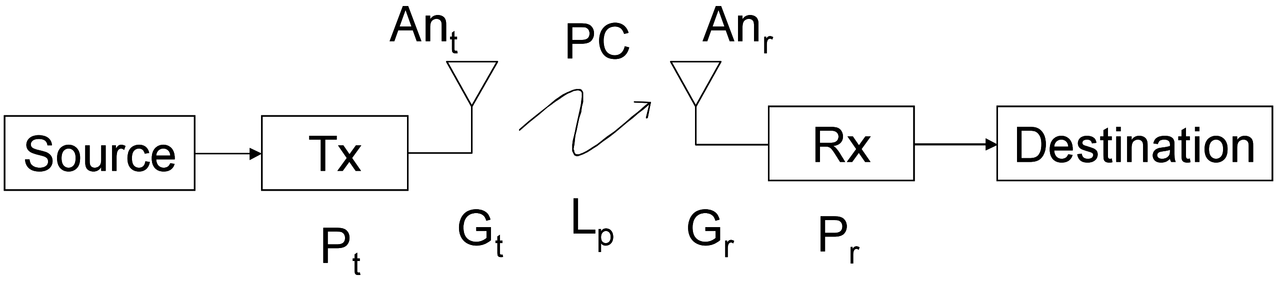
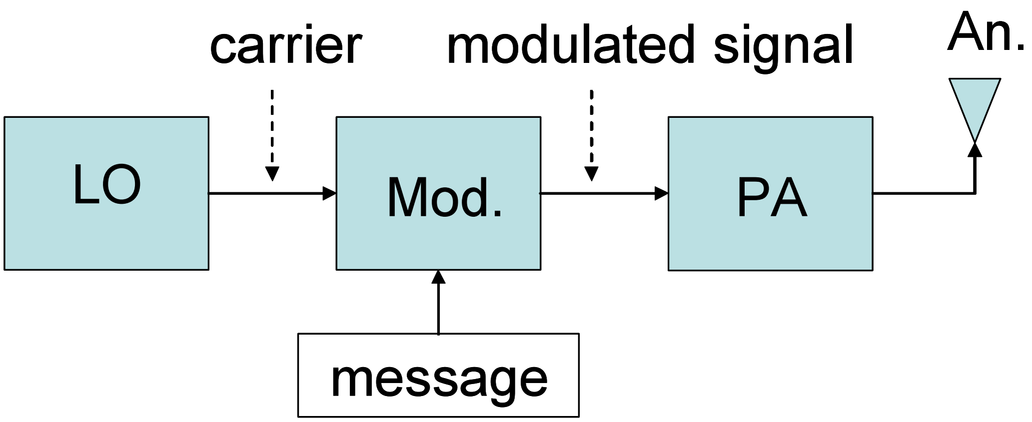
Wireless Communication System

Generic Block Diagram



- Source → a source of information to be transmitted
- Destination → a destination of the transmitted information
- Tx and Rx → transmitter and receiver
- An_t & An_r → Tx and Rx antennas
- PC = propagation channel
- Tx includes coding/modulation circuitry (or DSP), power amplifiers, frequency synthesizers etc.
- Rx includes LNA, down conversion, demodulation, decoding etc.
- Examples: cellular phones, WiFi, radio and TV broadcasting, GPS, cordless phones/keys, radar, etc.
- Main advantages: flexible (service almost everywhere), low deployment cost (compare with cable systems).
- Main disadvantages: PC is very bad, limits performance significantly, almost all development in wireless com. during last 50 years were directed to combat PC.

Radio Transmitter



- Local oscillator (LO) – generates the carrier
- Modulator (Mod.) – modulates the carrier using the message signal
- Power amplifier (PA) – amplifies the modulated signal to required power level
- Antenna (An.) – radiates the modulated signal as an electromagnetic wave

Check-up question: why modulation?

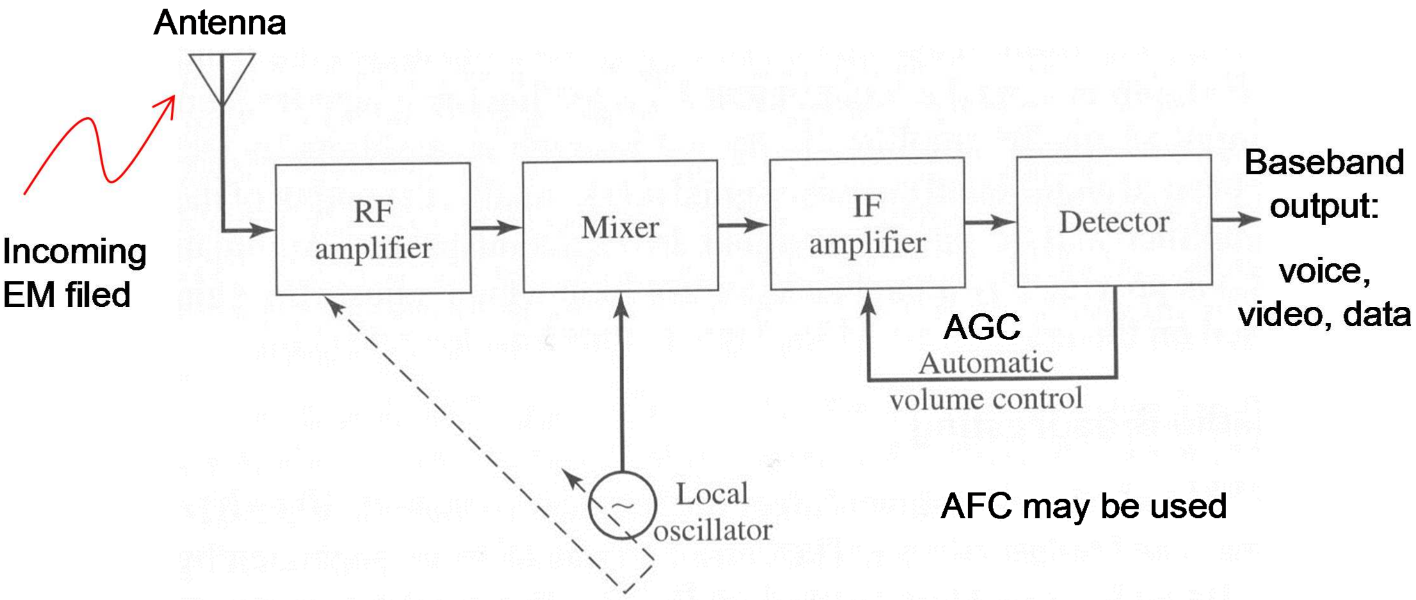
An example of modulation: DSB-SC AM,

$$x(t) = m(t) \cdot A_c \cos(2\pi f_c t)$$

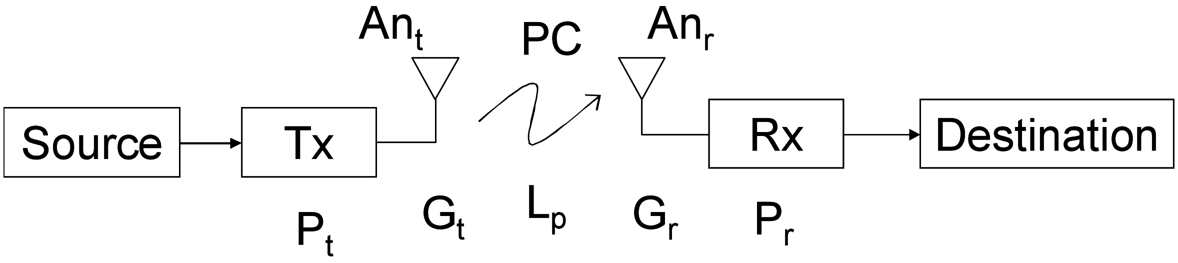
For more info and refreshment, see your ELG3175 (or ELG4176) textbook.

