RADIO WAVE PROPAGATION AND EMI

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Introduction

The importance of electromagnetic compatibility (EMC) for radio systems is an important system performance issue. It is important to improve and enforce EMC measures in order to accommodate the ever growing number of services and users, especially for mobile radio communicate systems.

In Nigeria, the exponential growth of mobile telephony coupled with the growth of radio equipment and systems, greatly increases the probability of mutual interference. The expected amount of interference may drastically affect the quality of radio systems and endanger their development.

The bottom line is a warning: without efficient and drastic EMC regulations policies, radio services and systems will mutually disturb each other; and chaos may prevail.

1.1 *EMC Definitions Applied to Radio Systems*

EMC definitions proper to radio engineering are as follows:

1. The ability of a device, circuit, or system to function satisfactorily in a given electromagnetic environment, without causing intolerable interference to the environment
2. The ability of desired radio signal, undesired signals, and external interference to co-exist without loss of information contained in the desired signal.

Thus, EMC is strongly related to electromagnetic interference or especially Radio Frequency Interference (RFI) in radio communication and radar systems.

Please refer to the EMC notes provided for the course for a detailed discussion on the subject.

I*t is not my intention to cover the system blocks of a radio communication system, however it is important to note the similarity (and differences) between the radio wave propagation and EMI model. These were discussed during the lecture.*

Contamination Sources

Contamination sources affect the radio systems. The main contamination sources are noise, distortions, and interference

Noise: Noise generated inside the transmission, receiver, or transducer blocks (of the radio communication system) is internal and that generated in the propagation medium or elsewhere is external. The main types of internal noise are thermal (white) noise generated by all resistive devices, scintillation (flicker) noise due to surface trap effects at the lowest frequency ranges, and delay mechanism or recombination noise from active devices at high frequency ranges.

External EM noise is natural or man-made. Natural noise is mainly of cosmic, solar, or lightning origin. Man made noise sources are automotive ignition systems; electrical motors; fluorescent lights; industrial, scientific , and medical (ISM) sources, and so on.

Distortion: This includes all effects that modify the form of an input signal in a non-desired way. The main type of distortion are as follows:

1. Amplitude Distortions: This originates from non-linear effects such as amplifier saturation or frequency

conversion. These distortions generate harmonics or intermodulation products.

2. Frequency Distortions: These originate from a nonuniform frequency response curve from amplifiers or filter stages. They can be reduced or suppressed using negative feedback or equalises.
3. Phase Distortions: This type of distortion originates from nonlinear effects when the output phase does not change linearly as a function of time. Group delay, filters, and AM to PM conversion are associated with phase distortions.

Interference: The most importance effects of interference are as follows:

1. Fading: This is due to reflection or refraction of the desired signals from ground, obstacles, and atmospheric layers which interfere with the direct signal path at the system Rx input. The amplitudes and phases due to (multiple path) fading are random because of the complex radio propagation medium and its non predictable characteristics. Fading effects analysis and development of mitigation methods are difficult tasks for radio system engineers.
2. Coupling: Coupling from mutual electric or magnetic fields between conductors. The coupling interference crosstalk particularly affects telephone lines and can be mitigated by using proper shielding.
3. Mutual Interference: This unintentional interference originates from the multitude of radio sources operating simultaneously at the same frequency (co-channel) as the desired signal or at adjacent channel sources. Mutual interference may be generated from equipment belonging to the same system (intra-system) or from different systems (inter-system).
4. Jamming: Jamming is intentional interference directed to a victim system. It has mainly military applications.
5. Cosite Effects: This usually generates nonlinear interference such as desensitisation or inter-modulation due to closely located transmission sources or even more distant high power sources such as broadcasting transmission.

