] is known as the path loss in the model of flat terrain. [16] can be rewritten in the form shown below using [15].

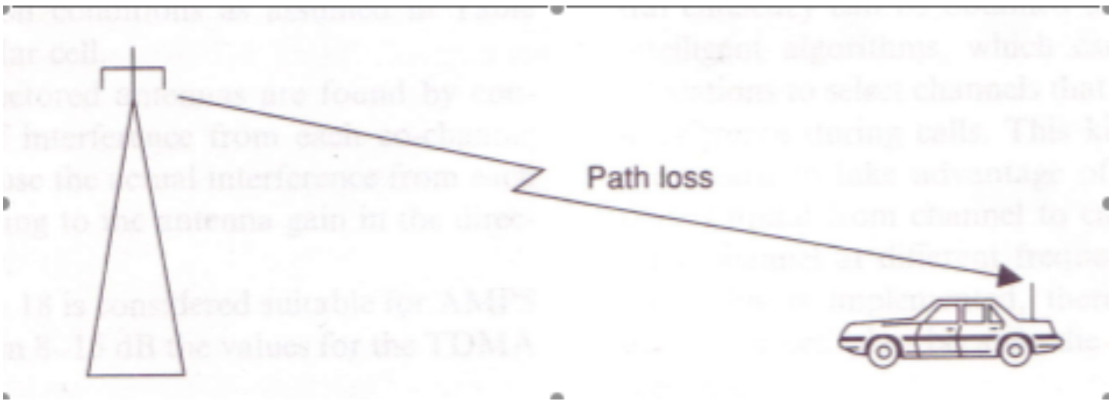
$$L = \begin{cases} L_B + 20\log\frac{r}{r_b} & r \le r_b \\ L_B + 40\log\frac{r}{r_b} & r > r_b \end{cases} \qquad [17]$$

Where L_B is the path loss in free space at the distance that equals the critical range.

Path Loss in Clutter Conditions – Non Line of Sight (NLOS) condition

Here we consider the situation where both transmit and receiver antenna are placed above ground in NLOS conditions. In this condition, diffraction phenomenon occurs due to the presence of obstacles such as trees or hill.

The diffraction phenomenon is based on Huygens' principle, furthermore each obstruction is replaced with a knife edge.

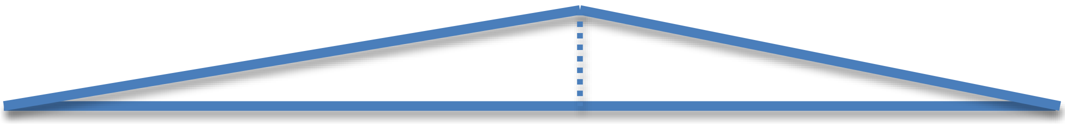


Propagation over a single knife-edge

Assume we can model an obstacle as a simple knife-edge – denoted in the figure below as OO' - which lies between the transmitter and the receiver. The phase difference $\Delta\varphi$ between the direct ray from the source (at point O) – denoted TOR and that diffracted from point O' – denoted TO'R can be obtained from the path difference and the phase difference assuming that the height of the obstacle is much smaller than the characteristics ranges between the antennas and the obstacles:

$$\Delta d \approx \frac{d_1 + d_2}{d_1 d_2}\frac{h^2}{2} \qquad [18]$$

$$\Delta\varphi = k\Delta d = \frac{2\pi}{\lambda}\Delta d \qquad [19]$$



We can re-write [19] in terms of the Fresnel Kirchhoff Diffraction parameter:

$$\Delta\varphi = \frac{\pi}{2}\upsilon^2 \qquad [20]$$

where υ is the Fresnel – Kirchhoff Diffraction parameter.

The effect of diffraction around an obstacle is determined by quantifying the required clearance over the obstacle. This is achieved analytically through the application of Fresnel zone ellipsoids, these are drawn around both ends of the radio link, transmitter and receiver. The cross sectional radius of any ellipsoid of the n Fresnel zone at a distance d_1 and $d_2 = d - d_1$ can be presented as a function of these parameters as shown below:

$$r_n \equiv h_n = \left(\frac{n\lambda d_1 d_2}{d_1 + d_2}\right)^{1/2} \qquad [21]$$

Taking into account [18 – 20], [21] the Fresnel (also called the diffraction parameter) can be written as:

$$\upsilon_n = h_n\left[\frac{2(d_1 + d_2)}{\lambda d_1 d_2}\right]^{\frac{1}{2}} = \left[\frac{2(d_1 + d_2)n\lambda d_1 d_2}{\lambda d_1 d_2 (d_1 + d_2)}\right]^{\frac{1}{2}} = (2n)^{1/2} \qquad [22]$$

Note: Contribution to the total field at the receiving point from successive Fresnel zones tends to be in phase opposition and therefore interfere destructively rather constructively.

Losses of the wave energy over a single knife-edge can be obtained analytically by use of so-called Fresnel complex integrals based on Huygens' principle:

$$E = E_0 \frac{1+j}{2}\int_{\upsilon}^{\infty} \exp\left(-j\frac{\pi}{2}t^2\right)dt \qquad [23]$$

The total field after diffraction from obstruction can be presented in the following form:

$$E = E_o \hat{D}\exp(j\Delta\varphi) \qquad [24]$$

Where E_0 is the incident wave from the transmitter located in free space, $\hat{D}$ is the diffraction coeff or matrix, and $\Delta\varphi$ is the phase difference between the diffracted and direct waves. We can represent the Fresnel integral as shown below:

$$\int_{\upsilon}^{\infty} \cos\left(-\frac{\pi}{2}t^2\right)dt = \frac{1}{2} - \int_{0}^{\upsilon} \cos\left(-\frac{\pi}{2}t^2\right)dt = \frac{1}{2} - C(\upsilon)$$