Superheterodyne Receiver

- Most popular type of a radio receiver so far.
- Used for AM/FM & TV broadcasting, cellular & satellite systems, radars, GPS etc.
- Main idea: downconvert RF signal to some fixed lower (intermediate) frequency, then amplify it and detect.



Wireless Propagation Channel



- This is a major obstacle to reliable and high quality wireless communications.
- Why? (3 key reasons)
  - Large signal attenuation.
  - High degree of variability (in time, space, etc.)
  - Out of designer's control (almost completely).
- Difference between wired (AWGN) and wireless (e.g., Rayleigh) channels.

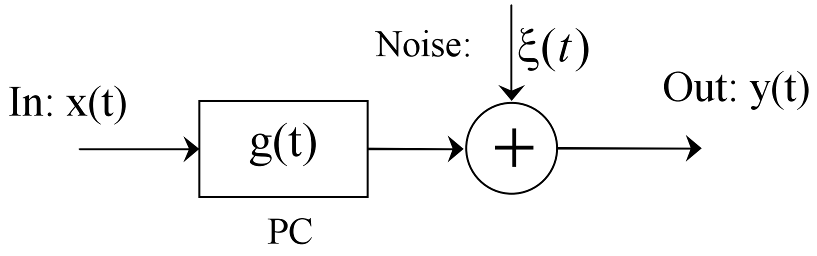
Much effort is spent on modeling, characterization and simulations of the wireless propagation channel.

Classification of Channel Models

- System level / propagation (electromagnetic) based
- Deterministic / stochastic
- Theoretical / empirical (semi-empirical)

Various techniques, goals, accuracies.

Example of a <u>system-level channel model:</u>



$$y(t) = g(t) * x(t) + \xi(t)$$

g is the channel gain; may be an impulse response, $g(t)$, or a frequency response , $g(f)$.

Channel can be LTI, but it can also be time-varying.

Almost all channels are modeled as linear.

Example of <u>propagation-based</u> model: free space model (or 2-ray model), to be discussed later on.

All the models above are <u>deterministic</u>.

Example of a <u>stochastic model</u>: Rayleigh channel. All the models above are theoretical.

Example of an <u>empirical model</u>: Okumura-Hata model.

Threshold Effect

All the communication systems exhibit a **threshold effect**: when signal-to-noise (SNR) ratio drops below a certain value (called threshold value), the system either doesn't operate at all, or operates with unacceptable quality.

The SNR is

$$\boxed{\gamma = \mathrm{SNR} = \frac{\text{signal power}}{\text{noise power}} = \frac{P_s}{P_n}} \tag{2.1}$$

For acceptable performance,

$$\boxed{\gamma \geq \gamma_{th} \leftrightarrow P_r \geq P_{th}} \tag{2.2}$$

where γ = SNR (at the Rx),
γ_{th} = a threshold SNR,
P_r = the Rx power,
P_{th} = the threshold Rx power (sensitivity),

i.e. P_r is bounded from below to provide satisfactory performance.

Outage event: if $\gamma < \gamma_{th} \leftrightarrow P_r < P_{th}$ → unsatisfactory system performance).

It is <u>very important</u> to evaluate correctly the Rx signal power P_r when designing a communication system (link).

P_{th} is affected by:

1) Bandwidth
2) Rx noise figure
3) Type of modulation (i.e, BPSK/QPSK/16-QAM);
4) Coding (i.e, no coding, (7, 4) Hamming code, etc.)

Noise power:

In an additive white (thermal) noise channel, the SNR can be expressed as

$$\boxed{\gamma = P_r / P_0} \tag{2.3}$$

where $P_0 = kT\Delta fF$ = Rx noise power,

$k = 1.38 \cdot 10^{-23} J/K$ = Boltzman constant,

T = Rx temperature (^{0}K),

Δf = equivalent (noise) bandwidth,

F = Rx noise figure (typically a few dBs).

γ_{th} is found based on a desirable error rate performance.

Link Budget Analysis

The link budget relates the Tx power, the Rx power, the path loss, Rx noise and additional losses and margins into a single equation:

$$P_r = P_t \frac{G_T G_R}{L_P L_a F_s} \tag{2.4}$$

where P_t = Tx power,
G_T = Tx antenna gain,
G_R = Rx antenna gain,
L_P = Propagation path loss,
L_a = Additional losses (i.e., cable, aging, etc.)
F_s = Fading (and other) margin;

Interference margin: can be added when the system operates in interference environment (i.e, cellular).

Fading margin: can be added when the system operates in a fading channel. $F_s = 1$ if no fading.

Link margin = γ / γ_{th} → how far away the link is from the threshold.

Link budget equation (2.3) can be used to find the required Tx power (P_t) or the maximum acceptable path loss (L_P). This is a first step in the design of a wireless system (link).

An example

Given

$$P_r = 10^{-12}\,\mathrm{W}(-90\ \mathrm{dBm});\quad L_p = 150\ \mathrm{dB}\ (10^{15});$$

$$G_r = 10\ \mathrm{dB};\qquad G_t = 10\ \mathrm{dB};\ L_a = 0\ \mathrm{dB};$$

find required P_t:

$$P_t = \frac{P_r L_p}{G_t G_r} \rightarrow \left(P_t = P_r + L_p - G_t - G_r\right)[dB] = 40dBm \rightarrow 10W;$$

Minimum P_r ("sensitivity") for a WiFi router Rx:

Sensitivity @PER	270M: -68dBm@10% PER;
	130M: -68dBm@10% PER
	108M: -68dBm@10% PER;
	54M: -68dBm@10% PER
	11M: -85dBm@8% PER;
	6M: -88dBm@10% PER
	1M: -90dBm@8% PER

<u>dB, dBm, etc.:</u>

power ratio: $100 \leftrightarrow 20\mathrm{dB} = 10\lg_{10}(100)$
amplitude (voltage/current) ratio: $100 \leftrightarrow 40\mathrm{dB} = 20\lg_{10}(100)$
dBm = dB w.r.t. 1mW:
$20\mathrm{dBm} \leftrightarrow 1\mathrm{mW}\cdot 10^{20/10} = 100\mathrm{mW} = 0.1\mathrm{W}$

Effect of Interference

No interference:

$$\gamma = SNR = \frac{P_s}{P_n} \geq \gamma_{th} \qquad (2.6)$$

As a simple model, assume that interference acts like noise:

$$\gamma = SNIR = \frac{P_s}{P_n + P_{\mathrm{i}}} = \frac{\mathrm{SNR}}{1 + \mathrm{INR}} \geq \gamma_{th} \qquad (2.7)$$

where $\mathrm{INR} = P_i / P_n$ = interference-to-noise ratio (INR).

