Main propagation mechanisms

Electromagnetics
and
Remote Sensing Lab
(ERSLab)

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Introduction
Friis transmission equation
Reflection
Plane Earth reflection
Surface scattering
Diffraction
Knife-edge
Fresnel zones

Outline

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   - Friis transmission equation
2. Reflection
   - Plane Earth reflection
3. Surface scattering
4. Diffraction
   - Knife-edge
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Introduction

The following large scale major propagation mechanisms affecting a radio link are reviewed.

1. Reflection: It describes the interaction between em waves and an object whose size is larger than the wavelength, e.g.; the earth's surface and large buildings.
2. Diffraction: It describes the interaction between em waves and an object characterized by sharp edges that obstruct the radio link.
3. Refraction: It occurs when a wave passes through an interface and the angle of the wave vector is changed. An important example is atmospheric refraction.
4. Surface scattering: It occurs when the em wave interacts with a rough surface.

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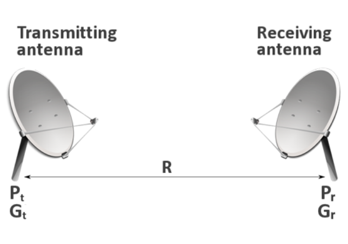
Friis formula

We consider two antennas in free space (no obstructions nearby) separated by a distance R.



- Let P_t the power delivered to the lossless TX antenna whose gain is G_t.
- Let P_r the power received by the lossless RX antenna which is in the far field wrt the TX antenna.
- Let $A_e = \frac{\lambda^2}{4\pi} G_r$ be the effective aperture of the RX antenna.

Friis formula

- The power density associated with the wave incident on the RX antenna is given by:

$$S = \frac{P_t}{4\pi R^2} G_t \tag{1}$$

- The power received by the RX antenna is given by:

$$P_r = \frac{P_t}{4\pi R^2} G_t A_e \tag{2}$$

- The latter can be written replacing A_e with G_r:

Friis formula

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \tag{3}$$

Path loss

- The difference between the TX and RX powers is termed as path loss.

Friis formula - LOS vs NLOS

Friis transmission equation (3) refers to a radio link where only one propagation path, i.e.; the Line of Sight (LOS) path, is present.

- Realistic radio links very often include also non-LOS (NLOS) paths due to obstacles that partially or totally obstruct the LOS path.
- NLOS propagation mainly involves reflection, refraction, diffraction and scattering mechanisms.

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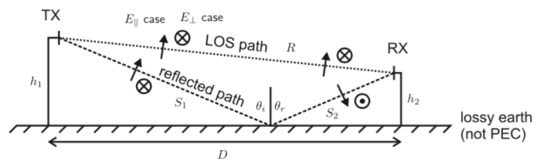
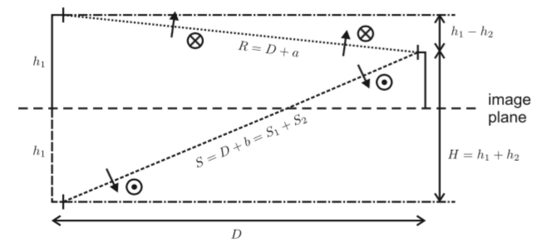
The geometry

It is the most significant source of reflection introduced by the environment when dealing with terrestrial links.



- There is a direct (LOS) path and a reflected one.
- The E-field is depicted in the TE and TM case.
- The reflected wave exhibits a 180° phase shift wrt the LOS wave. This results from grazing angle ($\vartheta_i \rightarrow 90°$) reflection at a lossy interface. Grazing condition relies on the fact that $h_1, h_2 \ll D$.
- There is also a path difference between LOS and reflected paths

Evaluating the received power



- We invoke a "modified" image theory that allows accounting for the 180° phase shift due to the sign of the reflection coefficient.
- We need to evaluate the path difference between the LOS and the reflected paths.
- We consider that the direct and the reflected paths consist of a common length (equal to the horizontal separation *D*) plus an extra length equal to *a* and *b*, respectively.

