Antennas and Radio Wave Propagation

EP2950

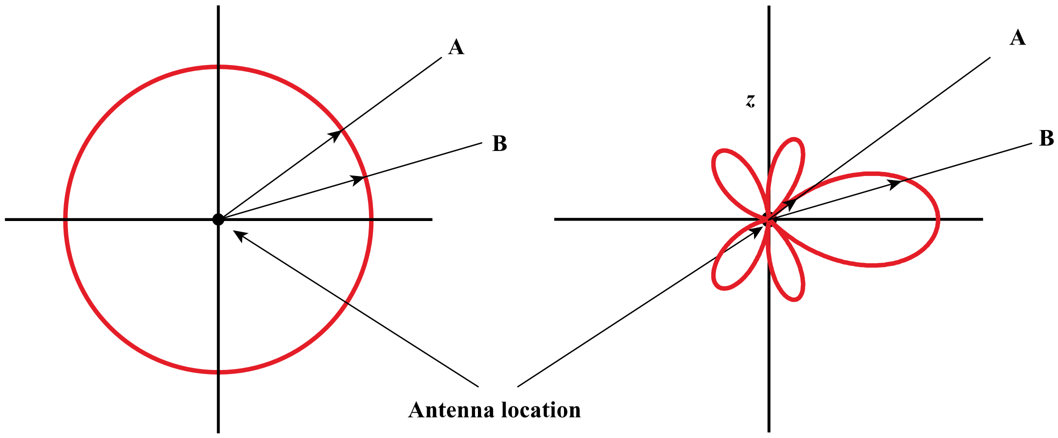
KTH Technology
and Health

Outline

- Antennas and radiation
- Wireless transmission impairment
- Multipath fading

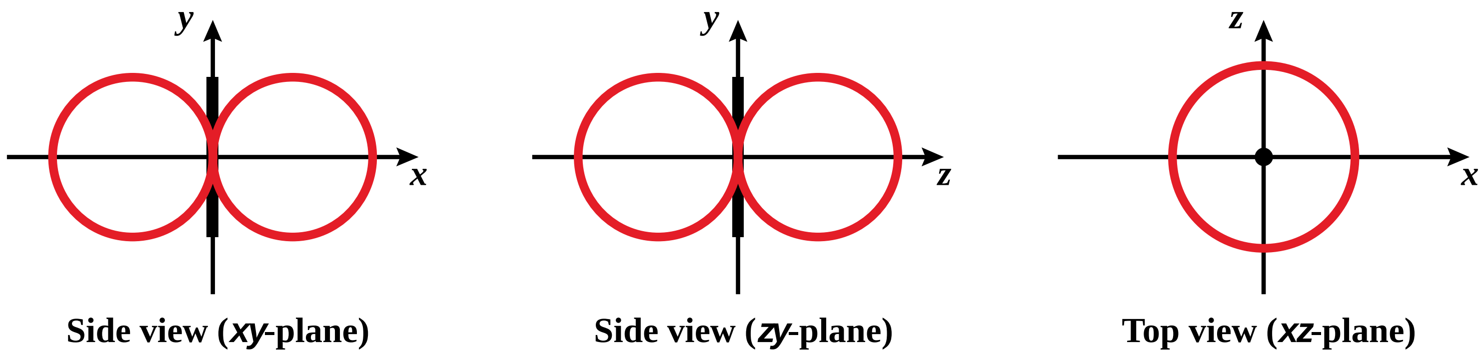
Antennas and radiation patterns

- Transmits and receives electromagnetic energy
- Idealized radiation patterns (isotropic)
- Omnidirectional and directional
- Main lobe, side lobes and nulls
- Beam width (half-power) – a measure of directivity