[25]

$$\int_{\upsilon}^{\infty} \sin\left(-\frac{\pi}{2}t^2\right)dt = \frac{1}{2} - \int_{0}^{\upsilon} \sin\left(-\frac{\pi}{2}t^2\right)dt = \frac{1}{2} - S(\upsilon)$$

Therefore [23] can re re-written as:

$$E = E_0 \frac{1+j}{2}\left[\left(\frac{1}{2} \pm C(\upsilon)\right) - j\left(\frac{1}{2} \pm S(\upsilon)\right)\right] \qquad [26]$$

Since the main goal of diffraction theory is to obtain the parameters $\hat{D}$ and $\Delta\varphi$ by use of the Fresnel integrals, we can do this by comparing [24] and [26].

$$\hat{D} = \frac{S + 1/2}{\sqrt{2}\sin\left(\Delta\varphi + \left(\frac{\pi}{2}\right)\right)}$$

[27]

$$\Delta\varphi = \tan^{-1}\left[\frac{\left(S + \left(1/2\right)\right)}{\left(C + \left(1/2\right)\right)}\right] - \frac{\pi}{4}$$

To obtain an exact solution by use of an integral equation such as [24] is very complicated. Empirical and semi-empirical models, based on numerous experimental data, have been developed and are usually used to obtain the diffraction losses in NLOS communication links. For knife-edge diffraction losses, the Lee's approximate model is used:

$$\begin{aligned}
L(\upsilon) &= L_{\Gamma}^{(0)} = 0\ dB && \upsilon \le -1 \\
L(\upsilon) &= L_{\Gamma}^{(1)} = 20\log(0.5 - 0.62\upsilon)\ dB && -0.8 < \upsilon < 0 \\
L(\upsilon) &= L_{\Gamma}^{(2)} = 20\log\left[0.5\exp(-0.95\upsilon)\right]\ dB && 0 < \upsilon < 1 \qquad [28] \\
L(\upsilon) &= L_{\Gamma}^{(3)} = 20\log\left[0.4 - \left(0.1184 - (0.38 - 0.1\upsilon)^2\right)^{1/2}\right] dB && 1<\upsilon<2.4 \\
\mathrm{L}(\upsilon) &= L_{\Gamma}^{(4)} = 20\log\frac{0.225}{\upsilon}\, dB && \upsilon > 2.4
\end{aligned}$$

Fading (re-visited)

Fading is due to shadowing, blockage and multipath. The term is applied to signal loss that changes fairly slowly relative to the signal bandwidth and the term scintillation is used to describe rapid variations in signal strength. These terms are usually applied to atmosphere phenomena, however.

When modelling a terrestrial mobile radio channel, the principal effects are usually due to terrain and terrain features. In this context it is customary to talk about fading in terms of large scale or small scale fading rather then scintillation. Small scale fading is further characterised as fast or slow and as spectrally flat or frequency selective.

Fading is roughly grouped into 2 categories: large scale and small scale fading. Large scale fading is sometimes called slow fading or shadowing although the term slow fading has a more precise meaning in the context of small scaling fading.

Large scale adding is often charaterised by a log normal probability density function and is attributed to shadowing and the resulting diffraction and/or multipath. Changes in large scale fading are associated with significant changes in the Tx/RX geometry, such as when changing location while driving.

Small scale fading is associated with very small changes in the TX/RX geometry, on the order of a wavelength. Small scale fading may be either fast or slow and is due to changes in multipath geometry and/or Doppler shift from changes in velocity or the channel

Surface Roughness

When determining if ground reflections is likely to be significant, a means of quantifying the smoothness (flatness) of the reflecting surface is required. The Rayleigh criterion provides a metric of surface roughness. The Rayleigh roughness is derived based on the terrain variation Δh that will provide a 90 degree phase shift at the Rx between a reflection at a terrain peak versus a reflection from a terrain valley at the same distance. The Rayleigh criterion is given as:

$$H_r = \frac{\lambda}{8 Sin\theta} \qquad [29]$$

From the geometry drawn on the board, it can be determined that:

$$Sin\theta = \frac{h_r + h_t}{d} \qquad [30]$$

[29] can be re-written as:

$$H_r = \frac{\lambda d}{8\left(h_r + h_t\right)} \qquad [31]$$

The surface is treated as smooth when $\Delta h << H_R$

More on Diffraction and Hugyen's Principle

Diffraction is the physical phenomena whereby an electromagnetic wave can propagate over or around objects that obscure the line of sight. Diffraction has the effect of filling in shadows, so that some amount of electromagnetic energy will be present in the shadowed region. The easiest way to view the effect of diffraction is in terms of Huygen's principles, which states that each point on a wavefront acts as the source of a secondary wavelet and all these wavelets combine to produce a new wavefront in the direction of propagation.

Compensating for diffractions from a rounded hilltop

The diffraction from a rounded hilltop or surface is determined by computing the knife edge diffraction for the equivalent height, h and then computing the excess diffraction loss, L_{exc} due to the rounded surface.

The first step is to determine the radius, r of the cylinder that circumscribes the actual diffraction points on the obstacles. Then the extent of the diffraction surface, D_s can be found.

The expression for the excess diffraction loss is given as:

$$L_{exc} = -11.7\alpha\sqrt{\frac{\pi r}{\lambda}} \qquad [32]$$

where

$$\alpha = \upsilon\left(\frac{\lambda\left(d_1 + d_2\right)}{2d_1 d_2}\right) \qquad [33]$$

$$r = \frac{2D_s d_1 d_2}{\alpha\left(d_1^2 + d_2^2\right)} \qquad [34]$$