Evaluating the received power

- The E-field at the receiver is given by the superposition of the LOS and the reflected waves. Note that, due to grazing conditions, the reflection coefficient is equal to -1:

$$E_d + E_r = \frac{e^{-j\beta R}}{R} - \frac{e^{-j\beta S}}{S} = \frac{e^{-j\beta R}}{R}\left(1 - \frac{e^{-j\beta(S-R)}}{S/R}\right). \tag{4}$$

- The term outside the parentheses is just a standard LOS propagation term.
- The term in parentheses can be seen as a correction term that describes the reflection. To specify this term, $S - R$ and S/R are to be evaluated.

$$S - R = D + b - D - a = b - a \qquad ; \qquad S/R \approx 1 \tag{5}$$

Evaluating the received power

- To evaluate the excess paths a and b, the large and small triangles in the previous figure must be analyzed.

$$H^2 + D^2 = S^2 = (D+b)^2 = D^2 + b^2 + 2Db \tag{6}$$
$$H^2 \approx 2Db$$

- The approximation is justified by the fact that $D \gg b$. Hence:

$$b = \frac{(h_1 + h_2)^2}{2D} \tag{7}$$

- Similarly (considering the small triangle) one can find:

$$a = \frac{(h_1 - h_2)^2}{2D} \tag{8}$$

- Hence:

$$S - R = b - a = \frac{2h_1 h_2}{D} \tag{9}$$

Evaluating the received power

- The correction term in eq.(4) can be rewritten as:

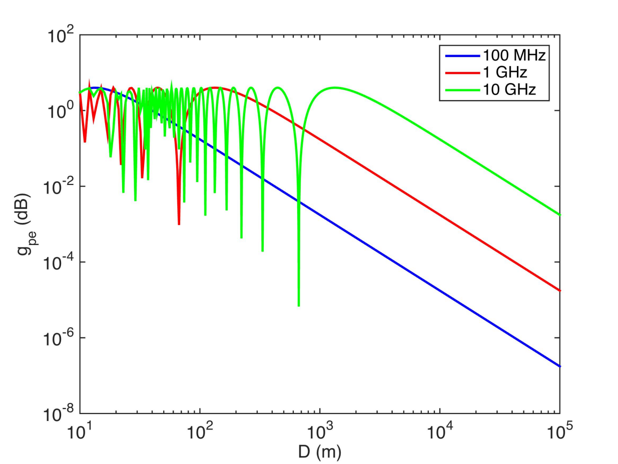
$$\begin{aligned} 1-\frac{e^{-j\beta(S-R)}}{S/R} &= 1-e^{-j\frac{4\pi}{\lambda}\frac{h_1h_2}{D}} \\ &= e^{-j\frac{2\pi}{\lambda}\frac{h_1h_2}{D}}\left(e^{j\frac{2\pi}{\lambda}\frac{h_1h_2}{D}}-e^{-j\frac{2\pi}{\lambda}\frac{h_1h_2}{D}}\right) \\ &= j2e^{-j\frac{2\pi}{\lambda}\frac{h_1h_2}{D}}\sin\left(\frac{2\pi h_1h_2}{\lambda D}\right) \end{aligned} \tag{10}$$

Plane Earth reflection term

- The square magnitude of this correction term is given by:

$$g_{pe}(\lambda,h_1,h_2,D)=4\sin^2\left(\frac{2\pi h_1h_2}{\lambda D}\right) \tag{11}$$

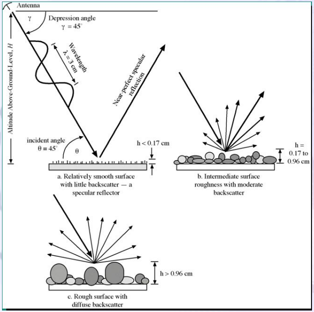
Plane Earth reflection term



The effects of constructive/destructive interference between the LOS and reflected waves depend on h_1, h_2, D, λ.