Noise Sources Effects and Analysis

Internal Passive Thermal Analysis: Thermal noise is produced by random fluctuations of electrons. The amplitudes of velocity and energy of the fluctuations are proportional to the absolute temperature in Kelvins (K). The electron fluctuations which disturb the regular movement of current in electrical conductors are called thermal or Johnson noise and are generated in all resistive electrical devices

The thermal noise amplitude is described by a zero mean Gaussian random process due to large amount of electrons concerned. The amplitude of the noise (n) at any arbitrary time t is characterised by the Gaussian probability density function $p(n)$:

$$p(n) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(1/2)(n/\sigma)^2} \qquad (1)$$

where σ^2 is the variance and σ is the root mean square values of n. The probability distribution function of the thermal noise $P(|n| < k_1\sigma)$ can be proved by the central limit theorem.

$$P(|n| < k_1\sigma) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-k_1\sigma}^{k_1\sigma} e^{-n^2/2\sigma^2} dn = \operatorname{erf}\left(\frac{k_1}{\sqrt{2}}\right) \qquad (2)$$

The equation above represents the tabulated error function.

Each passive resistive device is equivalent to a noiseless resistance R in series with a noise generator by using the Thevenin representation. The noise generator's electromotive force has a Gaussian statistical distribution. Nyquist found empirically that the noise voltage, V_n can be expressed as:

$$\sigma_n^2 = \overline{V_n^2} = 4KTRB \quad (3)$$

where $K = 1.38 \times 10^{-23} J/K$ is the Boltzmann thermodynamic constant, T is the resistance noise temperature in K, and B is the noise bandwidth in Hz.

Frequently, the source shunt Norton representation is used, where:

$$\sqrt{\overline{i_n^2}} = \sqrt{4KTgB} \quad (4)$$

where the left hand term represents the rms noise current in ampere and g is the conductance in mhos.

From electrical circuit theory, a noise source transmits the maximal available noise power to a connected electrical load matched by the complex conjugate impedance, $z^* = R - jX$ of the source internal impedance.

We can obtain the maximum available noise power $P_n \equiv N$:

$$N = \frac{\overline{V_n^2}}{4R} = KTB \quad (5)$$

A more precise model for the noise power given by the spectral density $G_n(f)$:

$$G_n(f) = \frac{hf}{e^{hf/KT} - 1} + \frac{hf}{\eta} \quad (6)$$

where $h = 6.63 \times 10^{-34} J.s$ is the Planck constant, f is the frequency in Hz and η is the quantum efficiency indicating the number of usable charge carriers generated by incoming photon energy. For all radio frequencies up to the submillimeter bands, $hf \ll KT$. Therefore, the following approximation can be used:

$$e^{hf/KT} \simeq 1 + \frac{hf}{KT} \quad (7)$$

Using (6), a simplified spectral density model is obtained:

$$G_n(f) \simeq KT \equiv N_0 \quad (8)$$

where N_0 is the white noise spectral power density in W/Hz units.

In several communication books, $G_n(f) = {N_0}/{2}$ appears, where the factor 2 is included to indicate that $G_n(f)$ is a two sided spectral power density.

Internal Noise Contribution of Active Devices

Shot or Schottky Noise: In active devices the average current carrier particle flow is affected by non-desired random fluctuations. These fluctuations are the origin of the shot or Schottky noise, which can be represent by a current spectral density function:

$$G_{ns}(f) = q_0 I_{DC} \quad (9)$$

where $q_0 = 1.6 \times 10^{-19} C$ and represents the charge of an electron. I_{DC} is the average direct current flowing through the active device. The simplest diode or junction rms shot noise current is equal to:

$$\sqrt{\overline{i_{ns}^2}} = \sqrt{2q_0 I_{DC} B} \quad (10)$$

The shot noise contribution is dominant in diodes, electronic tubes, field effect transistor (FET) circuits, and light detection by photodetectors. However, in bipolar transistors the shot noise is followed by thermal noise of about equal amplitude, because of the influential small input resistance. For most cases, the shot noise behave as a white noise and is characterised by a Gaussian distribution due to the average process applied to its computation. Therefore, shot noise power contribution can be superimposed with thermal noise in linear or quasi linear systems.