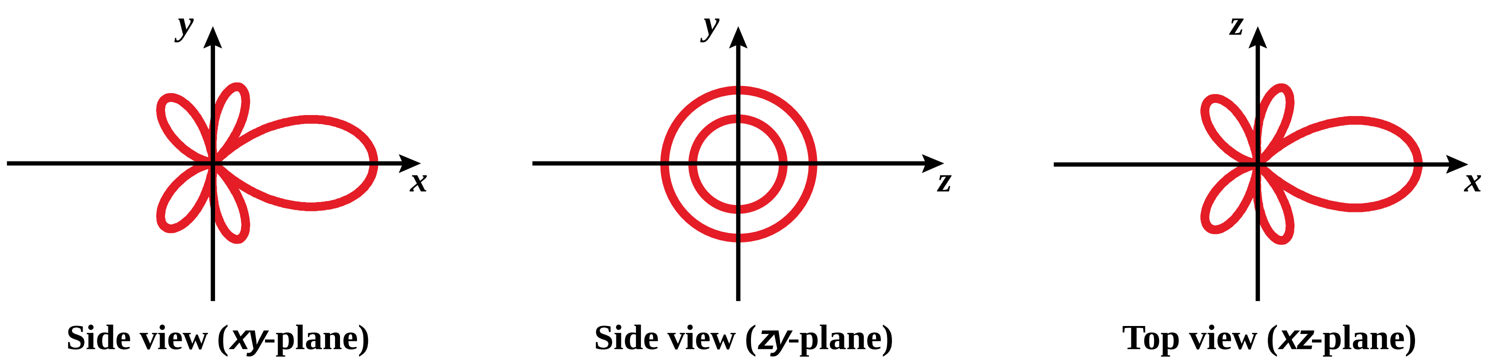


(a) Omnidirectional (b) Directional

Radiation patterns



(a) Simple dipole

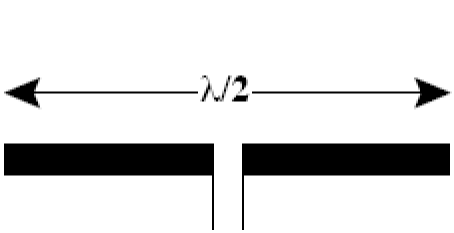


(b) Directed antenna

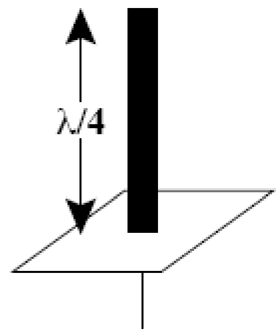
Types of antennas

- Isotropic antenna (idealized)
  - ✓ Radiates power equally in all directions
- Dipole
  - ✓ Half-wave dipole antenna (or Hertz antenna)
  - ✓ Quarter-wave vertical antenna (or Marconi antenna)
- Parabolic reflective antenna

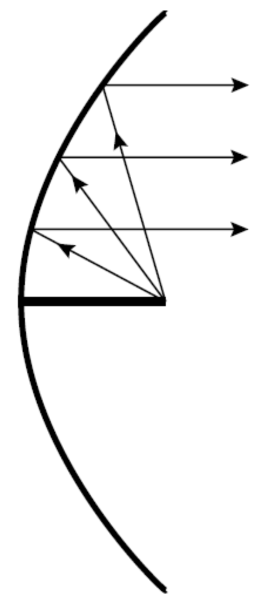
Antenna types



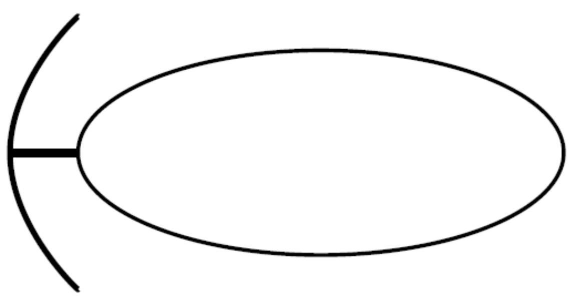
(a) Half-wave dipole



(b) Quarter-wave antenna

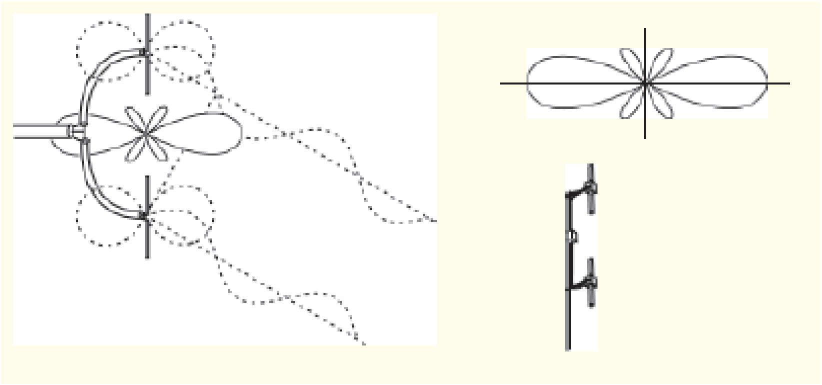


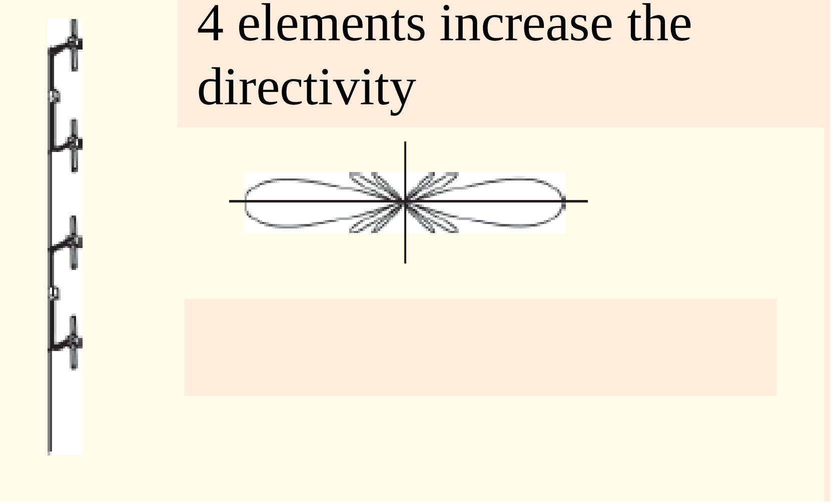
(b) Cross-section of parabolic antenna showing reflective property



(c) Cross-section of parabolic antenna showing radiation pattern

- Combining several antenna elements





4 elements increase the directivity

Antenna gain

- Antenna gain
  - ✓ Measure of directionality
  - ✓ Power output, in a particular direction, compared to that produced in any direction by a perfect omnidirectional antenna (isotropic antenna)
- Effective area - A_e
  - ✓ Related to physical size and shape

- Antenna gain and effective area

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

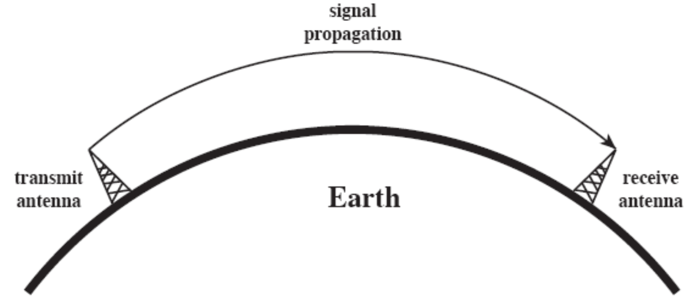
  - G = antenna gain
  - A_e = effective area
  - f = carrier frequency
  - c = speed of light ($\approx 3\times10^8$ m/s)
  - λ = carrier wavelength