Surface scattering

It applies when the interacting surface is no longer smooth.



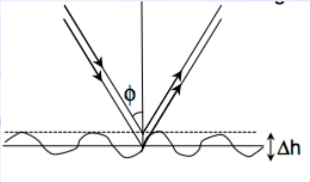
The reflected wave is scattered by a large number of scattering points on the surface. This process results in a broadening of the scattered energy.

Rayleigh criterion

Apparent roughness

The apparent roughness of the surface reduces:

- for incidence close to grazing angle ($\theta_i \approx \frac{\pi}{2}$);
- for longer em wavelength.



A surface that results in reflected waves whose phase shifts (with respect to each other):

$$\Delta\phi = \frac{4\pi \Delta h \cos\theta_i}{\lambda} \tag{12}$$

are very small can be considered smooth.

Rayleigh criterion

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- If the maximum admitted phase shift is $\Delta\phi = \frac{\pi}{8}$, one obtains that:

$$\sigma_s = \Delta h < \frac{\lambda}{16 \cos\theta_i} \tag{13}$$

Rayleigh criterion

Rayleigh criterion is important since it shows that the apparent roughness depends on both em wavelength and incidence angle. However, it does not include any information on the correlation length of the surface.

σ_s is also termed as Rayleigh parameter

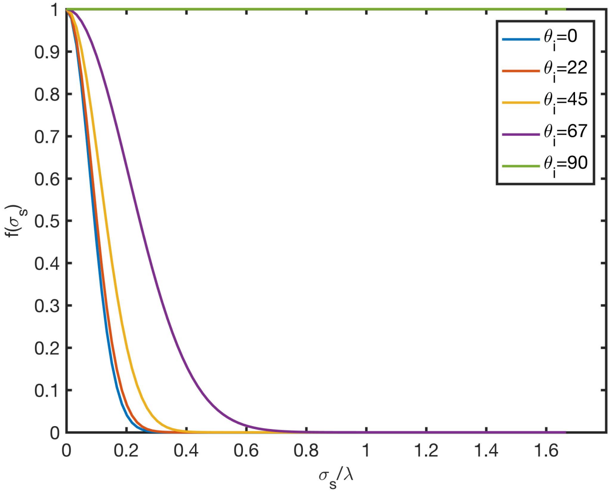
Surface scattering

- When the surface is considered rough, the amplitude of the specular component is reduced.
- This reduction is modeled by a roughness factor:

$$f(\sigma_s) = exp\left[-\frac{1}{2}\left(\frac{4\pi\sigma_s\cos\theta_i}{\lambda}\right)^2\right] \quad (14)$$

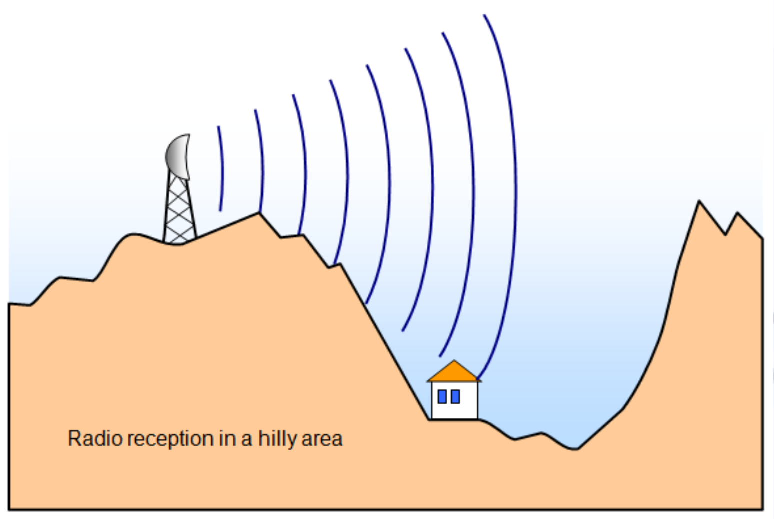
- Hence, an effective reflection coefficient can be used to account for surface roughness: $R_{eff} = Rf(\sigma_s)$.