Scintillation or Flicker Noise: This type of noise affects active circuits only at very low frequencies. its amplitude decreases with frequency and can generally be neglected above several hundred Hz, depending on the device characteristics. Therefore, flicker noise is also called $1/f$ noise. The origin of this noise is supposed to be irregularities in the active device surface layers which generate traps affecting randomly slow vibrating (low frequencies) current carriers.

High Frequency Transition Time Noise: Active devices operating above their transition frequency f_t are affected by additional types of noise which increase significantly with frequency. This additional noise appears when the current carriers' vibration period decreases and approaches the transit time delays in the active devices between vacuum tube electrodes or FET channels or the recombination time in electronic junctions.

Noise Factor, Figure, and Temperature

This topic was adequately covered during the course, however I shall summarise the concept here:

The noise factor *F* is an important measure of the additive nature of noise produced especially in Rx systems stages by amplifiers, frequency converters, and so on:

$$f = \frac{S_i/N_i}{\left(S_0/N_0\right)} \qquad (11)$$

where S_i and S_0 are respectively the mean signal power at the circuit input and output and N_i and N_0 are the average noise power at the circuit input and output.

For amplifier stages, as an example,

$$f = \frac{S_i G\left(N_i + N_0\right)}{N_i G S_i} = 1 + \frac{N_a}{N_i} \qquad (12)$$

where G is the amplifier power gain and N_a is any additional noise power generated into the stage itself. The most widely calculated and measured noise parameter is the noise factor in dB units. In some cases, the noise figure is given as the ratio of voltages:

$$F = 20\log\left(1 + \frac{V_{n_a}}{V_{n_1}}\right) \qquad (13)$$

instead of power:

$$F = 10\log\left(1 + \frac{N_a}{N_i}\right) \qquad (14)$$

Re-arranging (12) and using (5), we obtain the additional noise power of the stage:

$$N_a = N_i\left(f - 1\right) = KTB\left(f - 1\right) \qquad (15)$$

The concept of noise temperature shows that:

$$N_a = K\left(T + T_e\right)B \qquad (16)$$

where T_e is the effective noise temperature of the stage in K. Therefore, using (12)

$$f = \frac{K\left(T + T_e\right)B}{KTB} = 1 + \frac{T_e}{T} \qquad (17)$$

or the effective noise temperature shows that:

$$T_e = T\left(f - 1\right) \qquad (18)$$

For most Rx systems, the noise factor or figure is used. However, for very sensitive RX, especially satellite ground systems with very low noise levels, the concept of noise temperature is more convenient and useful.

In case of n stages in cascade, the composite noise factor f_m is obtained using (12) -(16)

$$f_m = f_1 + \frac{f_2 - 1}{G_1} + \frac{f_3 - 1}{G_1 G_2} + \ldots \qquad (19)$$

and the composite noise temperature is obtained using (16) - (18)

$$T_m = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \ldots. \qquad (20)$$

Please refer to the notes delivered in the class and the worked examples for fur ther reading. If time permits, I shall update to include a discussion on other aspects of noise such as Band Limited Noise etc.

Radio Propagation Medium Xteristics

Atmosphere and space are the cheapest propagation media free of charge for radio systems. The radio propagation media, however is complex, generally unpredictable (random), and strongly affected by contamination sources such as noise and interference. The physics of propagation is affected by constantly changing meteorological conditions and by complex boundary conditions on the earth's surface. Therefore interference between different systems may occasionally occur as a result of anomalous propagation along the earth to space or over horizon terrestrial paths.

The EMC Engineer in radio systems has to select a meaningful propagation model to predict the real signal and interference amplitude levels at the system RX input circuits as a function time, space conditions, frequency, and modulation methods. The propagation model may be deterministic , statistical or empirical according to the circumstances. The large increase in radio systems, equipment, and users linked to a limited frequency spectrum resource causes difficulties in frequency band sharing (spectrum management) between different services and systems.

An efficient spectrum management policy and the design of reliable radio system minimising EMI effects require analysis of the propagation and antenna characteristics.

