Wireless and Mobile Networks

Second Semester 2025

Birzeit University
Electrical and Computer Engineering Department

Dr. Mohammad Jubran

Course Information

Course number and name: *ENCS5323* – Wireless and Mobile Networks

Credits and contact hours: Credit: 3 (Lecture: 3, Lab.: 0)

Course Prerequisites:

- ENEE3309: Communication Systems
- ENCS3320: Computer Networks

Books:

- (textbook) Wireless Communications & Networking 1st Edition, Vijay Garg, 2007
- (Reference) Introduction to Wireless and Mobile Systems 3rd Edition, Agrawal and Zeng, 2011
- (Reference) Wireless Communication Networks and Systems 1st Edition, Cory Beard and William Stallings, Pearson, first edition, 2015

Course Information

Brief list of topics to be covered

- **Wireless Transmission Fundamentals:** Radio Frequency - Parameters & Units of Measure, Frequencies and Regulations, Antennas, Multiplexing, Digital Modulation, Spread Spectrum Technology, Medium Access Control
- **Wireless Networks:** Satellite Networks, Cellular Networks, WLANs, WiMAX, Mobile Ad hoc Networks, Wireless Sensor Networks, Bluetooth & ZigBee
- **IP and TCP over Wireless Network:** Mobile IP, Wireless TCP, Wireless Internet
- **Other interesting topics (if time permits),** RFIDs, vehicular networks, localization, sensing.

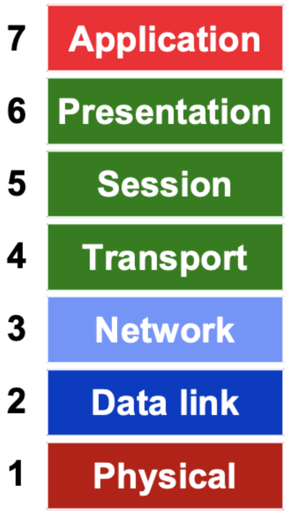
Tentative Evaluation and Grades: (PS: No make-up exams)

- Class work (quizzes and participation): 15%
- Project: 15%
- Midterm Exam: 35%
- Final Exam: 35%

Wireless and Mobile Networks

Wireless Transmission Fundamentals

- Transmission Basics
- Radio Frequency Fundamentals
- Frequencies and Regulations
- Antennas and Propagations



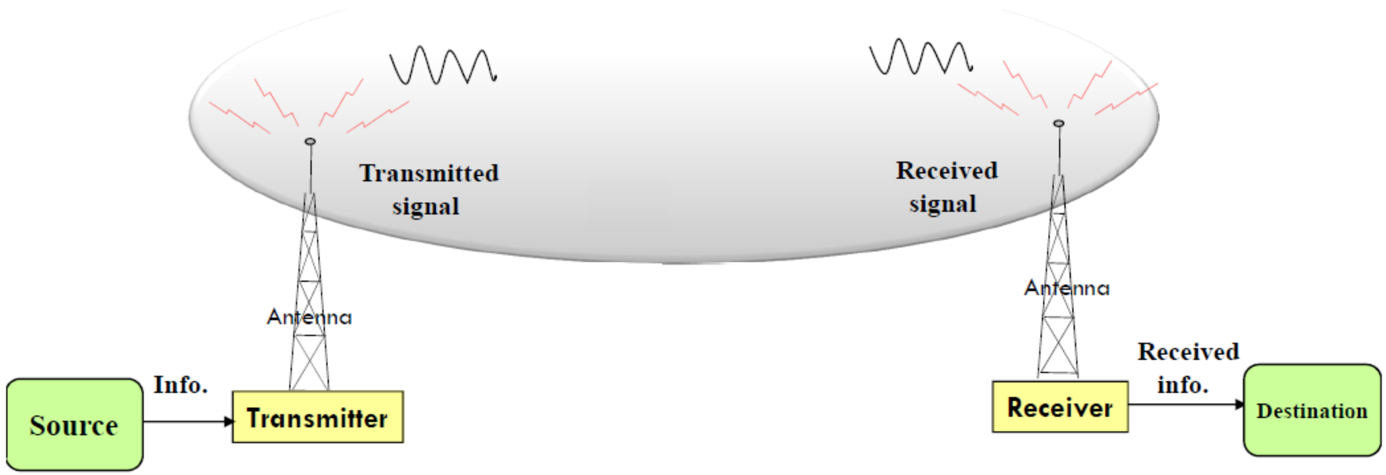
- **Physical: transmission of a bit stream.**