Satisfactory performance typically requires $\gamma_{th} \sim 10dB$.

Minimum required received power under no interference:

$$P_r = P_s \geq \gamma_{th} P_n \qquad (2.8)$$

Minimum received power with interference:

$$P_r \geq \gamma_{th}\left(P_n + P_i\right) = \gamma_{th} P_n \left(1 + \mathrm{INR}\right) \qquad (2.9)$$

Compare (2.9) to (2.8): the effect of interference is to boost the required Rx and thus Tx powers.

Noise dominated systems vs. interference dominated systems.

Three Factors in the Propagation Path Loss:

The propagation path loss is

$$L_P = L_A L_{LF} L_{SF} \tag{2.5}$$

where L_A = average path loss,
L_{LF} = large-scale fading,
L_{SF} = small-scale fading.

Propagation Path Loss Components

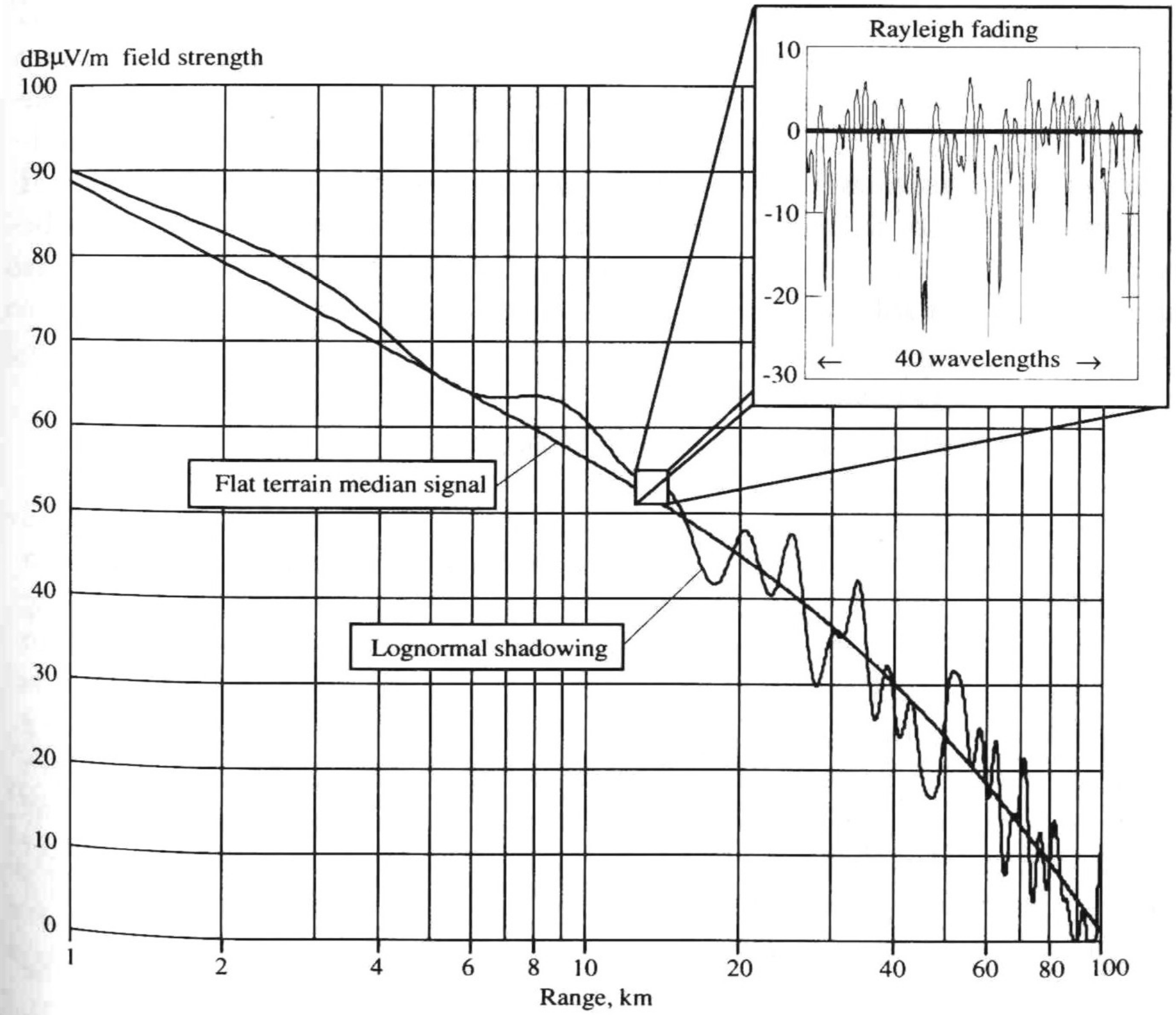
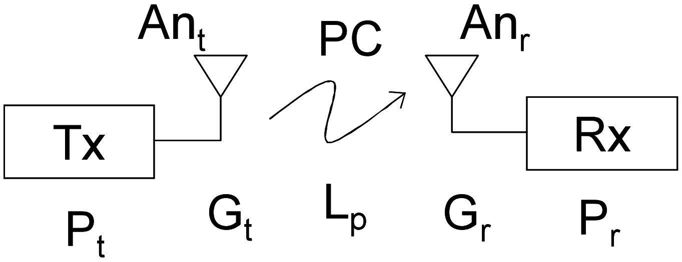


Figure 8.2 Signal behavior in a suburban region showing shadowing and multipath fading. (After: [1].)

Siwiak, Radiowave Propagation and Antennas for Personal Communications, Artech House, 1998

Propagation Channel: Basic Mechanisms

- Approximations are very important!
- LOS propagation: consider a communication link in free space



- Assume for a moment that the Tx antenna is isotropic, then power flux density at distance *R* is

$$\Pi_i = \frac{P_t}{4\pi R^2} \qquad (2.10)$$

- Since the antenna is not isotropic,

$$\Pi = \frac{P_t G_t}{4\pi R^2} \qquad (2.11)$$

- Equivalent isotropic radiated power (EIRP) is

$$P_e = P_t G_t \qquad (2.12)$$

This is the power radiated by isotropic antenna, which produces the same power at the receiver as our non-isotropic antenna.

Effective Aperture & Received Power: Free Space

- Effective aperture of Rx antenna, S_e:

$$G_R = \frac{4\pi}{\lambda^2} S_e \rightarrow S_e = \frac{\lambda^2}{4\pi} G_R \qquad (2.13)$$

- Power received by Rx antenna is

$$\mathrm{P}_r = \Pi \cdot S_e = G_t G_r P_t \left(\frac{\lambda}{4\pi R} \right)^2 = \frac{G_r P_e}{L_p}; \qquad (2.14)$$

where L_p is the propagation loss (Friis equation),

$$L_p = \left(\frac{4\pi R}{\lambda} \right)^2 \qquad (2.15)$$

- Friis equation (2.15) is valid in the **far field** only:

$$R \geq \frac{2D^2}{\lambda} \;\; \& \;\; \mathrm{R} \gg D, \lambda \qquad (2.16)$$

where D is the maximum antenna size.

