Basic of Propagation Theory

S-72.333

Physical Layer Methods in Wireless Communication Systems

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Introduction

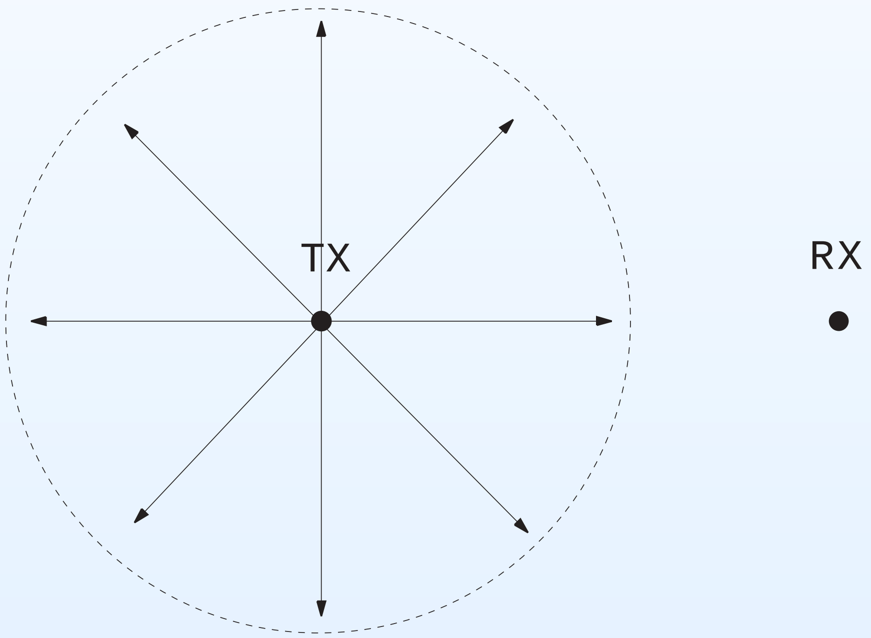
- The study of propagation is important to wireless communication because it provides
  1) prediction models for estimations the power required *to close a communication link* ⇒ reliable communications.
  2) clues to the receiver techniques for compensating the impairments introduced through wireless transmission.
- The propagation effects and other signal impairments are often collected and referred to as the *channel*.
- Channel models for wireless communications may be defined as *Physical models* and *Statistical Models*.
- RX signal is the combination of many propagation models ⇒ *multipath* and *fading*.
- In addition to propagation impairments, the other phenomena that limit wireless communications are *noise* and *interference*.

Free-Space Propagation

- The transmission is characterized by
  - the *generation*, in the transmitter (TX), of an electric signal representing the desired information,
  - *propagation* of the signal through space,
  - a receiver (RX) that estimates the transmitted information from the *recovered* electrical signal.
- The antenna converts between electrical signals and radio waves, and vice versa.
- The transmission effects are most completely described by the Maxwell's equations.
- Here we assume a linear medium in which all the distortions can be characterized by attenuation or superposition of different signals.

Isotropic Radiation

- An antenna is isotropic if it can transmit equally in all directions.
- It represents an ideal antenna and it is used as reference to which other antennas are compared.



Isotropic Radiation

- The *power flux density* of an isotropic source that radiates power P_T watts in all directions is

$$\Phi_R = \frac{P_T}{4\pi R^2} \qquad \left[\frac{W}{m^2}\right]$$

where $4\pi R^2$ is the surface area of a sphere.

- The power captured by the receiving antenna (RX) depends on the size and orientation of the antenna with respect to the TX

$$P_R = \Phi_R \, A_e = \frac{P_T}{4\pi R^2} \, A_e$$

where A_e is the *effective area* or *absorption cross section*.

- Effective area of an isotropic antenna in any direction: $A_e^{iso} = \frac{\lambda^2}{4\pi}$.
- The *antenna efficiency* is defined as $\eta = \frac{A_e}{A}$ where A is the physical area of the antenna.