Slides prepared by Dr. Aziz Qaroush

Transmission basics

- Data - entities that convey meaning, or information
- Signals - electric or electromagnetic representations of data
- Transmission – communication of data by the propagation and processing of signals

Simplified Block Structure of a Digital Communication System



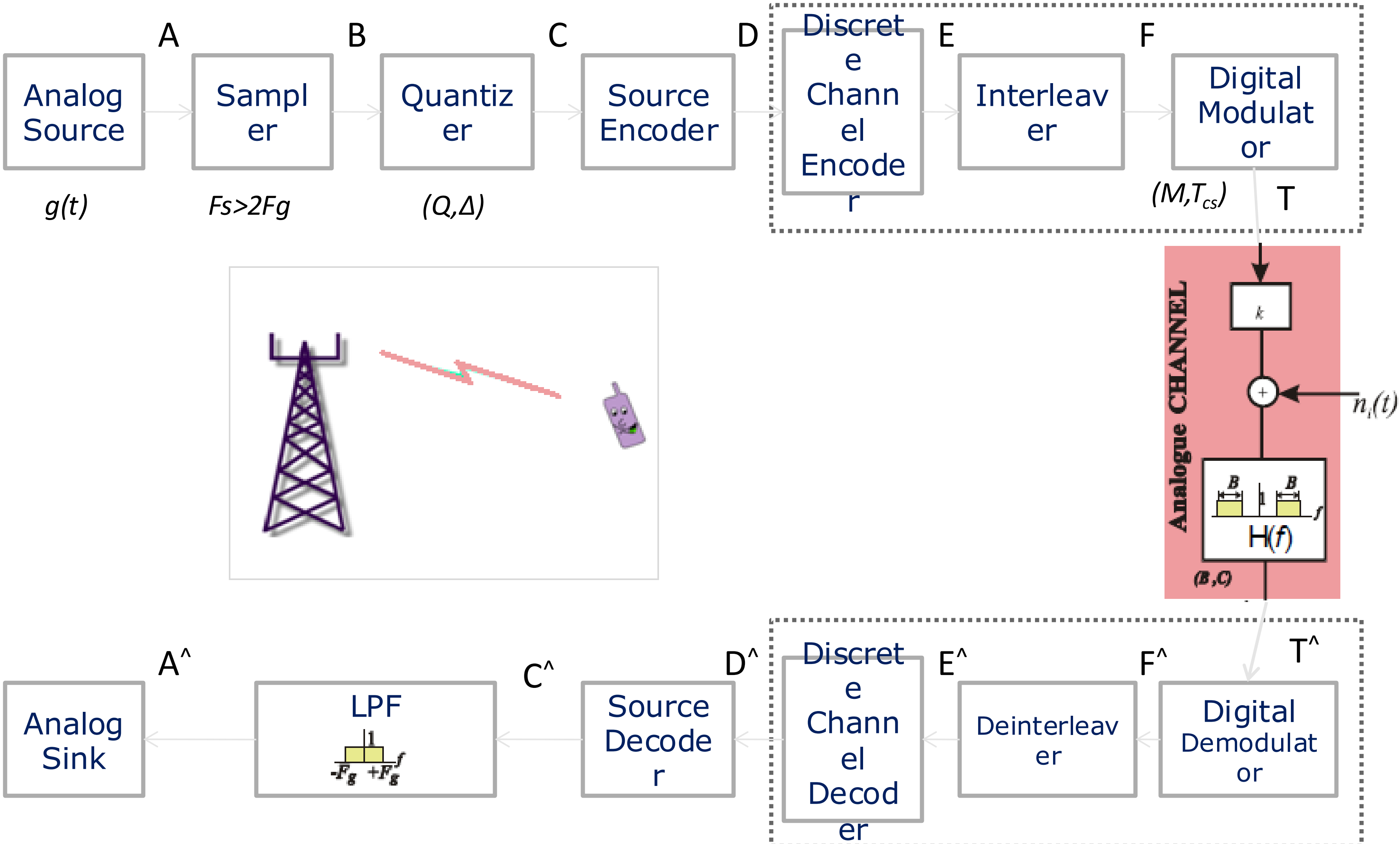
- If discrete information source

Discrete Information Source → Transmitter → Channel → Receiver → Discrete Information Sink