- Usually $R > \lambda$ and 2nd part reduces to $\mathrm{R} \gg D$; 1st part dominates in many cases.
- Free space propagation model is simple, but unrealistic. Real environments are more complex.
- However, the free space model provides good starting point for more complex models.

Relation between the power flux density Π and electric field magnitude E:

$$\Pi = \frac{E^2}{W_0}, \quad W_0 = 120\pi \ [\Omega] \approx 377 \ \Omega$$

where $W_0 = |E|/|H|$ is the free space wave impedance.

- Wavelength and frequency are related:

$$\lambda = cT = \frac{c}{f} \to \lambda[\mathrm{m}] = \frac{300}{f[\mathrm{MHz}]}$$

- where c=3*10^8 [m/s] – speed of light, T=1/f – the period.

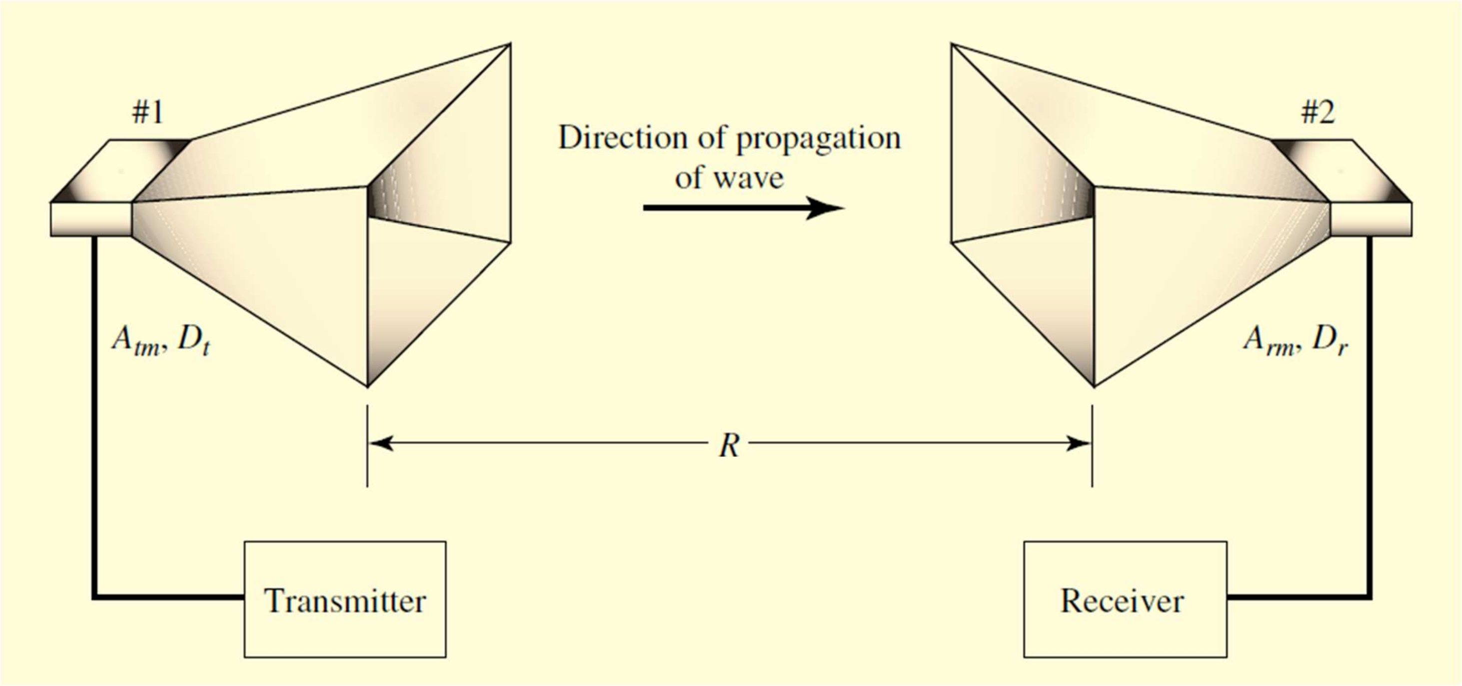
Another form of the Friis equation:

$$L_p = \left(\frac{4\pi R}{\lambda}\right)^2 = \left(\frac{4\pi R f}{c}\right)^2$$

Q.: For given P_t, G_t, and d, show that E at distance d can be expressed, in free space, as

$$E = \frac{\sqrt{30 P_t G_t}}{d}$$

Antenna = transition region between guided waves and free space waves (horn antennas are shown here)



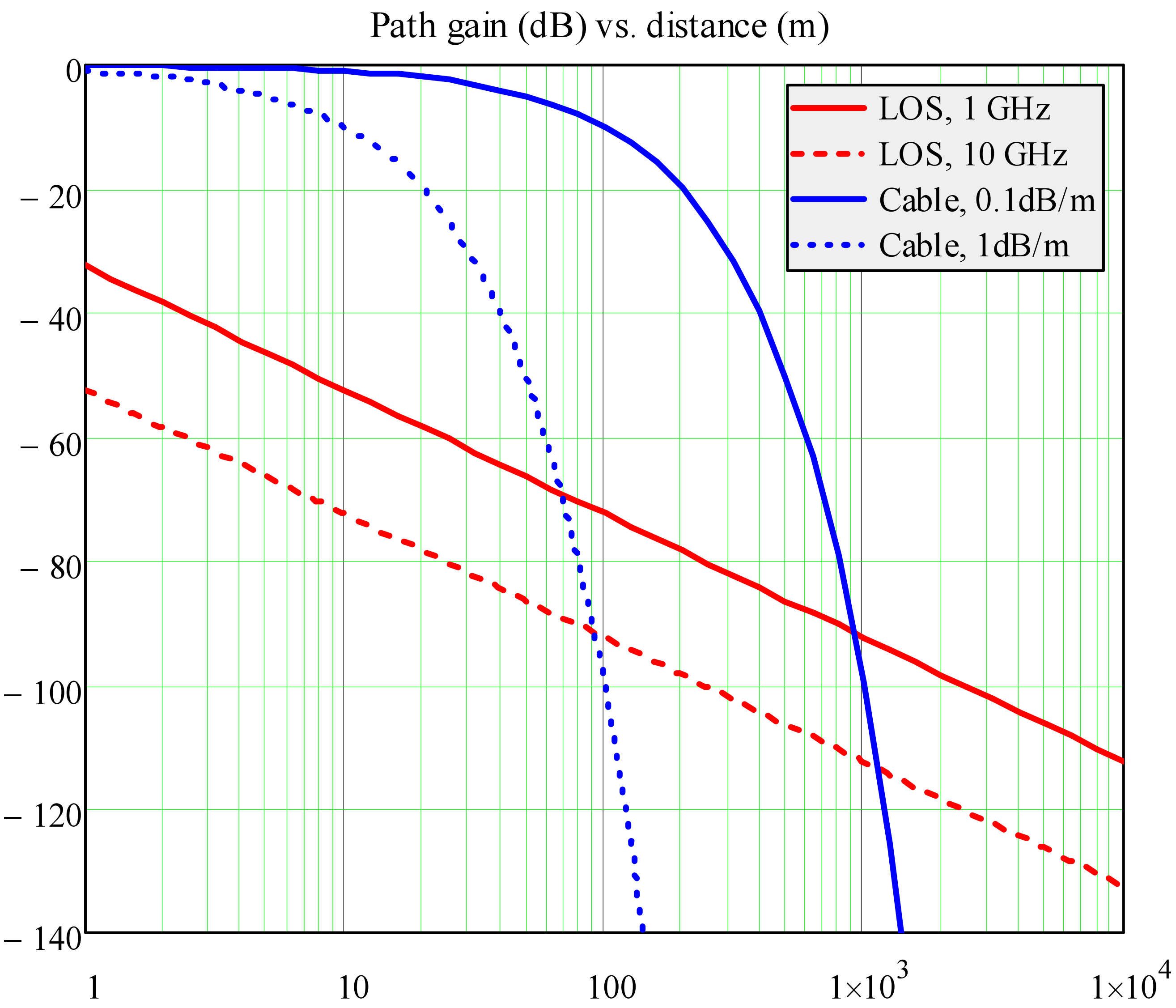
C.A. Balanis, Antenna Theory: Analysis and Design, John Wiley & Sons, 2005.