Isotropic Radiation

- The link between TX and RX power for isotropic antennas is

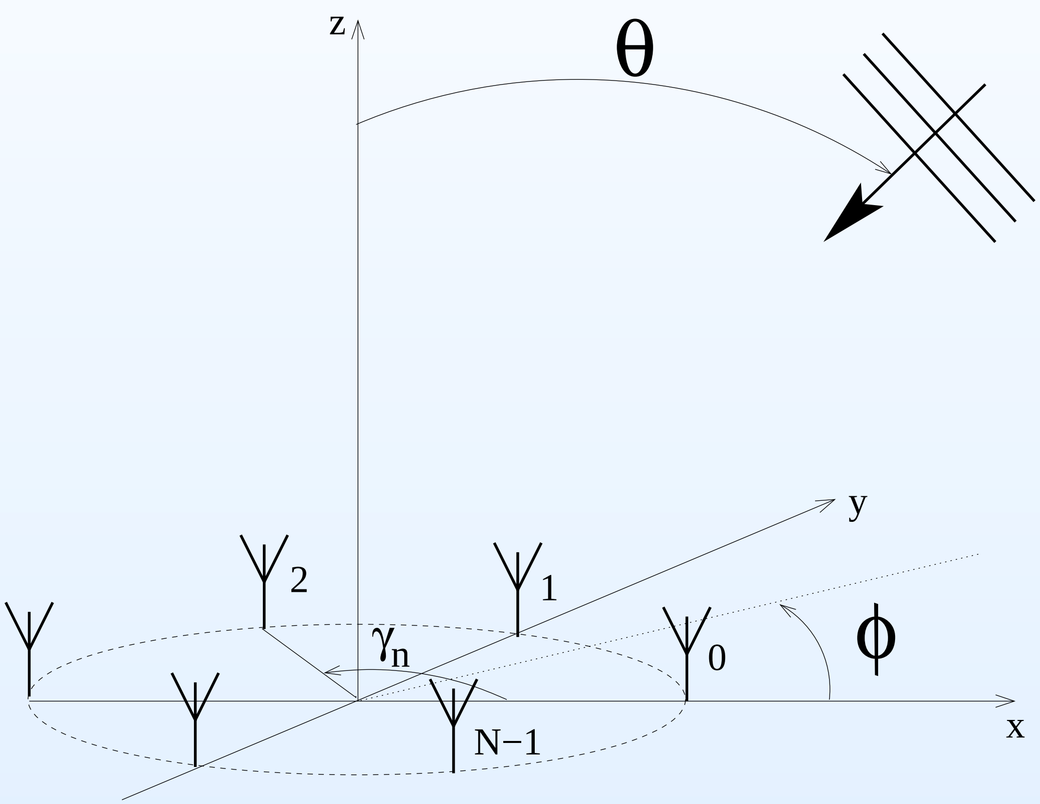
$$P_R = \left(\frac{\lambda}{4\pi R}\right)^2 P_T = \frac{P_T}{L_P}$$

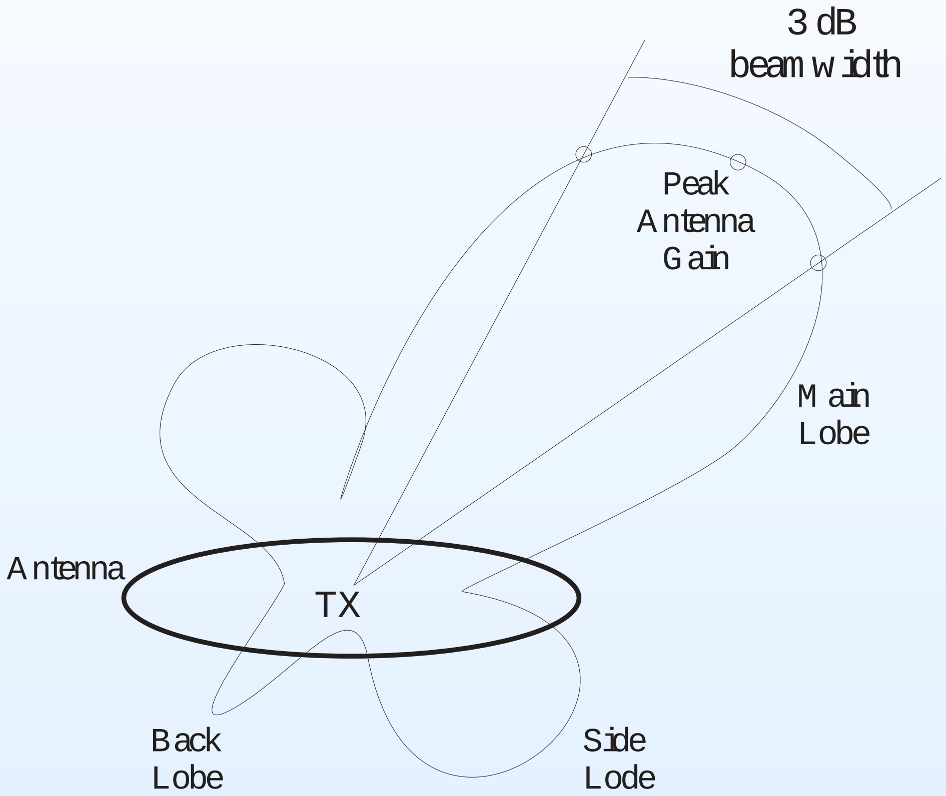
where $L_P = \left(\frac{4\pi R}{\lambda}\right)^2$ is the free-space path loss between two isotropic antennas.