- Antenna gain and directivity, $G=\eta\cdot D$

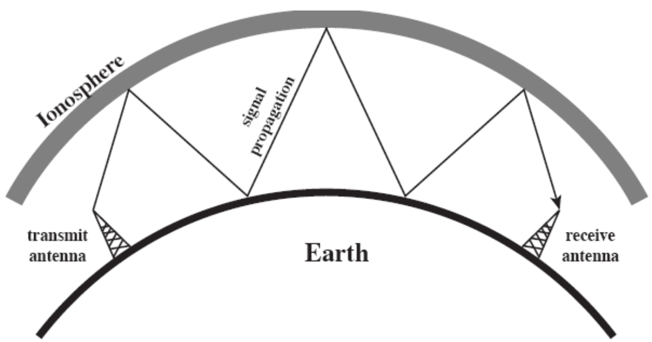
  - G = antenna gain
  - η = effeciency of the antenna
  - D = directivity
  - η is often close to 1.0

Propagation modes

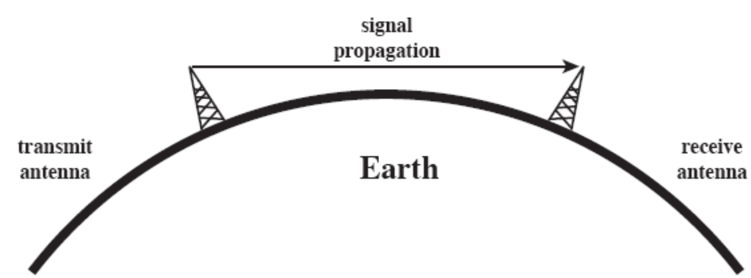
- Ground-wave propagation
- Sky-wave propagation
- Line-of-sight propagation



(a) Ground-wave propagation (below 2 MHz)



(b) Sky-wave propagation (2 to 30 MHz)



(c) Line-of-sight (LOS) propagation (above 30 MHz)

Table 5.3 Frequency Bands

Band	Frequency Range	Free-Space Wavelength Range	Propagation Characteristics	Typical Use
ELF (extremely low frequency)	30 to 300 Hz	10,000 to 1,000 km	GW	Power line frequencies; used by some home control systems.
VF (voice frequency)	300 to 3000 Hz	1,000 to 100 km	GW	Used by the telephone system for analog subscriber lines.
VLF (very low frequency)	3 to 30 kHz	100 to 10 km	GW; low attenuation day and night; high atmospheric noise level	Long-range navigation; submarine communication
LF (low frequency)	30 to 300 kHz	10 to 1 km	GW; slightly less reliable than VLF; absorption in daytime	Long-range navigation; marine communication radio beacons
MF (medium frequency)	300 to 3000 kHz	1,000 to 100 m	GW and night SW; attenuation low at night, high in day; atmospheric noise	Maritime radio; direction finding; AM broadcasting.
HF (high frequency)	3 to 30 MHz	100 to 10 m	SW; quality varies with time of day, season, and frequency.	Amateur radio; international broadcasting, military communication; long-distance aircraft and ship communication
VHF (very high frequency)	30 to 300 MHz	10 to 1 m	LOS; scattering because of temperature inversion; cosmic noise	VHF television; FM broadcast and two-way radio, AM aircraft communication; aircraft navigational aids
UHF (ultra high frequency)	300 to 3000 MHz	100 to 10 cm	LOS; cosmic noise	UHF television; cellular telephone; radar; microwave links; personal communications systems
SHF (super high frequency)	3 to 30 GHz	10 to 1 cm	LOS; rainfall attenuation above 10 GHz; atmospheric attenuation due to oxygen and water vapor	Satellite communication; radar; terrestrial microwave links; wireless local loop
EHF (extremely high frequency)	30 to 300 GHz	10 to 1 mm	LOS; atmospheric attenuation due to oxygen and water vapor	Experimental; wireless local loop
Infrared	300 GHz to 400 THz	1 mm to 770 nm	LOS	Infrared LANs; consumer electronic applications
Visible light	400 THz to 900 THz	770 nm to 330 nm	LOS	Optical communication

- Radio line-of-sight (LOS) equations
  - ✓ Maximum distance between two antennas
  - ✓ K due to refraction

    $d = 3.57(\sqrt{Kh_1} + \sqrt{Kh_2})$

  - ✓ K=4/3 (rule of thumb)

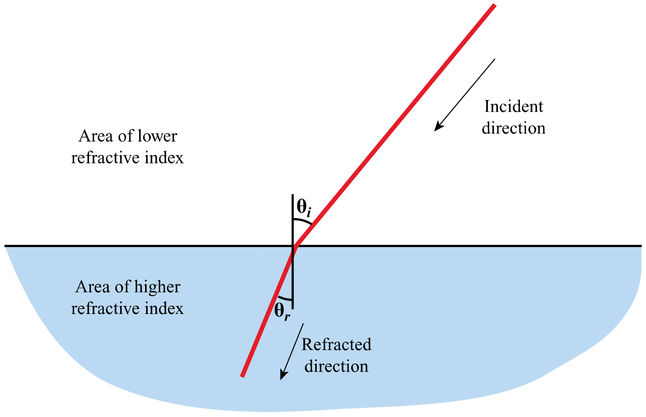
    $d = 4.1(\sqrt{h_1} + \sqrt{h_2})$

d = distance (km)
h_1 = height of antenna one (m)
h_2 = height of antenna two (m)