Full link budget computation:

$$P_r = P_t \frac{G_t G_r}{L_p}, \quad L_p = \left(\frac{4\pi R}{\lambda}\right)^2, \quad R \ge \frac{2D^2}{\lambda}$$

$$G = \frac{4\pi}{\lambda^2} S_e \ , \quad S_e = \eta_e ab, \quad \eta_e \approx 1 \ \ (0.5 \ldots 1)$$

Path Loss: Wireless (LOS) vs. Cable

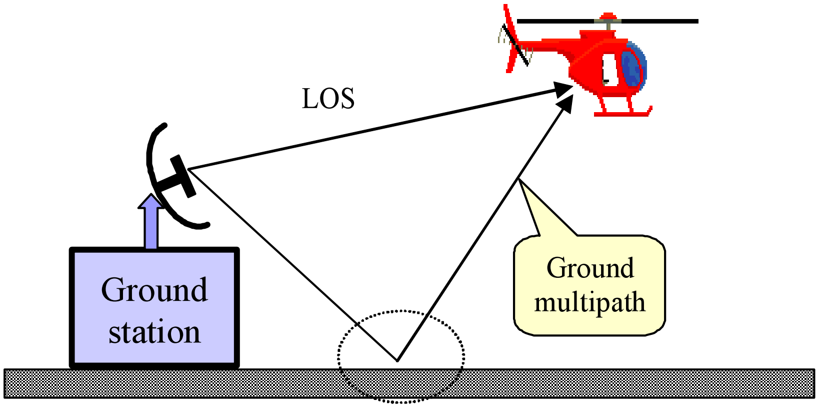


Three Basic Propagation Mechanisms

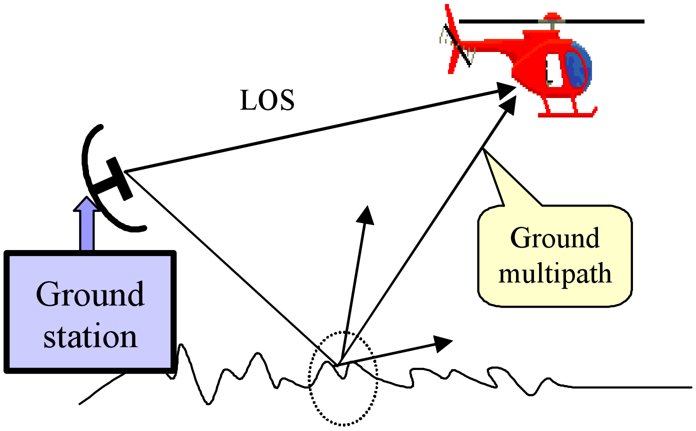
- **Reflection**: EM wave impinges on an object of very large size (much greater than λ), like surface of Earth; large buildings, mountains, etc.
- **Diffraction**: the Tx-Rx path is obstructed by an object or large size (>> λ), maybe with sharp irregularities (i.e. edges). Secondary waves are generated (i.e. bending of waves around the obstacle).
- **Scattering**: the medium includes objects or irregularities of small size (<<λ). Examples: rough surface, rain drops, foliage, atmospheric irregularities (>10GHz).

- Diffraction: direction of propagation differs from ray optics predictions.
- All three mechanisms are important in general. Individual contributions vary on case by case basis.
- In order to model accurately the PC, one must be able to model all 3 mechanisms.

Propagation Mechanisms: Illustrations



Reflection



Scattering (diffuse reflection)

Scattering & Reflection: specular and diffuse

For more information, see

S. Loyka, A. Kouki, Using Two Ray Multipath Model for Microwave Link Budget Analysis, IEEE AP Magazine, v. 43, N. 5, pp. 31-36, Oct. 2001.

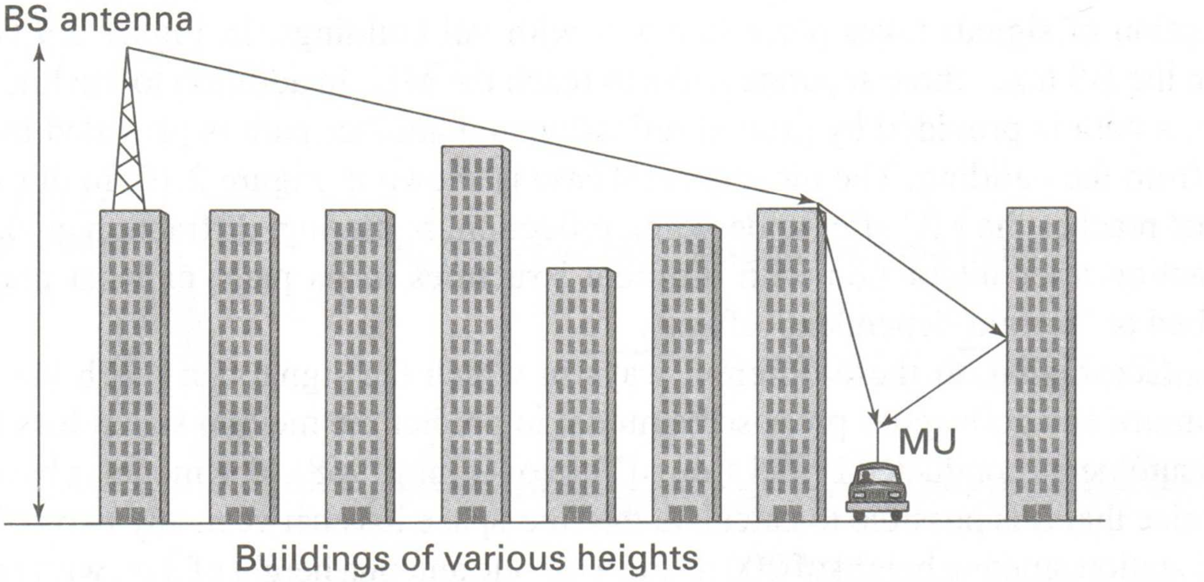


FIGURE 2.8 The signal reaches the receiver through reflection and diffraction.