- The path loss depends on the wavelength of transmission.
- The *sensitivity* is a receiver parameter that indicates the minimum signal level required at the antenna terminals in order to provide reliable communications.

Directional Radiation

- Real antenna is not isotropic and it has *gain* and *directivity* which may be functions of the azimuth angle ϕ and elevation angle θ.





Directional Radiation

- Transmit antenna gain: $G_T(\phi, \theta) = \frac{\text{Power flux density in direction}(\phi,\theta)}{\text{Power flux density of an isotropic antenna}}$.
- Receive antenna gain: $G_R(\phi, \theta) = \frac{\text{Effective area in direction}(\phi,\theta)}{\text{Effective area of an isotropic antenna}}$.
- Principle of reciprocity $\Rightarrow$ signal transmission over a radio path is reciprocal in the sense that the locations of the transmitter and receiver can be interchanged without changing the transmission characteristics.
- Maximum transmit or receive gain

$$\frac{G}{A_e} = \frac{4\pi}{\lambda^2}$$

- Side-lode and back-lobe are not considered for use in the communications link, but they are considered when analyzing interference.

The Friis Equation: Link Budget

- In case of non-isotropic antenna, the Free-Space loss relating the received and transmitted power is

$$P_R = \frac{P_T\, G_T\, G_R}{L_P} = P_T\, G_T\, G_R \left(\frac{\lambda}{4\pi R}\right)^2 \tag{1}$$

  or, as a decibel relation,

$$P_R(dB) = P_T(dB) + G_T(dB) + G_R(dB) - L_P(dB)$$

  where $X(dB) = 10\log_{10}(X)$.

- *Closing the link* means that the right hand side of eq.(1) provides enough power at the receiver to detect the transmitted information reliably $\Rightarrow$ RX sensitivity.
- The Friis equation (Link Budget), as presented so far, does not include the effect of noise, e.g. receiver noise, antenna noise, artificial noise, multiple access interference,...

The Friis Equation: Link Budget

- Let us assume the receiver noise as dominant an let us model it by the single-sided noise spectral density N_0.
- To include the noise, the Link Budget may now be expressed as

$$\frac{P_R}{N_0} = \frac{P_T\, G_T\, G_R}{L_P\, k\, T_e} \tag{2}$$

where $N_0 = k\, T_e$, k is the Boltzmann's constant and T_e is the equivalent noise temperature of the system.

- In satellite application, eq.(2) is written as $\frac{C}{N_0} = \text{EIRP} - L_p + \frac{G}{T} - k$:

◇ $\frac{C}{N_0} = \frac{P_R}{N_0} \rightarrow$ received carrier-to-noise density ratio (dB/Hz)

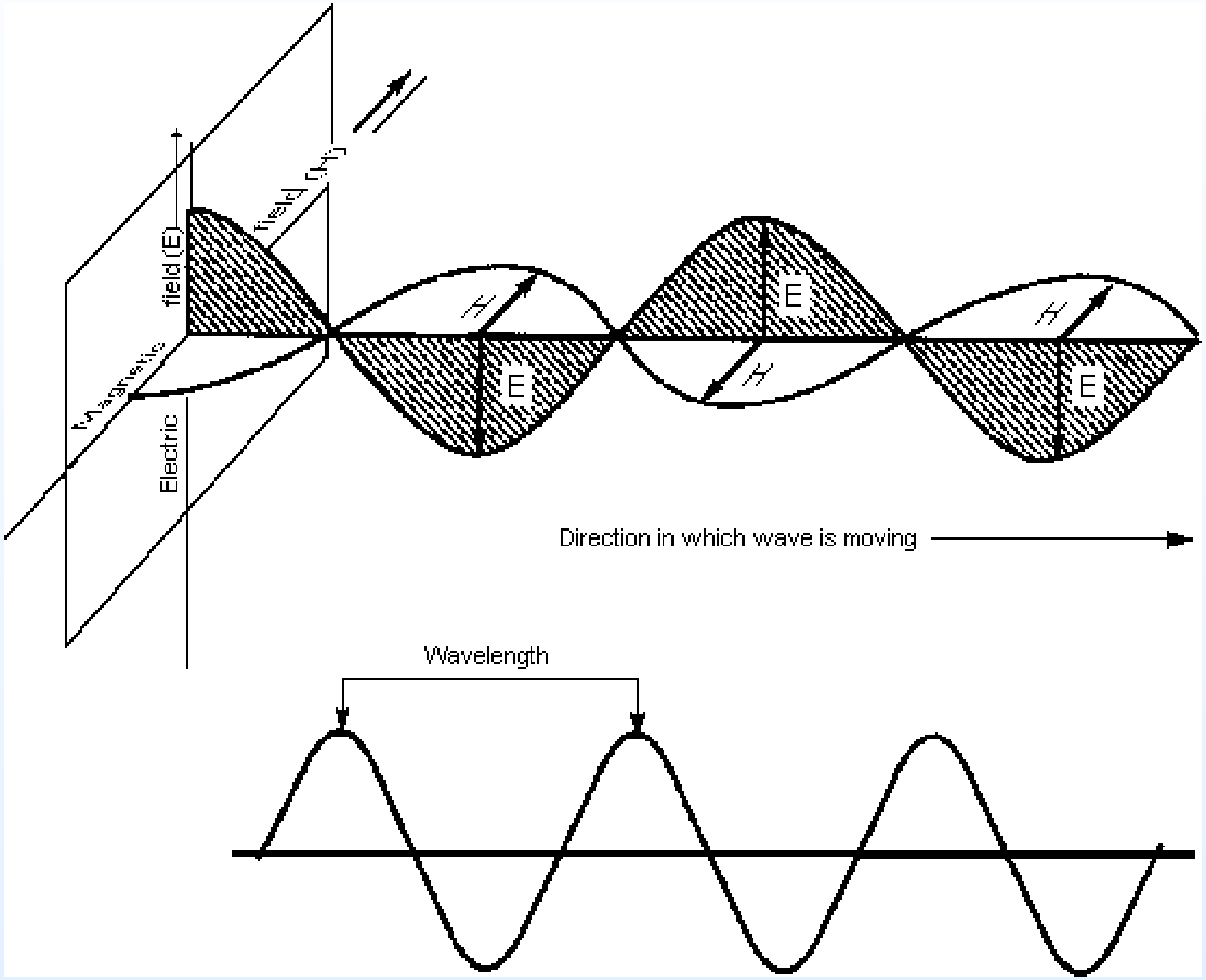
◇ $\text{EIRP} = P_T\, G_T \rightarrow$ TX Equivalent Isotropic Radiated Power (dBW)