- Five basic propagation mechanisms
  - ✓ Free-space propagation
  - ✓ Transmission through a medium

    Refractions
  - ✓ Reflections
  - ✓ Diffractions

    “Bending” round corners
  - ✓ Scattering



Wireless transmission impairment

- Free space loss
- Noise
- Atmospheric absorption
- Multipath
- Refraction

- Free space loss
  - ✓ Ideal isotropic antenna

$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2}$$

P_t = signal power at transmitting antenna
P_r = signal power at receiving antenna
λ = carrier wavelength
d = propagation distance between antennas
c = speed of light ($\approx 3\times10\ 8$ m/s)
where d and λ are in the same units (e.g., meters)

- Expressed in dB

$$L_{dB} = 10\lg\frac{P_t}{P_r} = 20\lg\left(\frac{4\pi d}{\lambda}\right)$$

$$= -20\lg(\lambda) + 20\lg(d) + 21.98\ \mathrm{dB}$$

$$= 20\lg\left(\frac{4\pi f d}{c}\right) = 20\lg(f) + 20\lg(d) - 147.56\ \mathrm{dB}$$

- If expressed as path loss exponent

$$20\lg(f) + 10n\lg(d) - 147.56\ \mathrm{dB}$$

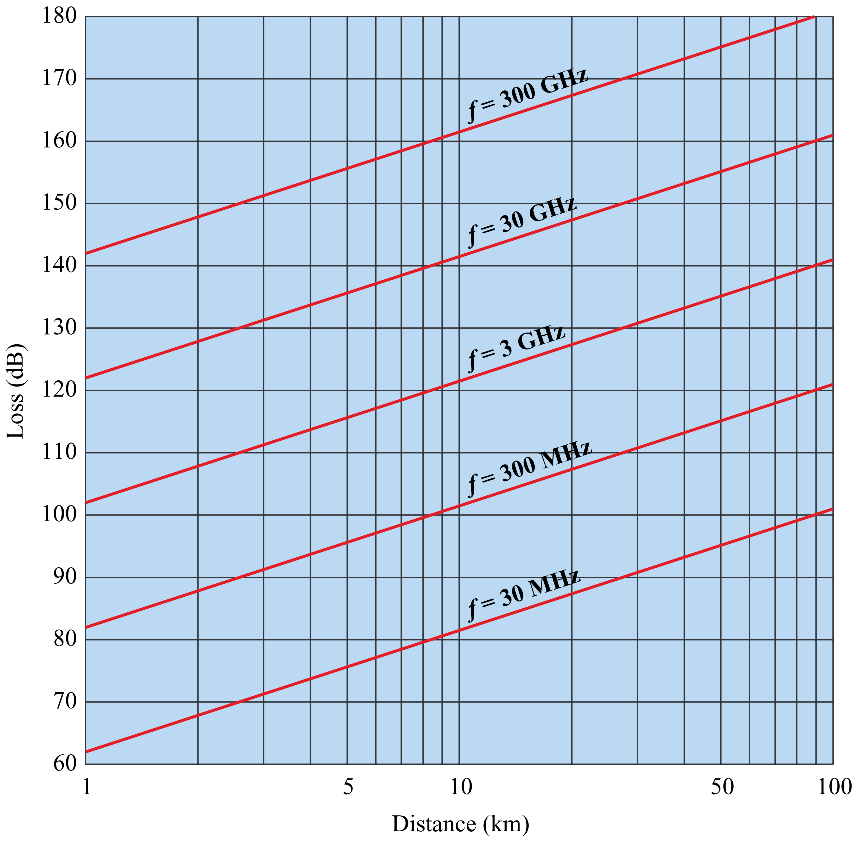
- Path loss exponents

Table 6.5 Path Loss Exponents for Different Environments [RAPP02]

Environment	Path Loss Exponent, *n*
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

- Example: f=300 MHz, d=1 km

$$L_{dB} = -147.56 + 20 \cdot \lg(1000) + 20 \cdot \lg(300 \cdot 10^6) =$$
$$-147.56 + 60 + 169.54 = 82\ dB$$



- Taking antenna gain into account

$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{G_r G_t \lambda^2} = \frac{(\lambda d)^2}{A_r A_t} = \frac{(cd)^2}{f^2 A_r A_t}$$

G_t = gain of transmitting antenna $G=(4\pi A_e)/\lambda^2$
G_r = gain of receiving antenna
A_t = effective area of transmitting antenna
A_r = effective area of receiving antenna

$$L_{dB} = 20\lg(\lambda) + 20\lg(d) - 10\lg(A_t A_r)$$

$$= -20\lg(f) + 20\lg(d) - 10\lg(A_t A_r) + 169.54\text{dB}$$

Thermal noise

- Amount of thermal noise to be found in a bandwidth of 1Hz in any device or conductor is

$$N_0 = \mathrm{k}T \text{ (W/Hz)}$$

N_0 = noise power density in watts per 1 Hz of bandwidth
k = Boltzmann's constant = 1.3803×10^{-23} J/K
T = temperature, in Kelvin (absolute temperature)