Surface scattering



f=1GHz; σ_S=linspace(0,0.5,100)/lambda

Diffraction



Huygens

CHRISTIAAN HUYGENS

Huygens is a Dutch physicist, mathematician, and an astronomer. He is renowned for his arguments that light was in the form of waves.

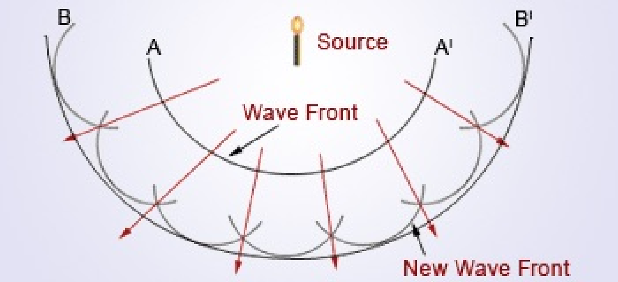
Huygens contributed in the field of astronomy by discovering Saturn's largest moon Titan in 1655. He also provided detailed studies about Saturn's rings and discovered that its rings are made up of rocks.

Mons Huygens and the Huygens probe (part of the Cassini-Huygens Saturn satellite) were named after Christiaan Huygens.

Huygen's principle

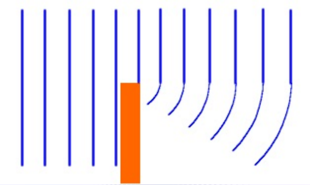
Huygens' principle

Each element of a given wavefront can be considered as a source of a secondary disturbance that produces spherical wavelets. The envelope of all such wavelets gives rise to the next wavefront.



Diffraction

Huygen's principle provides the physical framework to understand diffraction phenomena, i.e.; the behavior of em waves at the edge of absorbing materials.



Even if a region is shadowed by an obstruction, diffraction around the object's edges produces waves that propagate into the shadowed region.

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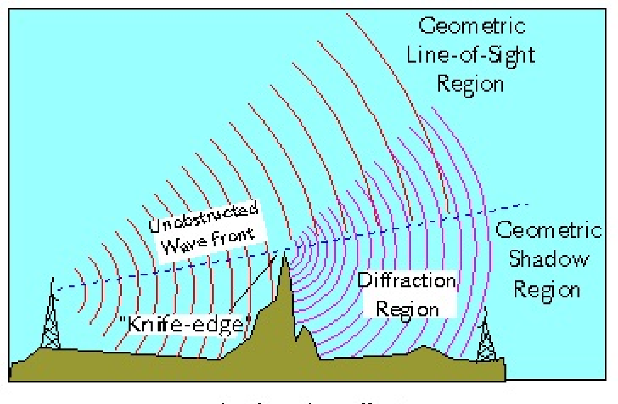
Knife-edge

A simplified model is assumed, termed as knife-edge diffraction, which consists of approximating the obstruction as a knife edge. This model can be used to conservatively estimate more realistic diffraction effects.



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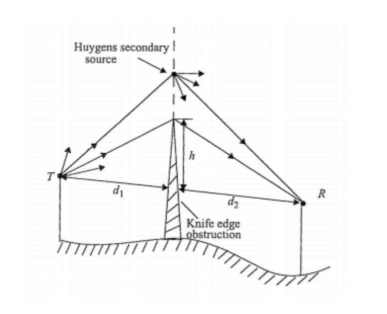
Single knife-edge diffraction

The single knife-edge diffraction model assumes that:



- A knife-like obstruction protrudes into the LOS path.
- The obstacle is assumed to have infinite extent.
- No signal can penetrate the obstruction, therefore, some of the rays emanating from the transmitter will not reach the receiver.