Atmospheric Propagation Xteristics

A. Free Space Propagation Condition

From electromagnetic theory the important free space secondary parameters are the characteristics impedance Z_0 , the propagation factor γ , and the propagation velocity υ

$$Z_0^2 = \frac{\mu_0\mu_r}{\varepsilon_0\varepsilon_r} \qquad (21)$$

From (21), the free space $Z_0 = 120\pi = 377\Omega$

$$\gamma = \alpha + j\beta\left(\frac{1}{m}\right) \qquad (21)$$

where α is the attenuation factor in dB/m which is null for free space and dry atmosphere, and β is the phase factor:

$$\beta = \frac{2\pi}{\lambda}(\mathrm{rad/m}) \qquad (22)$$

For free space

$$\upsilon = \frac{1}{\sqrt{\mu_0\varepsilon_0}} = c \simeq 3\times10^8\,\mathrm{m/s}$$

which is also the light velocity in free space conditions. For other propagation media:

$$\upsilon = \frac{c}{\sqrt{\mu_r\varepsilon_r}}\,\mathrm{m/s} \qquad (24)$$

From Maxwell's equation the following relation is obtained:

$$S = E\times H \qquad (25)$$

where S is the power density in $\left(\mathrm{W/m^2}\right)$.

All three vectors are orthogonal under free space conditions. Therefore, using ohm's law, the following relation are obtained:

$$S = \frac{E^2}{Z_0} \qquad (26)$$

and

$$P_r = SA_r \qquad (27)$$

where P_r is the received power and A_r is the effective area of the Rx antenna.

An isotropic post source antenna

$$S_r = \frac{P_T}{4\pi d^2} \qquad (28)$$

and

$$A_L = \left(\frac{4\pi d}{\lambda}\right)^2 \qquad (29)$$

where P_T is the Tx antenna output power and d is the separation distance between the terminals. Therefore, the radio system propagation dispersion losses A_L decreases in proportion to the square of the distance and frequency under free space propagation conditions. However, the field strength intensity E_r decreases in proportion to the distance.

B. Atmospheric Radio Refraction

The atmosphere's refractive index $n = \sqrt{\varepsilon_r}$ is a variable function in space and time. Since n is close to unity, the refractivity N is usually used:

$$N = 10^{-6}(n-1) \qquad (30)$$

The dependence of N on the physical characteristics of the atmosphere is approximately

$$N = \frac{77.6}{T}\left(p + 4810\frac{e}{T}\right) \qquad (31)$$

where $p, T, \text{and } e$ are the atmospheric pressure in millibars, the absolute temperature in K and the partial pressure of water vapour in millibar, which depends on the air humidity. The refractive effects bends the radio waves as shown by the geometric optical ray model. The refractivity usually decreases with height `above ground.

For a standard atmosphere the measured mean refractivity gradient $dN/dh \simeq -39\text{units}/\text{km}$ is obtained. Propagation computations in LOS conditions may be simplified by using ther flat earth concept of the radio horizon limit distance d_{LOS}, the modified radio refractivity M, and the modified earth radius R_m

$$M = N + \frac{h}{a}10^6 \qquad (32)$$

where a is the real earth radius (a=6370 km).

$$R_m = \frac{10^6}{dN/dh} \qquad K_e = \frac{R_m}{a} \qquad (33)$$

The K_e factor can be expressed as:

$$K_e = \frac{1}{1 + a(dN/dh)10^{-6}} = \frac{157}{dM/dh} \qquad (34)$$

The d_{LOS} is obtained from simple geometric principles if $h \ll a$

$$d_{LOS} = \sqrt{2K_e a}\left(\sqrt{h_T} + \sqrt{h_R}\right) \qquad (35)$$

For the optical ray tracing model, if $K_e = 1$ for a flat earth model, we obtain:

$$d_{LOS} = 3.6\left(\sqrt{h_T} + \sqrt{h_R}\right) \qquad (36)$$

and for standard atmospheric median values $dM/dh = 118M$ units, $K_e = \frac{4}{3}$ and

$$d_{LOS} = \sqrt{17}\left(\sqrt{h_T} + \sqrt{h_R}\right) \qquad (37)$$

(37) is often used for calculating the radio propagation d_{LOS} distance limit, which is usually larger than the optical LOS $(K_e = 1)$ limit distance.