P.M. Shankar, Introduction to Wireless Systems, Wiley, 2002.

Propagation Loss Components

- In terms of signal variation in space (i.e. distance) and time, there are 3 main factors as well, in propagation path loss:
- Attenuation: average signal power vs. distance ignoring small and large-scale variations; keep only very large-scale effects, i.e. spreading of power with distance as in free space.
- Large-scale fading (shadowing): over ~ 100m, ignoring variations over a few wavelengths and smaller.
- Small-scale fading (multipath): over fraction of λ to few λ.

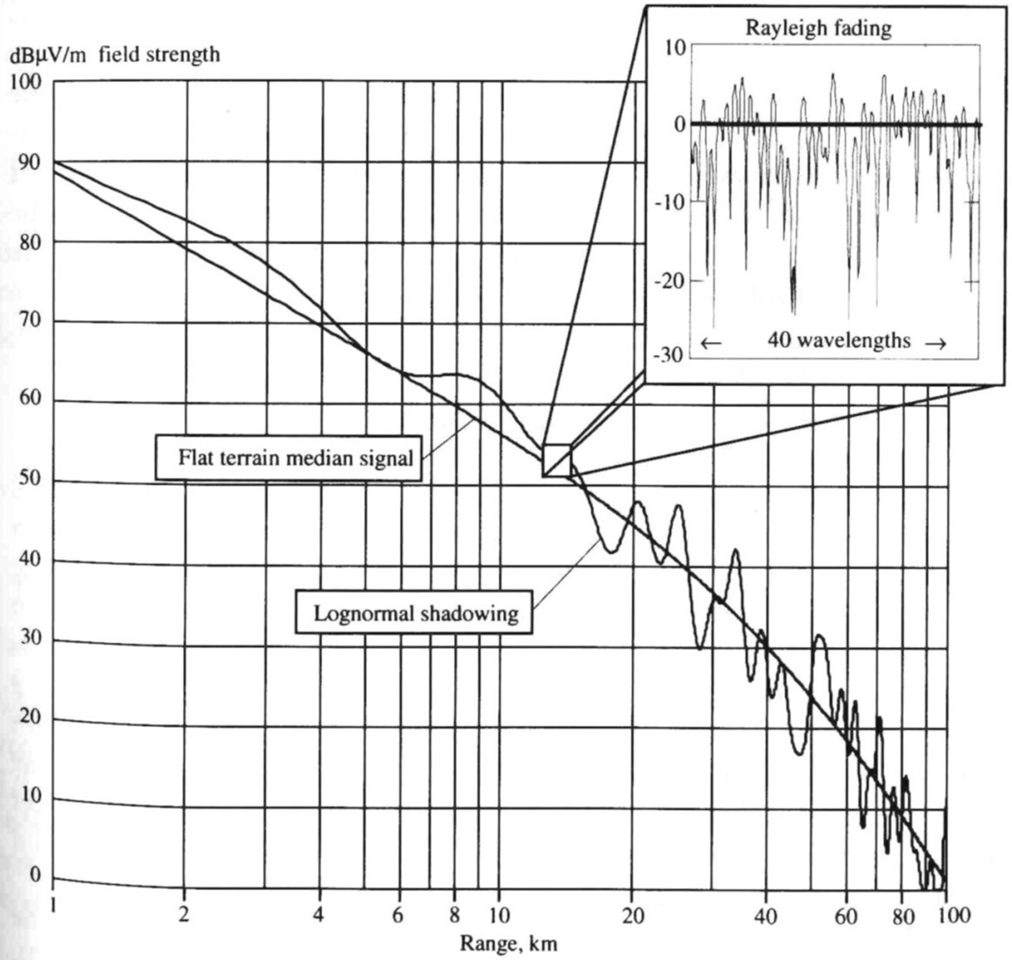


Figure 8.2 Signal behavior in a suburban region showing shadowing and multipath fading. (After: [1].)

Siwiak, Radiowave Propagation and Antennas for Personal Communications, Artech House. 1998

Average path loss (attenuation) → similar to free space, but path loss exponent may be different.

The average received power P_{ra} is

$$P_r = \frac{P_t G_t G_r}{L_p} = P_t G_t G_r \frac{a_\nu}{R^\nu} \sim \frac{1}{R^\nu}; \ \nu = 2...8 \qquad (2.17)$$

- In free space, $\nu = 2$; in general, it depends on environment; in practice, it is obtained from measurements ($\nu = 1.5...8$).
- Smart antennas are useful in combating all three factors, but they are most efficient for #3 (small-scale fading).

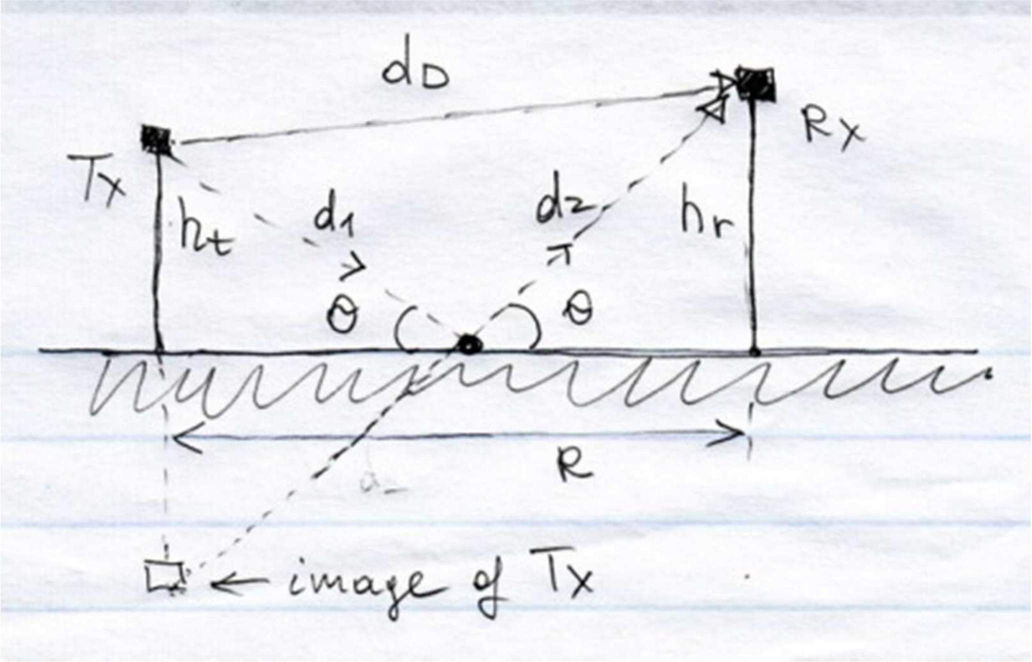
While the average path loss is modeled deterministically, large and small scale fading are modeled as random variables (processes).