◇ $\frac{G}{T} = \frac{G_R}{T_e} \rightarrow$ RX gain-to-noise temperature ratio (dB/K)

◇ $L_p \rightarrow$ Path loss (dB)

◇ $k \rightarrow$ Boltzmann's constant

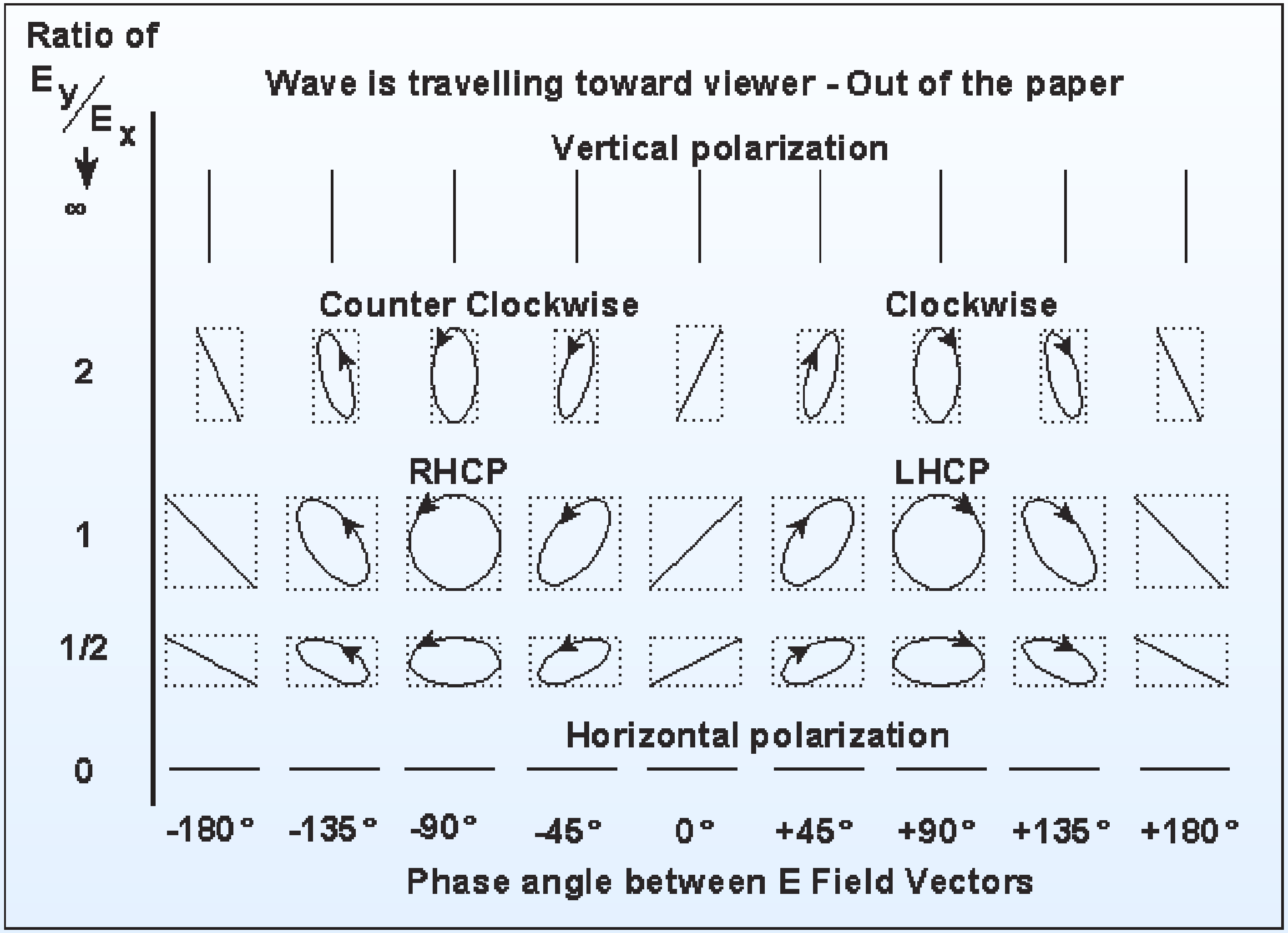
Polarization



Polarization

- The electric field may be expressed as $\overrightarrow{E} = E_x \overrightarrow{u}_x + E_y \overrightarrow{u}_y$.
- In the phasor domain we can write $\overrightarrow{E} = \cos(\alpha)\overrightarrow{u}_x + \sin(\alpha)e^{j\phi}\overrightarrow{u}_y$.
  - $\forall\alpha$ & $\phi = 0 \Rightarrow$ Linear polarization,
  - $\alpha = \frac{\pi}{4}$ & $\phi = \pm\frac{\pi}{2} \Rightarrow$ Right-hand (-) and Left-hand (+) circular pol.
- Examples:
  - VP: $\alpha = \frac{\pi}{2}$ & $\phi = 0 \Rightarrow \overrightarrow{E} = \overrightarrow{u}_y$,
  - HP: $\alpha = 0$ & $\phi = 0 \Rightarrow \overrightarrow{E} = \overrightarrow{u}_x$,
  - RHCP: $\alpha = \frac{\pi}{4}$ & $\phi = -\frac{\pi}{2} \Rightarrow \overrightarrow{E} = \frac{1}{\sqrt{2}}\overrightarrow{u}_x - j\frac{1}{\sqrt{2}}\overrightarrow{u}_y$,