Standard atmospheric conditions usually occur for common temperature climates. If atmospheric data and K_e are unknown, it is industry practice to use the standard $K_e = \frac{4}{3}$ value. Please refer to the notes given in class on how this value is derived and how it is used.

The refractivity effects bend the radio waves as a function of N or M gradients.

C. Ducting

I mentioned Ducting during the lecture but do not remember covering it, hence I have included it here.

The most dramatic non-standard effects are those caused by negative gradients $dM/dh < 0$, which are also called trapping gradients. Anticyclonic climatic conditions persisting above an area cause an elevated duct through subsidence; that is, the high pressure air in the upper atmosphere warms up adiabatically, subsides, and traps the humid and cooler lower layers. this elevated duct is relatively stable at altitudes up to about 6 km, its altitude and thickness varying in time.

The intrusion of the marine layer due to the breeze is a mesoscale phenomenon affecting several tens of kilometers from the coast line. It can produce ground based or low altitude ducts due to the cooler marine air, producing a shift toward lower temperatures in the normal temperature profile. This phenomenon has a specific diurnal variation pattern. Internal reflections are generated at both the duct layer upper and lower extremes, which trap high frequency radio wave similar to waveguide modes. The waveguides reduced power attenuation is proportional to distance d, in comparison with the d^2 minimal LOS free space dispersion losses. Therefore, during ducting conditions, non-desired signal power level are significantly enhanced for frequencies above 100 MHz and may interfere with remote radio or television RX systems operating on the same or adjacent channel frequencies.

Passage of hot dry air over the sea produces strong evaporation. Although the temperature profile shows only a slight change at the lower end due to the cooling produced by evaporation, the humidity profile shows a dramatic change towards higher values at the lower end. This leads to evaporation ducting. Ducts produced this way usually have a low altitude of several tens of meters. Thus, they have less importance from the broadcasting view point, but they strongly influence microwave links.

It is important to note however that however that evaporation ducting effects occur for frequencies above 3 GHz and the lower limit frequency increases with decreasing height of the trapped layer. The duct interfering distance limit decreases significantly for the higher ranges of frequencies due to extra attenuation from rough sea surfaces and absorption by atmospheric gases.

Radiated desired signals are also trapped during ducting conditions and may not reach their desired Rx. Ducting conditions can persist for hours and thier effects have to be compared for high frequency radio links where a statistical reliability of more than 95% of the time has to be considered.

D. Multipath Effects from Ground Reflection

This again is a topic which we adequately covered in class, I shall however provide some text supplement the discussions we have during the lectures.

For a limited distance separation between the terminals, where $d < 0.3d_{LOS}$ the flat earth configuration (refer to figure drawn in class) may be applied.

The reflecting area position on the ground can be obtained from the following geometric relations:

$$\frac{h_T}{d_1} = \frac{h_R}{d_2} \qquad d_1 + d_2 = d \tag{38}$$

and the electric field intensity at the Rx antenna $E_R = E_i - E_r$, where E_i and E_r are the direct and reflected electric fields. Using (26) and (28) and Taylor series approximation:

$$|E_R| = \frac{E}{d}\sqrt{1 - 2|r|\cos\theta + |r|^2} \tag{39}$$

where $|r|$ is the module of the reflection coefficient $r = |r|e^{j\theta}$ and θ is the reflection angle:

$$\theta = \beta l \simeq \frac{2\pi}{\lambda}\frac{4h_T h_R}{2d} \quad (40)$$

From Fresnel wave optics theory, expressions are obtained for the r coefficient in case of vertical and horizontal polarisation waves:

$$r_V = \frac{\eta_r \sin\psi - \sqrt{\eta_r - \cos^2\psi}}{\eta_r \sin\psi + \sqrt{\eta_r - \cos^2\psi}}$$

$$(41)$$

$$r_H = \frac{\sin\psi - \sqrt{\eta_r - \cos^2\psi}}{\sin\psi + \sqrt{\eta_r - \cos^2\psi}}$$

where η_r is the complex ground relative permittivity.

$$\eta_r = \varepsilon_r - j\frac{\sigma}{\varepsilon_0\omega} = \varepsilon_r - j60\sigma\lambda \quad (42)$$

where σ is the ground conductivity in mho/m.