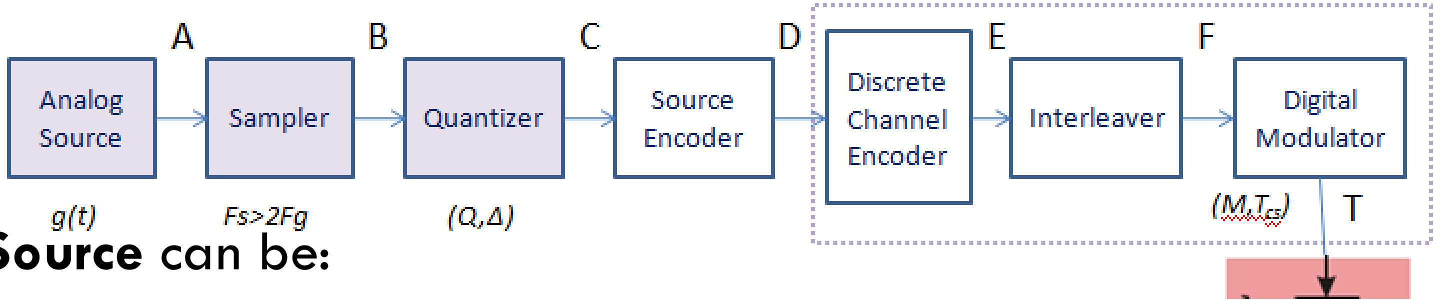
- If continuous (analog) information source

Analog Information Source → ADC → Transmitter → Channel → Receiver → DAC → Analog Information Sink

General Block Structure of a DCS

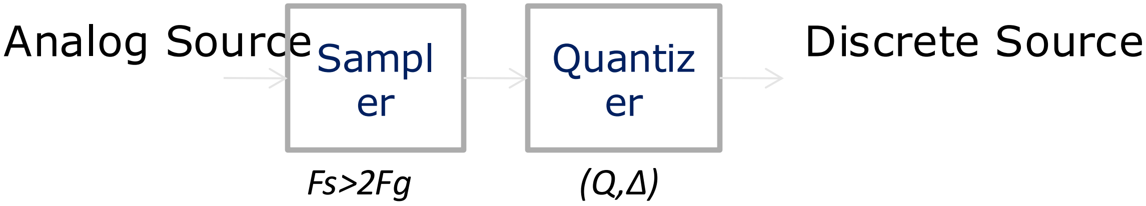


General Block Structure of a DCS

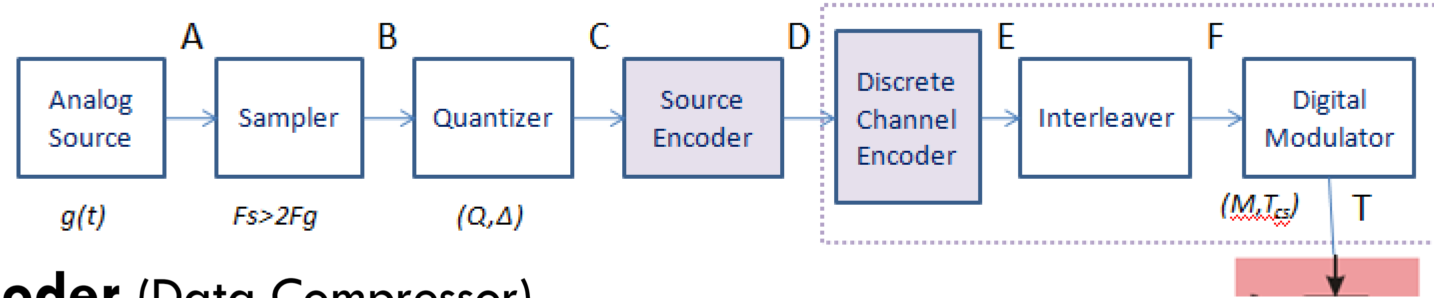


- Information **Source** can be:
  - Continuous (Analog) . e.g.: voice
  - Discrete (Digital). e.g.: email

  *Discrete source can be a direct input to the source encoder (point **C**)*
- The **Sampler** is used to convert the analog signal to discrete-time continuous-amplitude signal. (Nyquist Rate $F_s = 2F_g$)
- The **Quantizer** is used to convert the discrete-time continuous-amplitude signal to a discrete-time discrete-amplitude signal.