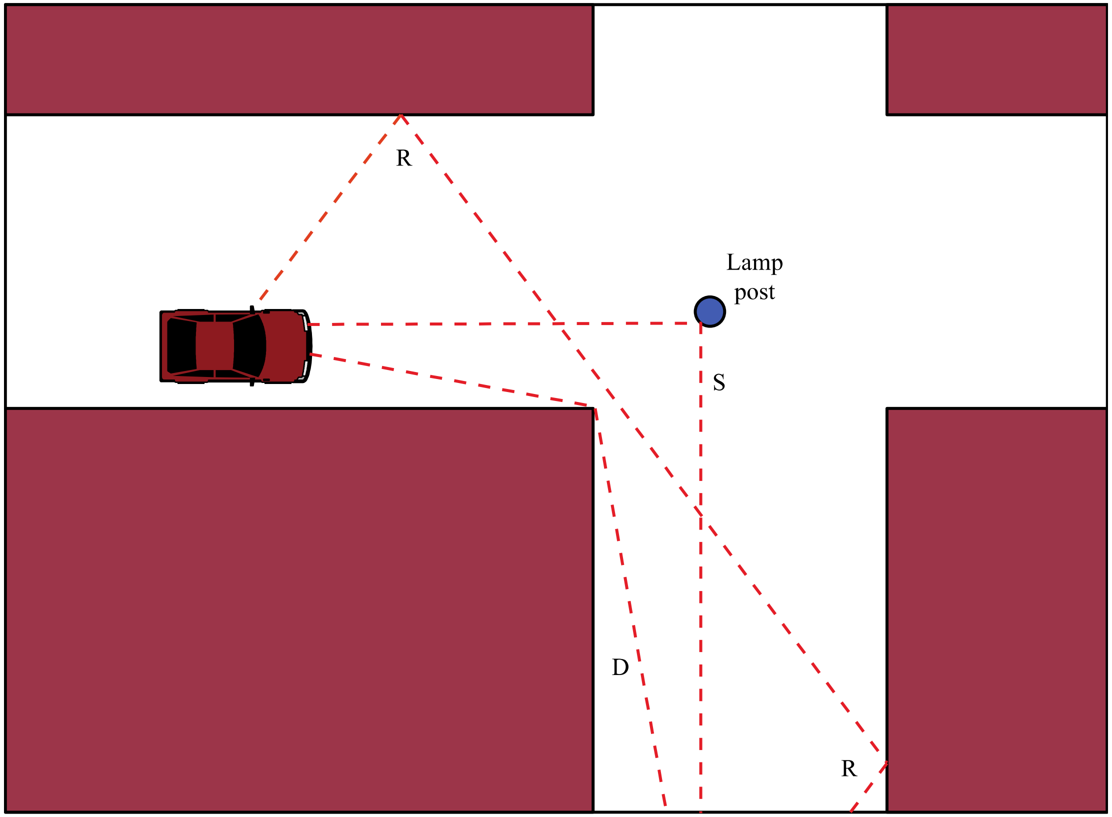
$$N = \mathrm{k}TB$$

$$N = 10 \lg \mathrm{k} + 10 \lg T + 10 \lg B$$

$$= -228.6 \,\mathrm{dBW} + 10 \lg T + 10 \lg B$$

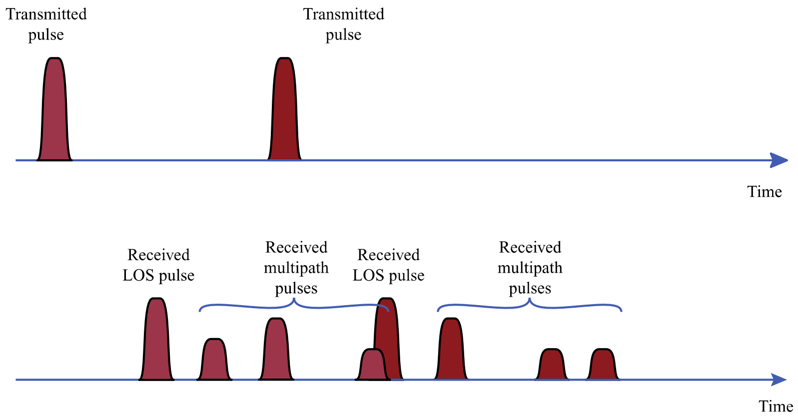
Multipath propagation and fading

- Reflection (R), scattering (S) and diffraction (D)



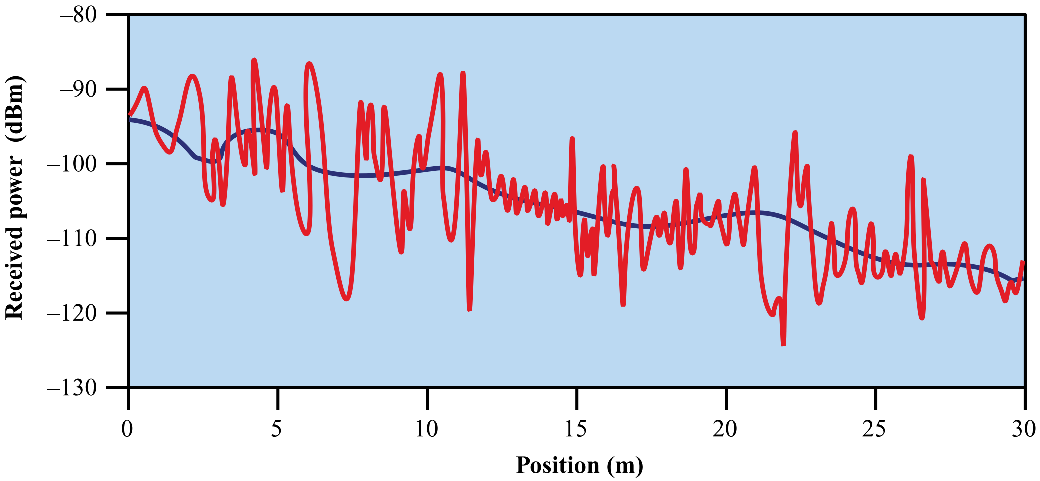
Effect of multipath propagation

- Multiple copies of a signal may arrive at different phases
  - ✓ If phases add destructively, the signal level relative to noise declines, making detection more difficult
- Inter-symbol interference - ISI
  - ✓ One or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit

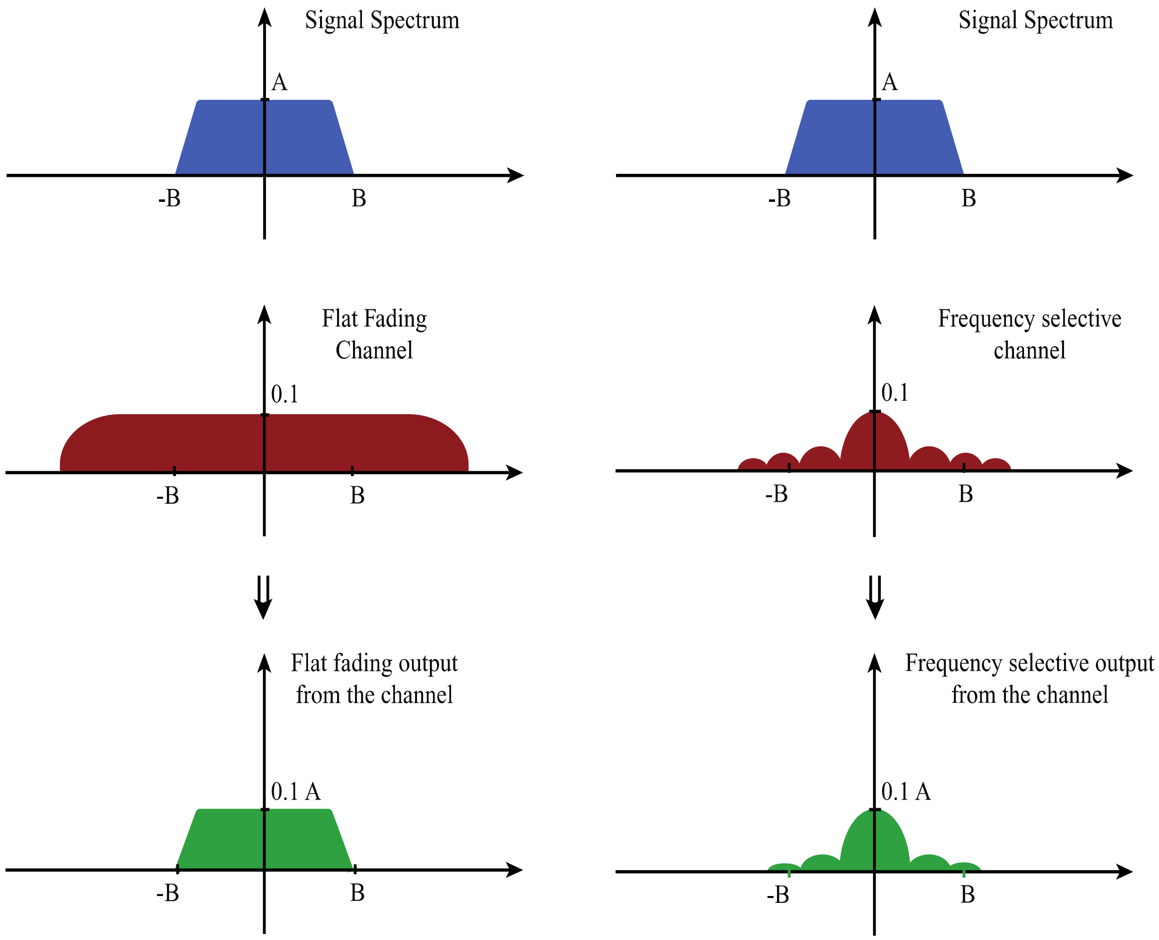


Types of fading

- Fast fading
- Slow fading
- Flat fading
- Selective fading
- Rayleigh fading
- Rician fading



Flat and frequency selective fading



- Fast or short-term fading
  - Rapid variation in signal strength, e.g. MS moves in urban area
  - Short reflections – delay < 20 % of symbol time $\approx$ 3.7 μs (220 m)
  - Rayleigh/Rice fading
- Slow or long-term fading
  - Shadowing e.g. large buildings, mountains etc.
  - Time dispersion (delay spread), inter-symbol interference (ISI)
- Okumura-Hata path loss model
  - L_{dB}(urban), L_{dB}(suburban) and L_{dB}(open)
  - Stallings p. 175-176

- Coherence bandwidth and time
  - ✓ B_C is the range of frequencies where the channel is “flat”
  - ✓ Coherence time $T_C = 1/B_C$, the time when the channel is stable
- Signal bandwidth and time
  - ✓ T_B bit time, $T_B=1/r_B$ where r_B is the bit rate.
  - ✓ Symbol time $T_S=T_B$ (if one bit per symbol)
  - ✓ B_S is the signal bandwidth ($B_S \approx r_B$)
- If $T_C >> T_S$, coherence time >> symbol time
  - ✓ Slow fading, otherwise fast fading
- If $B_C >> B_S$, channel bandwidth >> signal bandwidth
  - ✓ Flat fading, otherwise frequency-selective
- Delay disperse (T_D) and symbol time (T_S)
- Inter-symbol interference (ISI)
  - ✓ T_D larger than T_S

Example slow fading

- Doppler spread
  - Frequency fluctuations caused by movement
  - Coherence time T_c characterizes Doppler shift
    - How long a channel remains the same
  - Coherence time $T_c >> T_b$ bit time $\rightarrow$ *slow fading*
    - The channel does not change during the bit time
  - Otherwise *fast fading*
- Example 6.11
  - T_c = 70 ms, bit rate r_b = 100 kbps
  - Bit time $T_b = 1/100 \times 10^3$ = 10 μs
  - Is $T_c >> T_b$? 70 ms >> 100 μs
  - True, slow fading