For very small grazing angles ψ , when $h_T h_R \le d^2/100$, we obtain $r_V = r_H \simeq -1$. However, for vertical polarisation these conditions are fulfilled only when $f \ge 100\text{ MHz}$. The following simplified equation is obtained:

$$|E_r| = \frac{E4\pi h_T h_R}{\lambda d^2} \quad (43)$$

The propagation losses A_r for relatively short antennas is given by:

$$A_r = \frac{d^4}{h_T^2 h_R^2} \quad (44)$$

(44) is correct for multipaths even in the case of reflecting ground with low conductivity, such as desert areas (North of Nigeria). Therefore, the multipath reflection losses are proportional to d^4 instead of the d^2 typical of ideal free space conditions.

For higher separation distance $0.3d_{LOS} \le d < d_{LOS}$, the terrestrial curvature becomes influential and applying simply geometry, we obtain:

$$h_T \simeq h_1 - \frac{d_1^2}{2K_e a}$$

$$h_R \simeq h_2 - \frac{d_2^2}{2K_e a} \quad (45)$$

These approximation can be applied in several cases for terrestrial radio links but not for elevated aircraft and satellite links.

For really rough reflection surfaces, r is significantly reduced and diffusion or scattering of the incident waves may occur. This is typical for wavy sea, high grass, vegetation, or other rough terrain, for which the Rayleigh Criteria have to be checked:

$$H_R = \frac{\sigma_h}{\lambda}\sin\psi = \frac{\lambda}{8\sin\psi} \quad (46)$$

where σ_h is the standard deviation of the surface irregularities relative to the mean height of the surface.

Recall the diagram I drew In class plus the relationship with terminals heights.

E. Fresnel Zones

Again another recap on this, it was covered extensively in Class.

In the case of large obstacles, such as tree, buildings or terrain features, the LOS conditions can be obstructed and additional diffraction losses are generated.

An efficient criterion for radio path clearance at $d < d_{LOS}$ was developed by Fresnel using classical optics techniques. the regions in space between successive ellipsoids of revolution whose focus is at the Tx and Rx antennas are called Fresnel zones.

The surfaces of the ellipsoids are defined by the condition that the combined distances from any point on the surface to the Tx and Rx antennas by an integer multiple of one half wavelength. The first Fresnel zone is the region within the innermost ellipsoid, its cut representing a circular disk and higher zones representing circular rings.

The Fresnel zone is the radius h of the circle formed by the intersection of the first Fresnel zone with a plane perpendicular to the line between the terminals. Referring to the Figures below and assuming that Tx and Rx distances from the plane are large compared with the wavelength, the value of h_n is given by:

$$h = \sqrt{\frac{\lambda d_1 d_2}{d_1 + d_2}} \quad (47)$$

In the case of $d_1 = d_2 = \frac{d}{2}$

$$h = \sqrt{\frac{\lambda d}{2}} \simeq 17.3\sqrt{\frac{d}{4f}} \quad (48)$$

The radius of the nth Fresnel zone h_n is found by multiplying h by $\sqrt{n}$. If d_2 is about $0.1d_1$ or less, for instance, and if $f = 0.9\text{GHz}$ then $h \simeq 18.3\sqrt{d_2}$. The Fresnel zone clearance ratio υ is defined by:

$$\upsilon = \frac{\sqrt{2}h_u}{h} \quad (49)$$

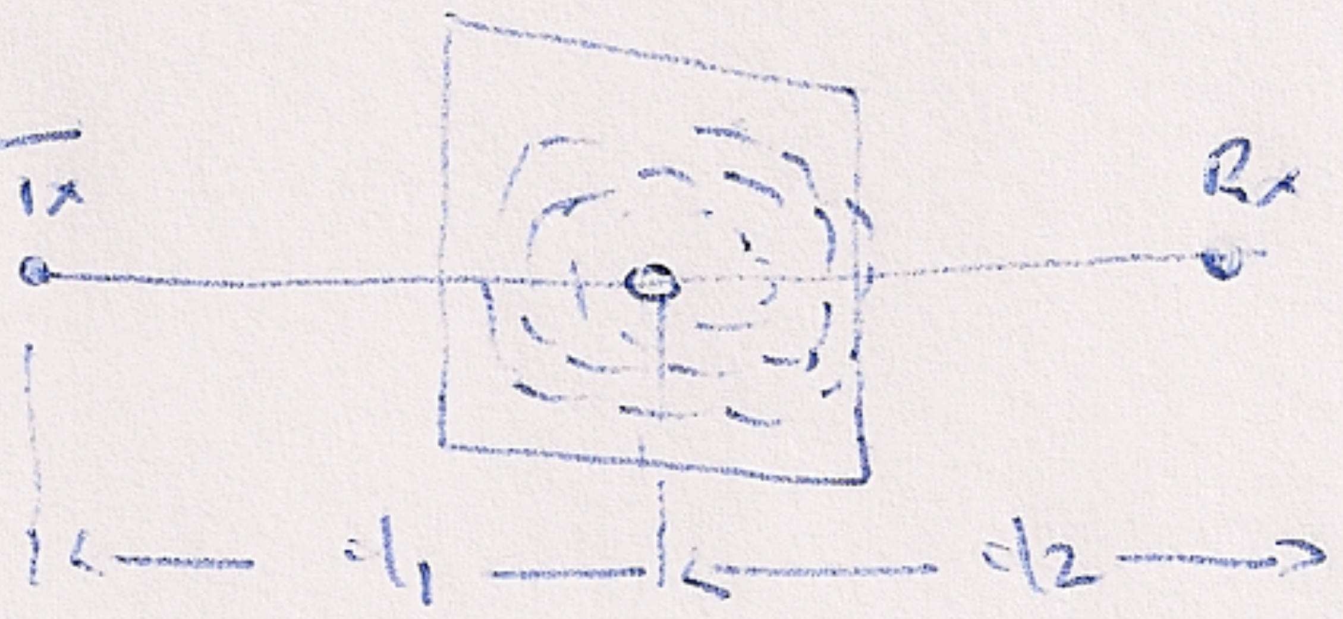
where h_u is the distance from the direct line between the antennas to the path obstacle shown in the Figure below. Recollect the example we solved in class on the topic!