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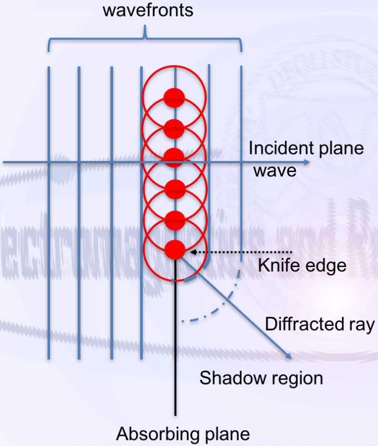
Single knife-edge diffraction

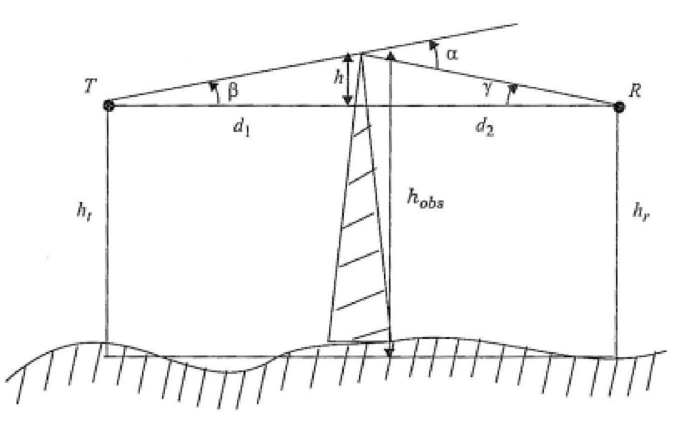
According to Huygen's principle:



- In an imaginary plane located in line with the obstruction, points above the obstruction can be considered secondary sources of wavelets, which combine to form waves propagating toward the receiver to the right of the screen.

Single knife-edge diffracted waves

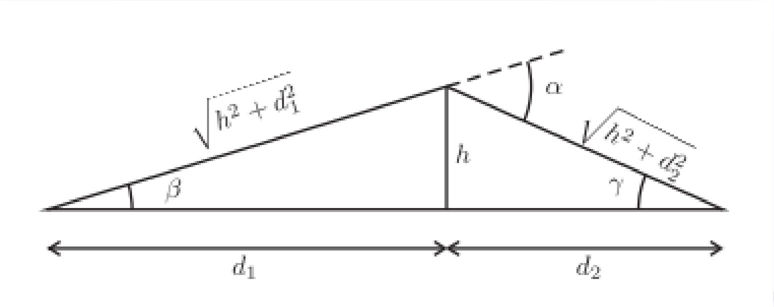
To predict the diffracted waves, we start with the analysis of a single wave; then the superposition principle is invoked to deal with all the diffracted contributions.



Single knife-edge diffracted waves

- h_{obs},h_t and h_r stand for the heights of the obstacle, TX and RX, respectively.
- The distance TX/obstacle (d_1) and RX/obstacle (d_2) are considered wrt the LOS path.
- The diffracted ray makes an angle β and γ with respect to LOS path on the transmitter and receiver sides, respectively.
- Although in the picture $h_t = h_r$, this is not a limiting assumption provided that the separation distance between TX and RX is large compared to their heights.

Diffracted wave



Diffracted wave

We are interested in finding the wave received from the diffracted path with respect to the LOS path.

Diffracted wave

- The path difference between the LOS and diffracted paths is given by:

$$\begin{aligned}
\Delta &= \sqrt{d_1^2 + h^2} + \sqrt{d_2^2 + h^2} - (d_1 + d_2) \qquad (15) \\
&= d_1 \sqrt{1 + \frac{h^2}{d_1^2}} + d_2 \sqrt{1 + \frac{h^2}{d_2^2}} - d_1 - d_2 \\
&\approx d_1 \left(1 + \frac{h^2}{2d_1^2}\right) + d_2 \left(1 + \frac{h^2}{2d_2^2}\right) - d_1 - d_2 \\
&= \frac{h^2}{2} \left(\frac{1}{d_1} + \frac{1}{d_2}\right) \\
&= \frac{h^2}{2} \frac{d_1 + d_2}{d_1 d_2}
\end{aligned}$$

the approximation holds since $(1 + x)^n \approx (1 + nx)$.