The received power under large and small scale fading is:

$$P_r = g_l g_s P_{ra} \qquad (2.17a)$$

where g_l and g_s are the large and small scale fading factors (typically modeled as log-normal and Rayleigh random variables).

Two-Ray (ground reflection) Model



- Total received field E_t is

$$E_t = E_D + E_R e^{j\Delta\varphi}$$

$$E_D = \frac{A}{d_D} = E_{FS}; \qquad E_R = \frac{A\cdot\Gamma}{d_1+d_2} = E_D\Gamma\frac{d_D}{d_1+d_2} \qquad (2.18)$$

$$|E_t| = \frac{A}{d_D}\left|1+\Gamma\frac{d_D}{d_1+d_2}e^{j\Delta\varphi}\right|$$

- E_D - direct line-of-sight (LOS) or free-space (FS) component,
- E_R - reflected component,
- $\Delta\varphi$ - phase difference (R – LOS)
- Γ - reflection coefficient; for the ideal dielectric plane,

$$\Gamma = \frac{\sin\theta - z}{\sin\theta + z},\ z = \varepsilon^{-1}\sqrt{\varepsilon - \cos^2\theta}\ \text{(VP)},\ \ z = \sqrt{\varepsilon - \cos^2\theta}\ \text{(HP)}$$

ε is relative dielectric constant (the textbook formulas/statements for VP are incorrect).

The phase difference is

$$\vartriangle\varphi = \frac{2\pi}{\lambda}(d_1 + d_2 - d_D) = \frac{2\pi}{\lambda}\vartriangle d \qquad (2.19)$$

- In many cases,

$$d_1 + d_2, d_D \gg \lambda;\ d_1, d_2, d_D \gg h_t, h_r \text{ and } \frac{d_D}{d_1 + d_2} \approx 1 \qquad (2.20)$$

- Reflection coefficient:
- For small θ $(\theta \ll 1) \rightarrow \Gamma \approx -1$ (for both polarizations)
- Under these approximations, the total received field becomes:

$$|E_t| \approx \frac{A}{d_D}\left|1 - e^{j\Delta\varphi}\right| \approx \frac{4\pi h_t h_r A}{\lambda R^2},\quad R > \frac{20 h_t h_r}{\lambda} \qquad (2.21)$$

- The total received power P_r

$$P_r = P_D\,|1 + \Gamma e^{j\Delta\varphi}|^2 \sim |E_t|^2 \sim \frac{1}{R^4}$$

- The path loss is

$$L_p = \frac{P_t}{P_r} = \frac{L_{FS}}{|1 + \Gamma e^{j\Delta\varphi}|^2} = \frac{R^4}{h_t^2 h_r^2} \qquad (2.22)$$

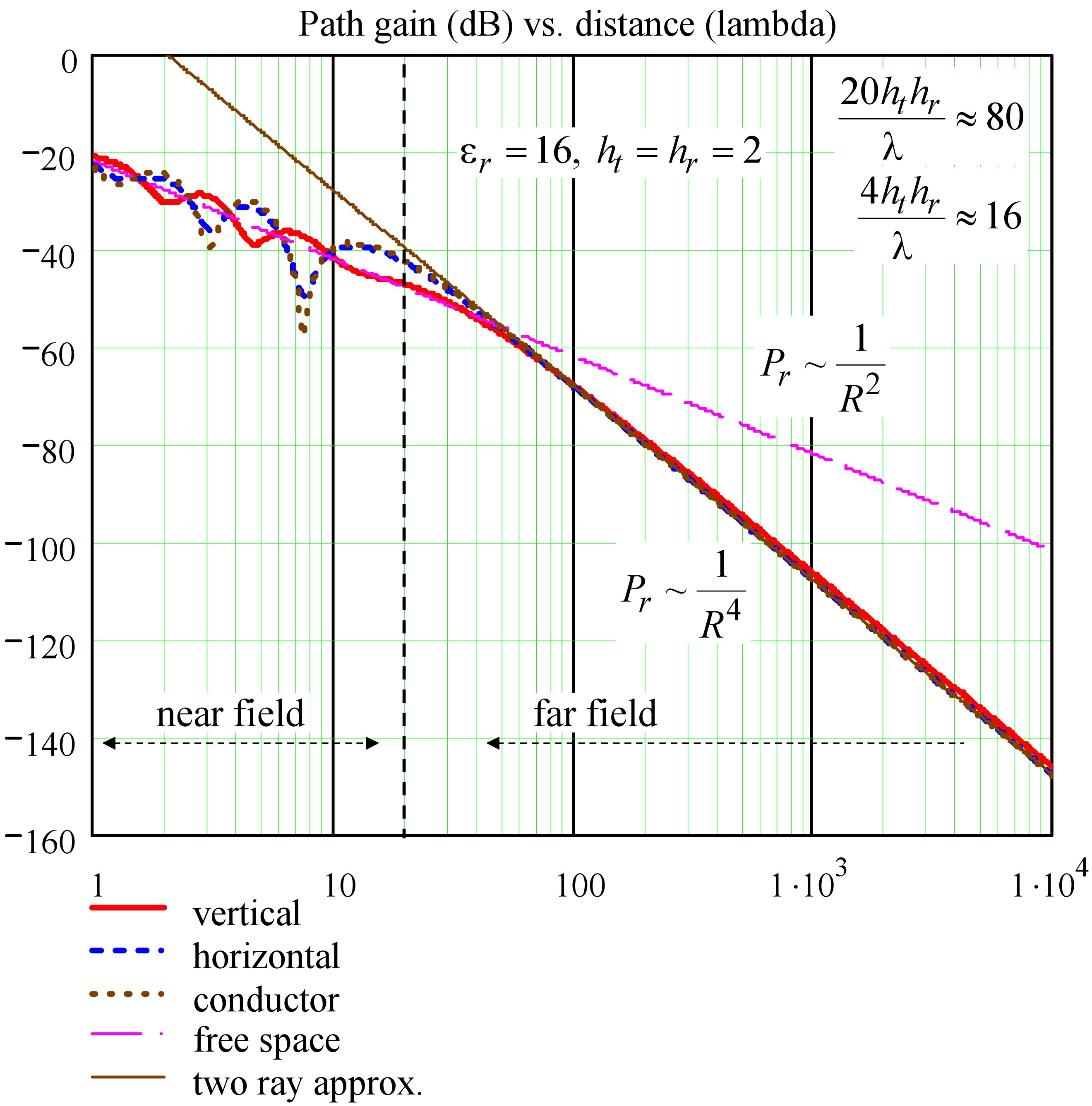
- Compare with **free space (FS)**:

$$P_{r,FS} = P_D \sim \frac{1}{R^2},\quad L_{FS} = \left(\frac{4\pi R}{\lambda}\right)^2$$