Example frequency selective fading

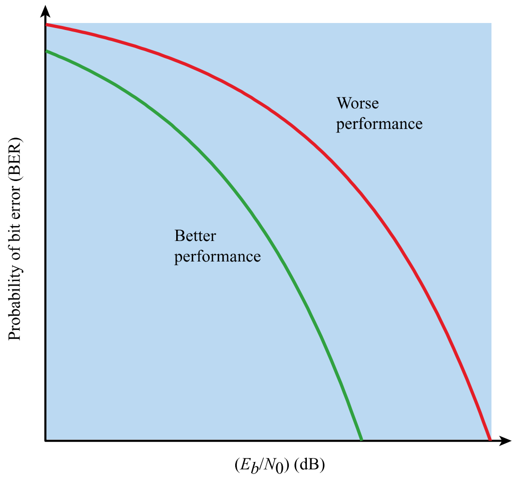
- Multipath fading
  - Multiple signals arrive at the receiver
  - Coherence bandwidth B_c characterizes multipath
    - Bandwidth over which the channel response remains relatively constant
    - Related to delay spread, the spread in time of the arrivals of multipath signals
  - Signal bandwidth B_s is proportional to the bit rate
  - If $B_c >> B_s$, then *flat fading*
    - The signal bandwidth fits well within the channel bandwidth
  - Otherwise, *frequency selective fading*
- Example 6.11
  - B_c = 150 kHz, bit rate r_b = 100 kbps
  - Assume signal bandwidth $B_s \approx r_b$, B_s = 100 kHz
  - Is $B_c >> B_s$? 150 kHz >> 100 kHz?
  - False, so frequency selective fading

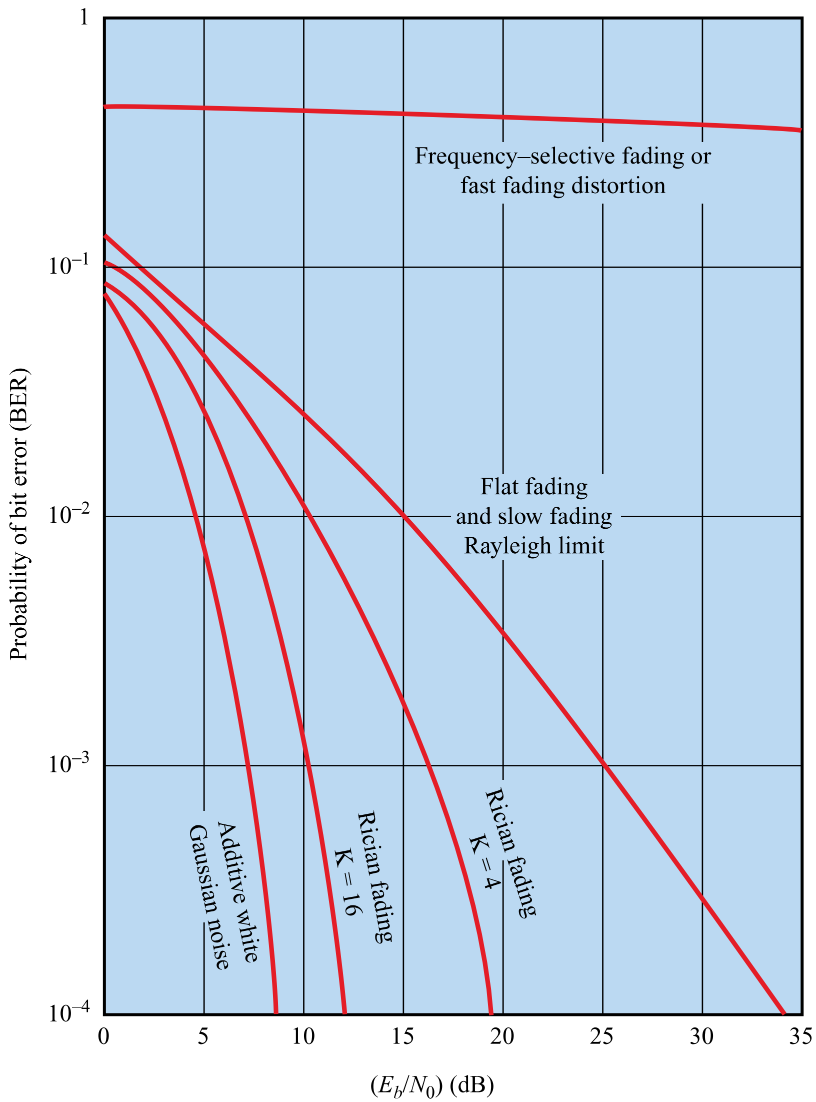
The expression E_b/N_0

- Ratio of signal energy per bit to noise power density per Hertz

$$\frac{E_b}{N_0} = \frac{S/R}{N_0} = \frac{S}{\mathrm{k}TR} \quad \text{if R=B} \quad \frac{E_b}{N_0} = \frac{S}{\mathrm{k}TB} = \frac{S}{N}$$

- The bit error rate for digital data is a function of E_b/N_0
  - ✓ Given a value for E_b/N_0 to achieve a desired error rate, parameters of this formula can be selected
  - ✓ As bit rate R increases, transmitted signal power must increase to maintain required E_b/N_0





$$K = \frac{\text{Power in dominant path}}{\text{Power in the scattered paths}}$$