  - LHCP: $\alpha = \frac{\pi}{4}$ & $\phi = \frac{\pi}{2} \Rightarrow \overrightarrow{E} = \frac{1}{\sqrt{2}}\overrightarrow{u}_x + j\frac{1}{\sqrt{2}}\overrightarrow{u}_y$,
- In time domain $\overrightarrow{E}(t) = \cos(\alpha)\cos(wt)\overrightarrow{u}_x + \sin(\alpha)\cos(wt+\phi)\overrightarrow{u}_y$.
- *Scattering effects* tend to create cross-polarization interference.

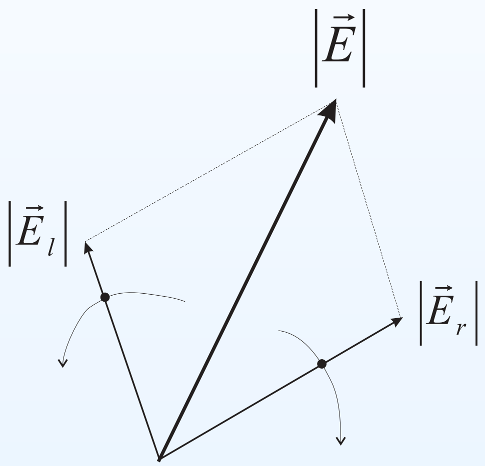
Polarization



Polarization

- Projection matrix: $\begin{pmatrix} E_r \\ E_l \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & j \\ 1 & -j \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix}$

  where E_r and E_l are the right and left circular bases, respectively.



- Axial ratio: $R = \frac{|E_l|-|E_r|}{|E_l|+|E_r|} = \begin{cases} 1 & \text{Left-Hand Circular Pol.} \\ 0 & \text{Linear Pol.} \\ -1 & \text{Right-Hand Circular Pol.} \end{cases}$

  if $R \in (0,1)$ Left-Hand Elliptical Pol. and if $R \in (-1,0)$ Right-Hand Elliptical Pol.