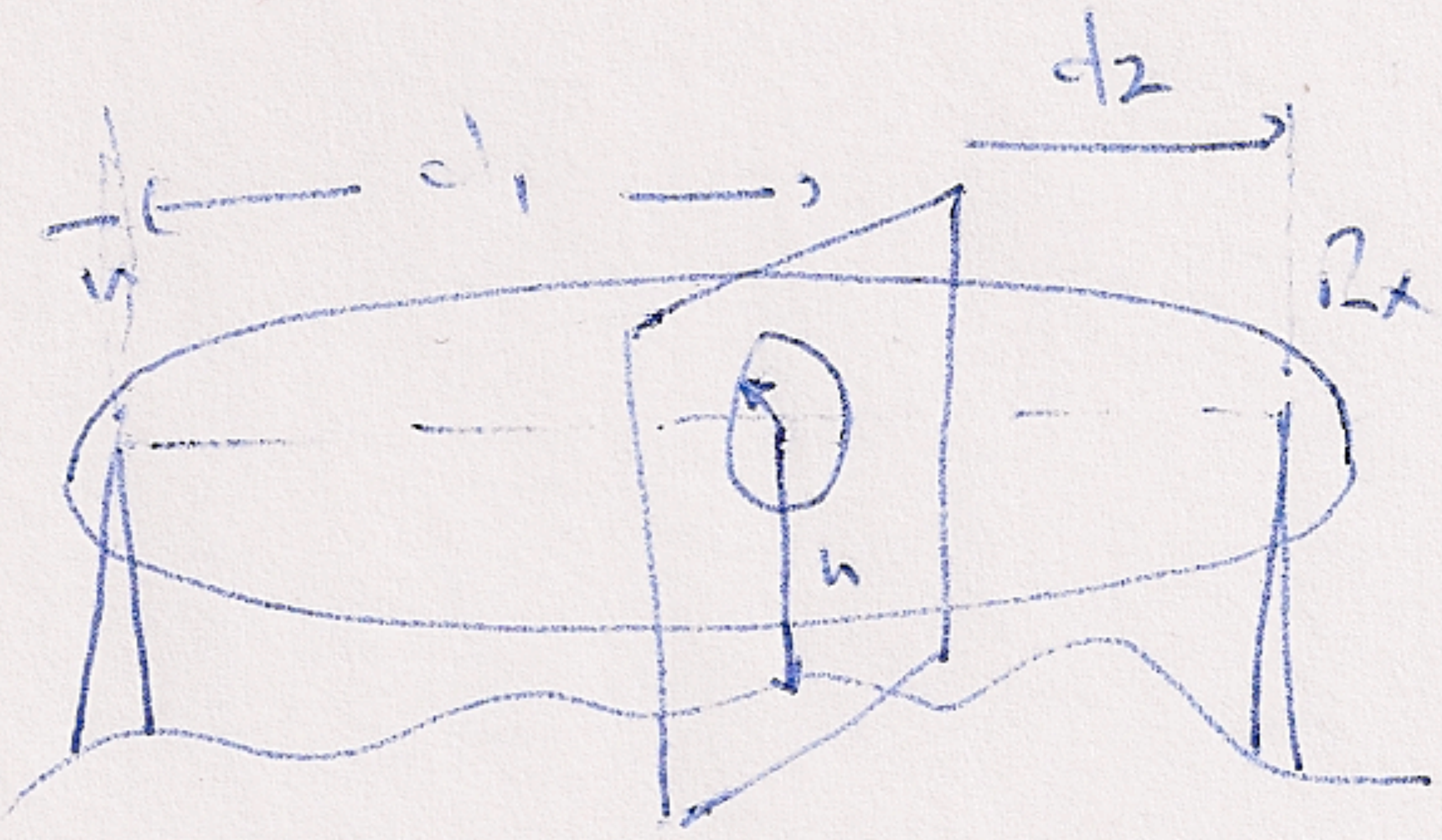
A few things we learn from Fresnel zones

1. About 50% of the radiating energy from the Tx antenna is concentrated in the first Fresnel zone
2. Free space propagation conditions are kept if the direct line between Tx and Rx antennas is free of obstruction and about 60% of the first Fresnel ellipsoid is kept clear of obstructions and reflection objects
3. The required antenna height h for the path clearance of the nth Fresnel zone

$$h = \frac{1}{2}\sqrt{n\lambda d} + \frac{d^2}{8K_e a}$$

4. The signal power level at the Rx antenna can be significantly reduced by multipath reflections and diffraction losses my arise if less than 60% of the first Fresnel zone is kept clear of obstruction and reflection. Theoretically, the power level can change from 6 dB above the free space LOS propagation level down to $-\infty$ dBm
5. The diffraction loss may become important for $\upsilon \leq 0.6$ due to the random variations in the refractive ratio generating fading, and the median diffraction losses can be expressed empirically by the υ factor.





F. Principle of Fading Effects

Multipath effects at the Rx antenna also results from random atmospheric refractive and diffractive effects which result in fading. Fading effects can result in defocusing, blocking, and random varied lengths at the radio system Rx antenna. Fading is a self interference effect which may generate disturbance of the desired signal even for low power levels of noise and in the absence of other interference signals. Fading is severe especially for earth mobile communication, and its high rate is a function of frequency, distance of operation, and velocity of the mobile antenna. In addition to fast fading, there is a much slower variation of the median signal level in each sector as a result of shadowing by terrain features or man made obstructions.