- Conclusion: multipath can significantly affect the path loss!
- **Composite model** in practice:

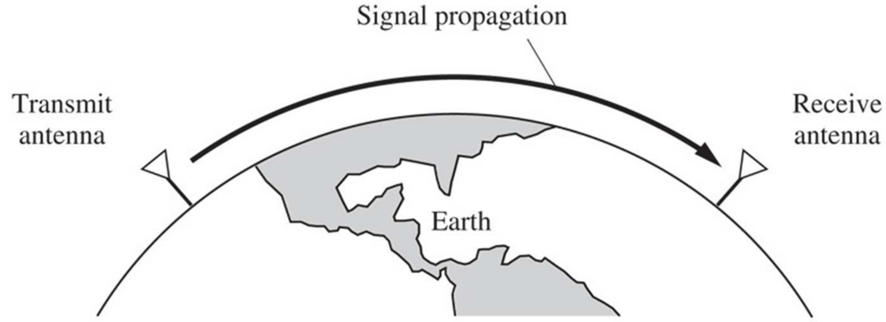
$$L = \max\{L_{2-ray}, L_{FS}, L_{\min}, G_t G_r\}$$

Example of Two-Ray Path Loss

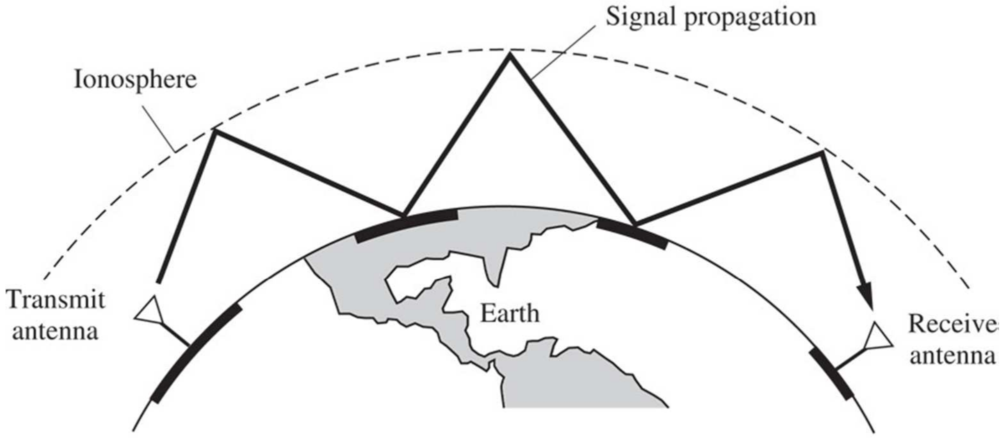


Q.: do it yourself using Matlab.

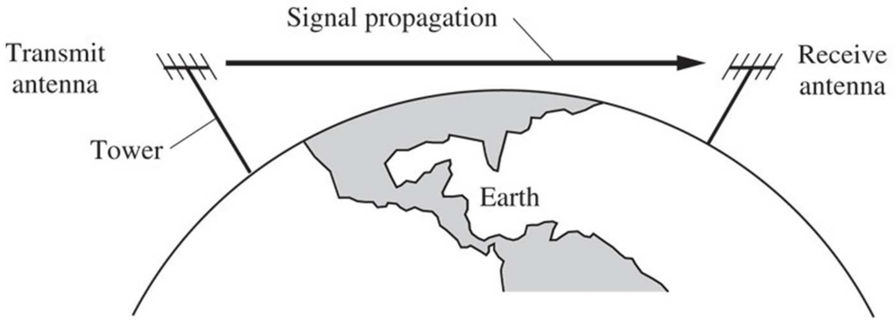
Propagation of Electromagnetic (Radio) Waves



(a) Ground-Wave Propagation (Below 2 MHz)



(b) Sky-Wave Propagation (2 to 30 MHz)



(c) Line-of-Sight (LOS) Propagation (Above 30 MHz)

Digital and Analog Communication Systems, Eighth Edition by Leon W. Couch II

LOS and Radio Horizon

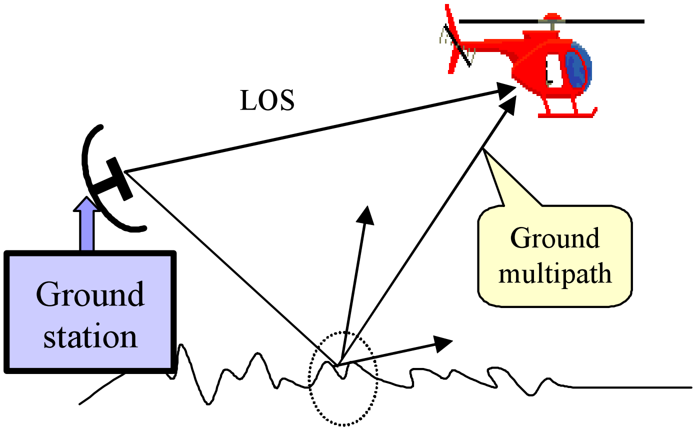
Two-ray model is valid as long as there is an LOS Tx-Rx path,

$$R < d_{LOS} \approx 4\left(\sqrt{h_t} + \sqrt{h_r}\right) \text{ [km]}$$

where h_t, h_r are in meters, and d_{LOS} is the maximum LOS distance in km. This is so-called radio-horizon.

When $R > d_{LOS}$, the LOS as well as reflected paths are obstructed by Earth and path loss increases significantly due to extra diffraction loss. Two-ray model cannot be used.

Rough Surface: Scattering



Scattering (diffuse reflection)

- Rough surface -> Rayleigh criterion:

$$\Delta h \geq \frac{\lambda}{8\sin\theta} \qquad (2.23)$$

where Δh is r.m.s. variation in surface height.

- Flat surface reflection coefficient is multiplied by a scattering loss factor:

$$\rho_s = \exp\left[-8\left(\frac{\sigma_h}{\Delta h_0}\right)^2\right] I_0\left[8\left(\frac{\sigma_h}{\Delta h_0}\right)^2\right] \leq 1 \qquad (2.24)$$

where $\Delta h_0 = \lambda/(\pi\sin\theta)$, σ_h is standard deviation of the surface height, I_0 is the modified Bessel function of 1st kind and zero order.

Modified reflection coefficient:

$$\Gamma_{\text{mod}} = \Gamma \cdot \rho_s \rightarrow |\Gamma_{\text{mod}}| \leq |\Gamma| \qquad (2.25)$$

Summary

- Wireless propagation channel
- Various types of channel models
- Link budget analysis; effect of interference
- Three propagation mechanisms
- Path loss exponent
- Free-space propagation
- Ground reflection and two-ray model
- Rough surface and scattering

Reading:

- Rappaport, Ch. 4.

References:

- S. Salous, Radio Propagation Measurement and Channel Modelling, Wiley, 2013. (available online)
- J.S. Seybold, Introduction to RF propagation, Wiley, 2005.
- Other books (see the reference list).

Note: Do <u>not</u> forget to do end-of-chapter problems. Remember the learning efficiency pyramid!