Polarization

- Example: verify, by using the axial ratio, that a left-hand circular polarization can be identified by setting $\alpha = \frac{\pi}{4}$ & $\phi = \frac{\pi}{2}$.

$$\begin{cases} E_x = \cos(\alpha) = \frac{1}{\sqrt{2}} \\ E_y = \sin(\alpha)\, e^{j\phi} = j\frac{1}{\sqrt{2}} \end{cases}$$

$$\begin{pmatrix} E_r \\ E_l \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & j \\ 1 & -j \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{2}} \\ j\frac{1}{\sqrt{2}} \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

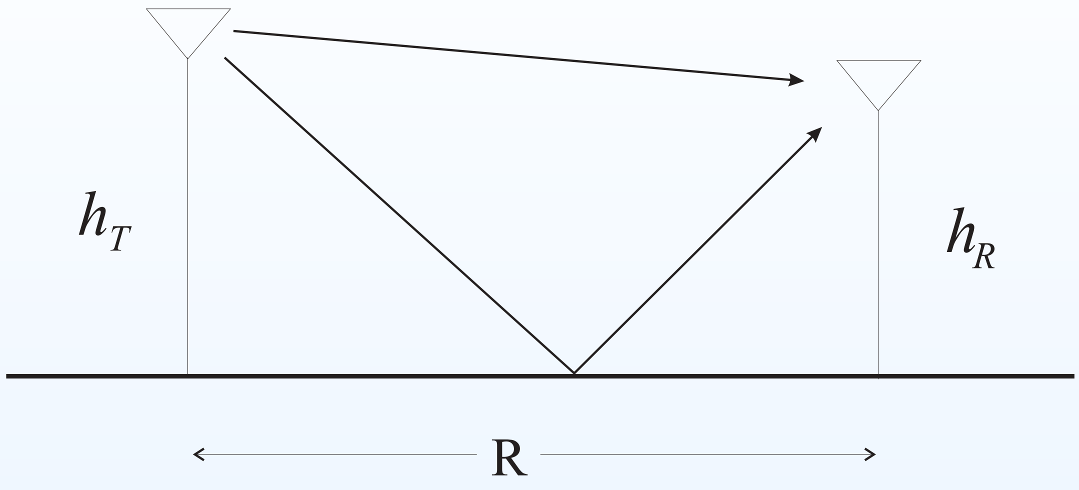
$$R = \frac{|E_l| - |E_r|}{|E_l| + |E_r|} = \frac{1-0}{1+0} = 1$$

$\Rrightarrow$ Left-Hand Circular Polarization!

Terrestrial Propagation: Physical Models

- They consider the exact physics of the propagation environment (site geometry). It provides reliable estimates of the propagation behavior but it is computationally expensive.
- Basic modes of propagation:
  - *Line-of-Sight (LOS) transmission* $\Rightarrow$ clear path between transmitter (TX) and receiver (RX), e.g. satellite communications.
  - *Reflection* $\Rightarrow$ bouncing of electromagnetic waves from surrounding objects such as buildings, mountains, vehicles,...
  - *Diffraction* $\Rightarrow$ bending of electromagnetic waves around objects such as buildings, hills. trees,...
  - *Refraction* $\Rightarrow$ electromagnetic waves are bent as they move from one medium to another.
  - *Ducting* $\Rightarrow$ physical characteristic of the environment create a waveguide-like effect.
- RX signal is the combination of this models $\Rightarrow$ *multipath* and *fading*.

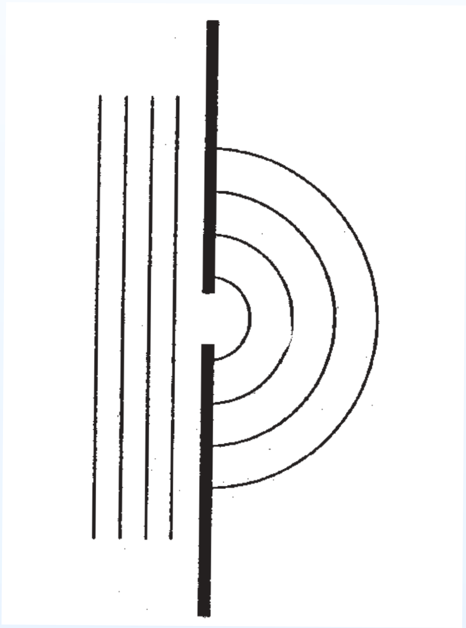
Reflection and the Plane-Earth Model

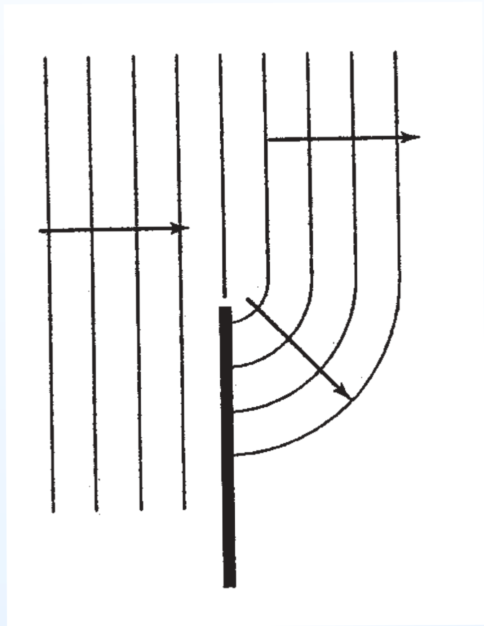


- Plane-Earth propagation equation: $P_R = P_T G_T G_R \left(\frac{h_T h_R}{R^2}\right)^2$
  - Assuming $R \gg h_T, h_R \Rightarrow$ the equation is frequency independent,
  - inverse fourth-power law,
  - dependence of antennas height.