K=0 => Rayleigh fading
K> 0 =>Rician fading
K= infinite => AWGN

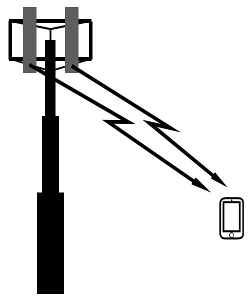
Channel correction mechanisms

- Forward error correction
- Adaptive equalization
- Adaptive modulation and coding
- Diversity techniques and MIMO
- OFDM
- Spread spectrum
- Bandwidth expansion

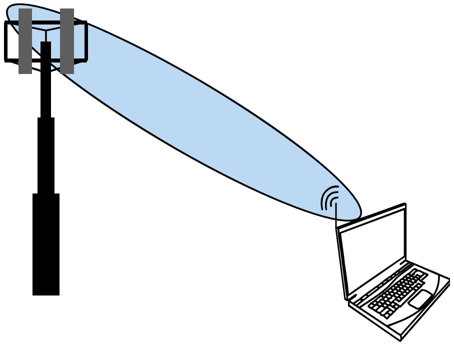
Multiple input multiple output (MIMO)

- Use antenna arrays for
  - ✓ Same stream - several antennas
  - ✓ Multiple streams – increase capacity
  - ✓ Beamforming – directional antennas
  - ✓ Multi-user MIMO – directional beams to multiple simultaneous users
- Modern systems
  - ✓ 4×4 (4 transmitter and 4 receiver antennas)
  - ✓ 8×8
  - ✓ Future: massive MIMO with many more antennas

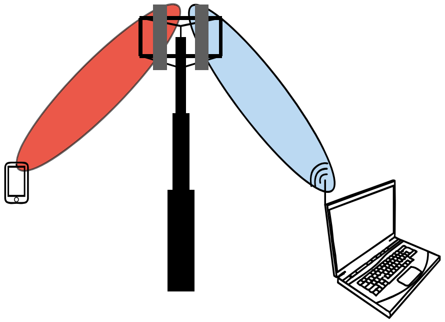
Four cases of MIMO



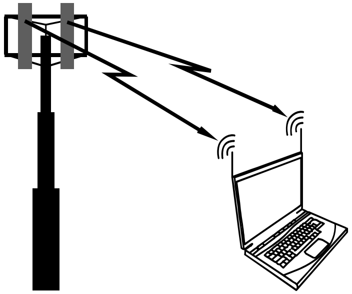
Diversity for improved
system performance



Beam-forming for improved coverage
(less cells to cover a given area)



Spatial division multiple access
("MU-MIMO") for improved capacity
(more user per cell)



Multi layer transmission
("SU-MIMO") for higher data rates
in a given bandwidth

Link budget calculations

1.	Transmitter power, P_t ………………………………	+	………..	[dBW]
2.	Attenuation in cable ………………………………..	-	………..	[dB]
3	Transmitting antenna Gain, G_t ……………………..	+	………..	[dBi]
4.	Free space loss, L_s …………………………..	-	………..	[dB]
5.	Atmospheric absorption ……………………….	-	………..	[dB]
6.	Effect of rain …………………..…………	-	………..	[dB]
7.	Effects of vegetation …………………………..	-	………..	[dB]
8.	Fading …………………………..………..	-	………..	[dB]
9.	Receiving antenna gain …..………………..	+	………..	[dBi]
10.	Attenuation in cable ……………………	-	………..	[dB]
Power to receiver:	………………………………..	=	………...	[dBW]

Decibel (dB)

- See Appendix 2A
- $G_{dB} = 10 \cdot lg(P_{out} / P_{in})$ – a dimensionless ratio
  - 1B=10dB

$1000=10^3$	30 dB
$100=10^2$	20 dB
$10=10^1$	10 dB
$1=10^0$	0 dB
$0.1=10^{-1}$	-10 dB
$0.01=10^{-2}$	-20 dB
$0.001=10^{-3}$	-30 dB

2	$10lg2 \approx 3$	3 dB
4	$10lg4 \approx 6$	6 dB
8	$10lg8 \approx 9$	9 dB
1/2	$10lg1/2 \approx -3$	-3 dB
1/4	$10lg1/4 \approx -6$	-6 dB
1/8	$10lg1/8 \approx -9$	-9 dB

- Logarithms
  - $\lg(a \cdot b)=\lg(a)+\lg(b)$; $\lg(a/b)=\lg(a)-\lg(b)$
- $G_{dB}=10\times\lg(P_{ut}/P_{in})$
  - G positive → amplification
  - G negative → attenuation
- Reference levels
  - dBW means that 0 dBW=1 W
  - dBm means that 0 dBm=1 mW
  - 0 dBW=30 dBm
  - 0 dBm=-30 dBW
  - 100 mW=20 dBm=-10 dBW
  - 2 W≈3 dBW=33 dBm

- Exercise
  - Which amplification corresponds to 16 dB?
  - 16 dB=(10+3+3)dB means 10×2×2=40 times ($10^{1.6} \approx 40$)
  - "An electromagnetic wave is transmitted through an optical fibre that has attenuation 0.25 dB/km. Compute the distance from the starting point at which the power has decreased with 75 % of the original level."
  - Method 1: Power in: P_{in}. Power after L km: P_L.
    $P_L = \frac{1}{4} \times P_{in}$.
    $10 \times \lg(P_L / P_{in}) = -0.25L$
    $-0.25L = 10 \times \lg(\frac{1}{4}) \rightarrow L = 24$ km
  - Method 2:
    ¼ = −6 dB (attenuation 4 times).
    6 dB=0.25 dB×$L \rightarrow L$=24 km.