Diffracted wave

- Since the distances d_1, d_2 are much larger than h:

$$\beta = \tan^{-1}\frac{h}{d_1} \approx \frac{h}{d_1} \tag{16}$$

$$\gamma = \tan^{-1}\frac{h}{d_2} \approx \frac{h}{d_2} \tag{17}$$

$$\alpha = \beta + \gamma \approx \frac{h(d_1+d_2)}{d_1 d_2} \tag{18}$$

- The electrical length of the path difference Δ is given by:

$$\phi = k\Delta = \frac{2\pi}{\lambda}\frac{h^2}{2}\frac{d_1+d_2}{d_1 d_2} = \frac{\pi}{2}\nu^2 \tag{19}$$

$$\nu = h\sqrt{\frac{2(d_1+d_2)}{\lambda d_1 d_2}} = \alpha\sqrt{\frac{2d_1 d_2}{\lambda(d_1+d_2)}} \tag{20}$$

- where ν, which is termed as Fresnel-Kirchhoff parameter, is related to the height of the obstacle.

Single knife-edge diffraction

- The diffracted wave that reaches RX, normalized wrt the LOS wave, is given by (assuming the same magnitude for both the waves):

$$\frac{E_d}{E_{LOS}} = e^{-j\beta\Delta} = e^{-j\frac{\pi}{2}\nu^2} \tag{21}$$

- This is the effect of a single diffracted wave.

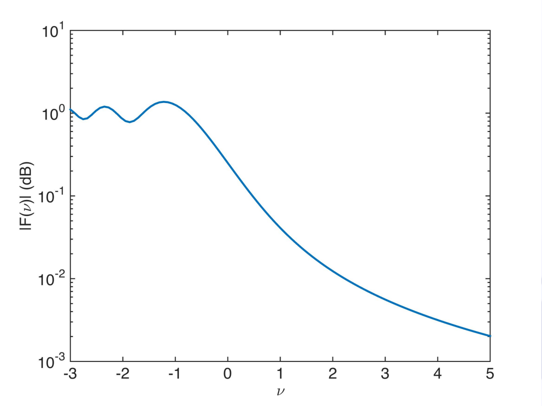
Fresnel integral

To include the effect of all the other rays produced by the Huygen's sources above the obstacle, we need to integrate from ν to ∞:

$$\frac{E_d}{E_{LOS}} = F(\nu) = \frac{1+j}{2}\int_{\nu}^{\infty} e^{-\frac{j\pi t^2}{2}}\,dt \tag{22}$$

$F(\nu)$ is termed as Fresnel integral

Do it yourself - Fresnel Integral



$$F(\nu) = \frac{1+j}{2}\left\{\left(\frac{1}{2} - C(\nu)\right) - j\left(\frac{1}{2} - S(\nu)\right)\right\} \quad (23)$$

A step drop is observed starting from $\nu = -1$.

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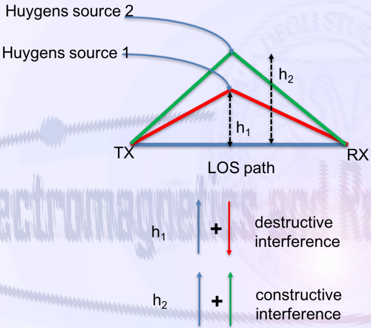
Fresnel zones

Let h be the height of the Huygen's source in the diffraction problem wrt the LOS path.



- If h is such that $\Delta = \frac{\lambda}{2}$, the phase shift ϕ between LOS and diffracted wave is π. A destructive interference occurs (see h_1).
- If h is such that $\Delta = \lambda$, ϕ is 2π. A constructive interference occurs (see h_2).