Diffraction

- When electromagnetic waves are forced to travel through a small slit, they tend to spead out on the far end of the slit.

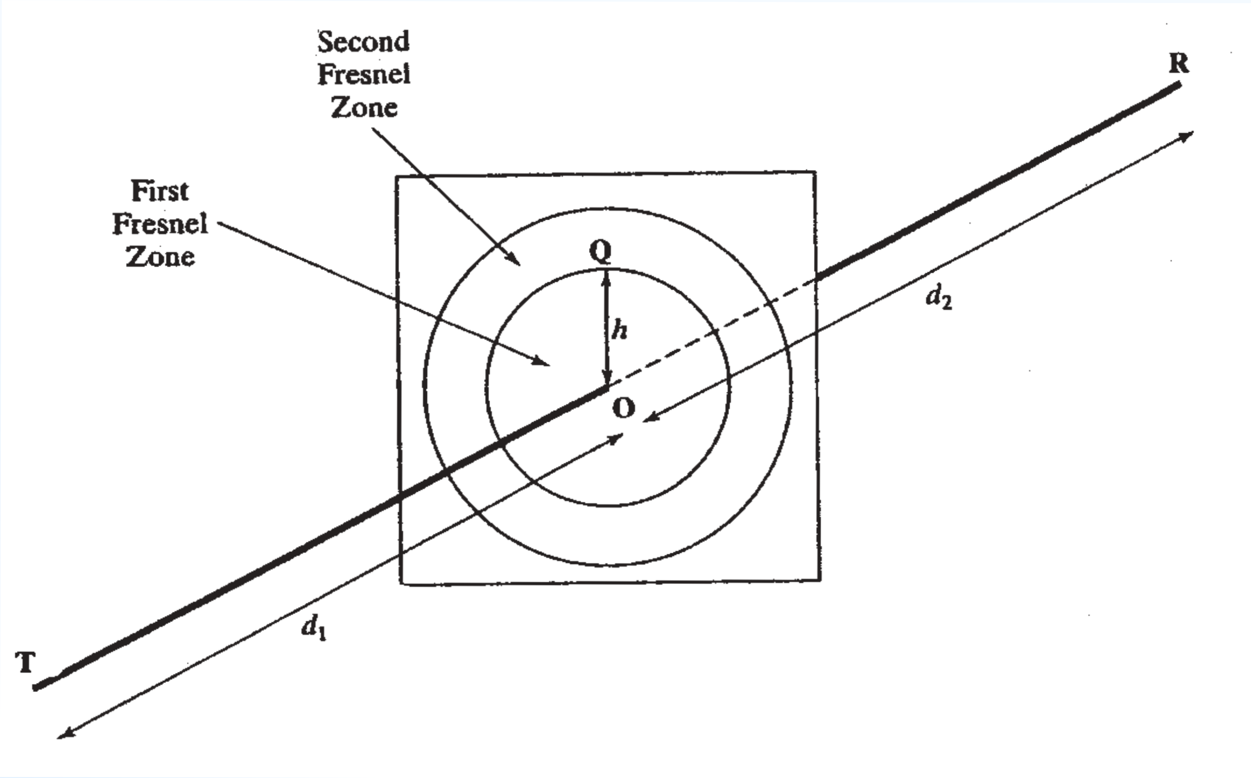




- *Huygens's principle*: each point on a wave front acts as a point source for further propagation. However, the point source does not radiate equally in all the directions, but favors the forward direction, of the wave front.

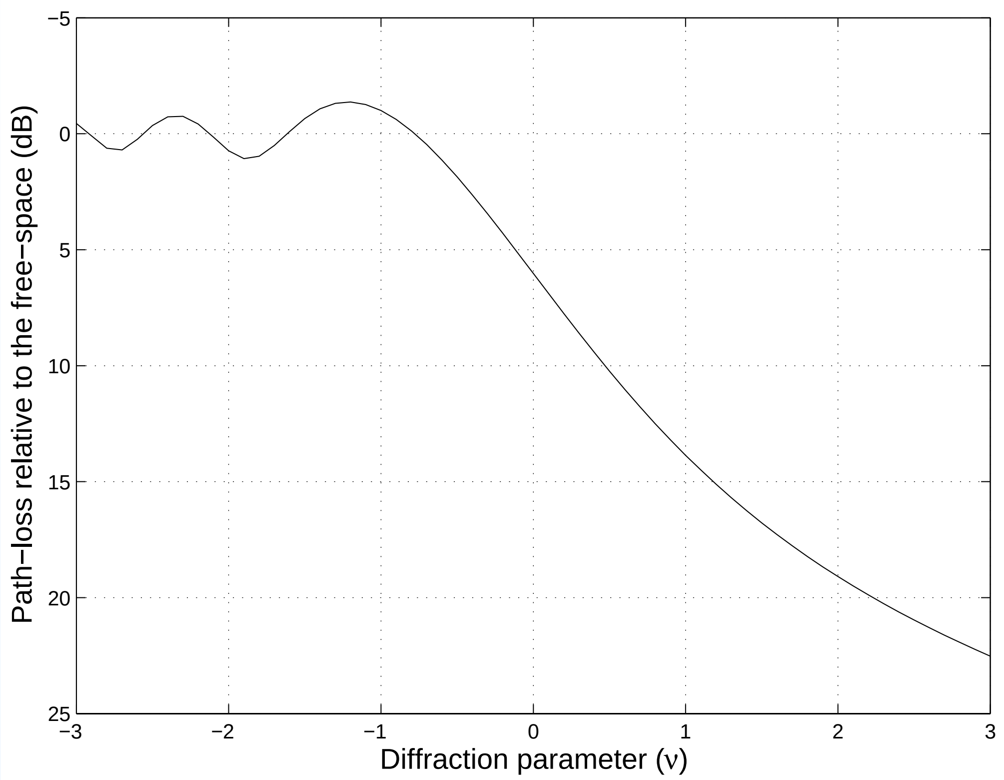
Diffraction

- Fresnel zones are important in order to understand the basic propagation phenomena.
- Rule of thumb: in order to obtain transmission under free-space condition, we have to keep the "first-Fresnel zone" free of obstacles.



- $\Delta R = |TQR| - |TOR|$
- $\frac{(q-1)\lambda}{2} \leq \Delta R \leq \frac{q\lambda}{2}$
- $h = \sqrt{\frac{q\lambda d_1 d_2}{d_1+d_2}}$

Diffraction Losses



- A perfectly absorbing screen is placed between the TX and RX.
- When the knife-edge is even with the LOS, the electric field is reduced by one-half and there is a 6-dB loss in signal power.

Terrestrial Propagation: Statistical Models

- By measuring the propagation characteristics in a variety of environments (urban, suburban, rural), we develop a model based on the measured statistics for a particular class of environments.
- In general, they are easy to describe but they are not accurate.
- The statistical approach is broken down into two components:
  - *median path loss*;
  - *local variations*;

Terrestrial Propagation: Statistical Models

- Median path loss: investigations motivate a general propagation model such as $\frac{P_T}{P_R} = \frac{\beta}{r^n}$, where r is the distance between TX and RX, n is the path-loss exponent and the parameter β represents a loss that is related to frequency , antenna heights, ...

Environment	n
Free-Space	2
Flat Rural	3
Rolling Rural	3.5
Suburban, low rise	4
Dense Urban, Skyscrapers	4.5

- Local variations: the variation about the median can be modelled as a log-normal distribution (shadowing).

Indoor propagation

- To study the effects of indoor propagations has gained more and more importance with the growth of cellular telephone.
- Wireless design has to take into account the propagation characteristics in high-density location.
- Wireless Local Area Networks (LAN's) are being implemented to eliminate the cost of wiring of rewiring buildings.
- Indoor path-loss model

$$L_P(dB) = \beta(dB) + 10\log_{10}\left(\frac{r}{r_0}\right)^n + \sum_{p=1}^{P} \text{WAF}(p) + \sum_{q=1}^{Q} \text{FAF}(q)$$

- WAF $\Rightarrow$ Wall Attenuation Factor
- FAF $\Rightarrow$ Floor attenuation Factor
- $r \Rightarrow$ dinstance TX and RX
- $r_0 \Rightarrow$ reference distance (1 m)
- Q and P $\Rightarrow$ number of floors and walls, respectively.

Conclusions

- The link budget may be improved by using directional instead of isotropic antennas.
- There is a trade off between the accuracy and the computational complexity for propagation models.
- The polarization of electromagnetic waves is an important issue for wireless communication.

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Homeworks

- Let us assume a right-hand circular polarization with $E_x = 1$ and $E_y = -j$. Compute the loss in dB in a wireless link when the horizontal component is attenuated by 6-dB.
- In case of physical models for terrestrial propagation, which are the basic models of propagation. Explain briefly each of them.