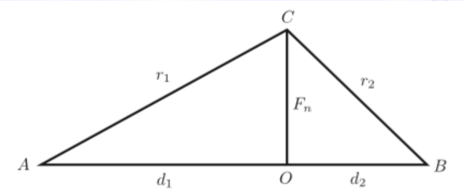
This is true over a locus of points forming a ring in the plane of the screen that is termed as Fresnel zone.

Fresnel zones

- This process repeats when increasing h, i.e.; Fresnel zones that provide constructive and destructive interference to the total received signal alternate every $\frac{\lambda}{2}$ increase of h.

nth Fresnel zone

The loci of points at which propagation produces an excess path length Δ equal to $n\frac{\lambda}{2}$ is termed as nth Fresnel zone.



Radius of the Fresnel zones

- To evaluate the radius of the *n*th Fresnel zone we consider the triangle ABC; where AB stands for the LOS path and ACB stands for the diffracted path.
- The point C is in the *n*th Fresnel zone when the following equation is satisfied:

$$r_1 + r_2 = d_1 + d_2 + n\frac{\lambda}{2}. \tag{24}$$

- This equation can be rewritten as:

$$\sqrt{d_1^2 + F_n^2} + \sqrt{d_2^2 + F_n^2} = d_1 + d_2 + n\frac{\lambda}{2}. \tag{25}$$

- Since F_n is much smaller than d_1, d_2, eq.(25) can be approximated as follows:

$$d_1 + \frac{F_n^2}{2d_1} + d_2 + \frac{F_n^2}{2d_2} = d_1 + d_2 + n\frac{\lambda}{2}. \tag{26}$$

Radius of the Fresnel zones

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- Hence, one obtains:

$$\frac{F_n^2}{2}\left(\frac{1}{d_1}+\frac{1}{d_2}\right)=n\frac{\lambda}{2} \tag{27}$$

Radius of the nth Fresnel zone

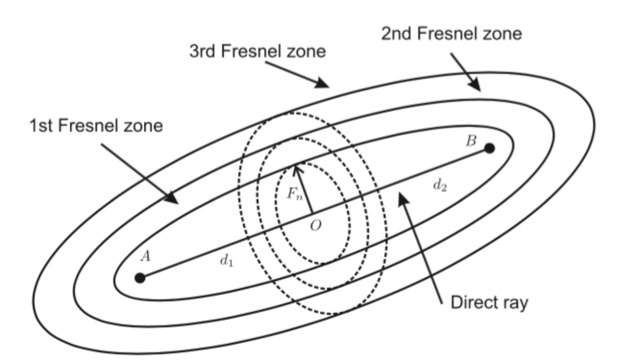
The radius F_n is given by:

$$F_n=\sqrt{\frac{n\lambda d_1 d_2}{d_1+d_2}} \tag{28}$$

- Each circle of radius F results in a Δ equal to $\lambda/2$, λ, $3\lambda/2$,etc.
- F_n is maximum when $d_1 = d_2$.

Fresnel zones

Fresnel zones are the geometric loci (ellipsoids) characterized by all the points resulting in Δ equal to an integer multiple of $\frac{\lambda}{2}$.



Total phase shift

When a signal is reflected two things happen:

1. The phase of the signal reverses and the signal changes in phase by 180°.
2. Since the signal is being reflected and not going in a direct line, it travels slightly further to the refection point and then on to the receiver. Therefore, the signal is shifted further in phase, by the difference in path length $\phi = k\Delta$.
3. This implies that the received signal results from the coherent combination of the LOS signal and the reflected one that will exhibit a phase shift equal to $\pi + \phi$.

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1st Fresnel zone

Most of the energy associated with the em wave lies in the 1st Fresnel zone.
In fact, the reflected signal is shifted by 180° of path distance plus $\phi = k\frac{\lambda}{2} = \pi$ from the actual reflection point totals 360° of phase shift. Hence, the LOS and reflected signals add together and they do not affect receiver performance.

- An absorbing obstacle that enters this zone will significantly affect the received power.