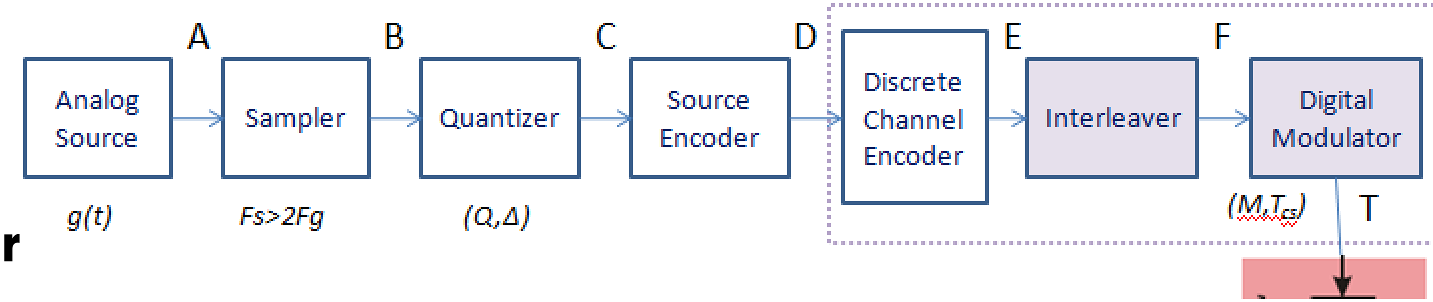


General Block Structure of a DCS

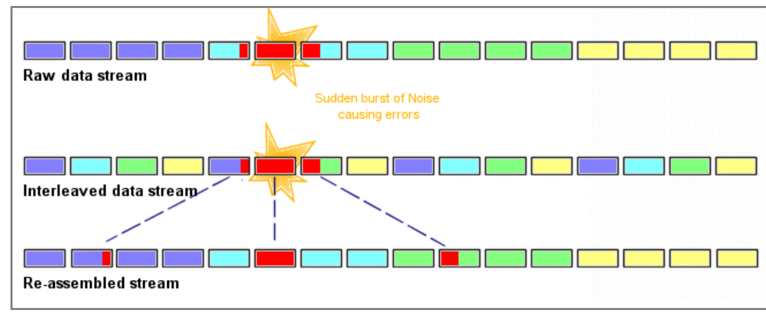


- **Source Encoder** (Data Compressor)
  - Is to represent the message symbols (or quantization levels) by as few digits as possible. This is by identifying and **removing any redundancy** in the input sequence.
  - The average information per symbol generated by the source is given by the so-called **entropy** of the source.
  - Optimum source encoder: Huffman Encoder
  - Assigns short-codes to symbols arriving more frequently, and long-codes to symbols arriving infrequently.
- Discrete **Channel Encoder**
  - **Adding deliberately some redundancy** which will make it possible for the receiver to detect and even correct errors.
  - Reduces the channel noise/interference effects.
  - e.g. Block coding

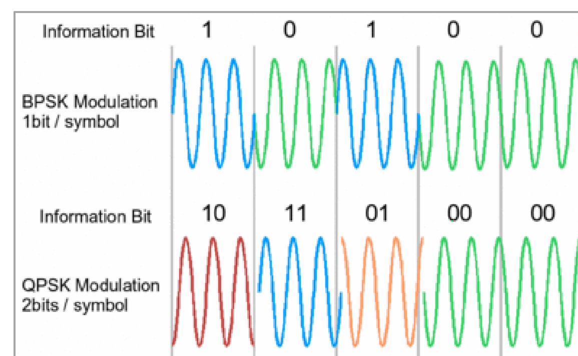
General Block Structure of a DCS



- **Interleaver**
  - A process of reorganizing the coded data.
  - Transforms the bursty channel (exhibits bursty errors) into a channel having independent errors.

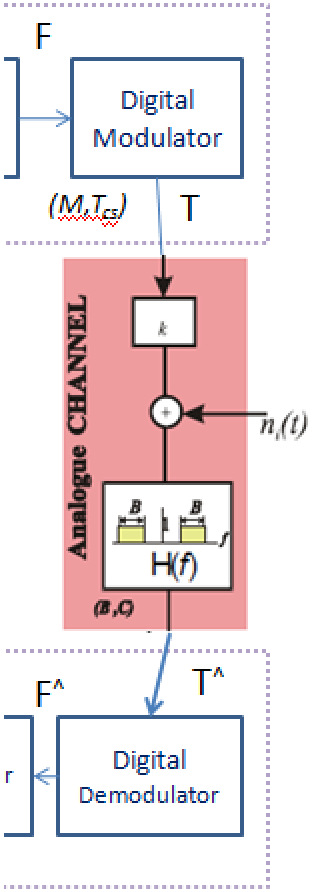


- **Digital Modulator**
  - The digital Modulator takes L bits at a time at some uniform rate r_{cs} and transmits one of $M = 2^L$ distinct waveforms $s_{1}(t), \ldots, s_{M}(t)$.

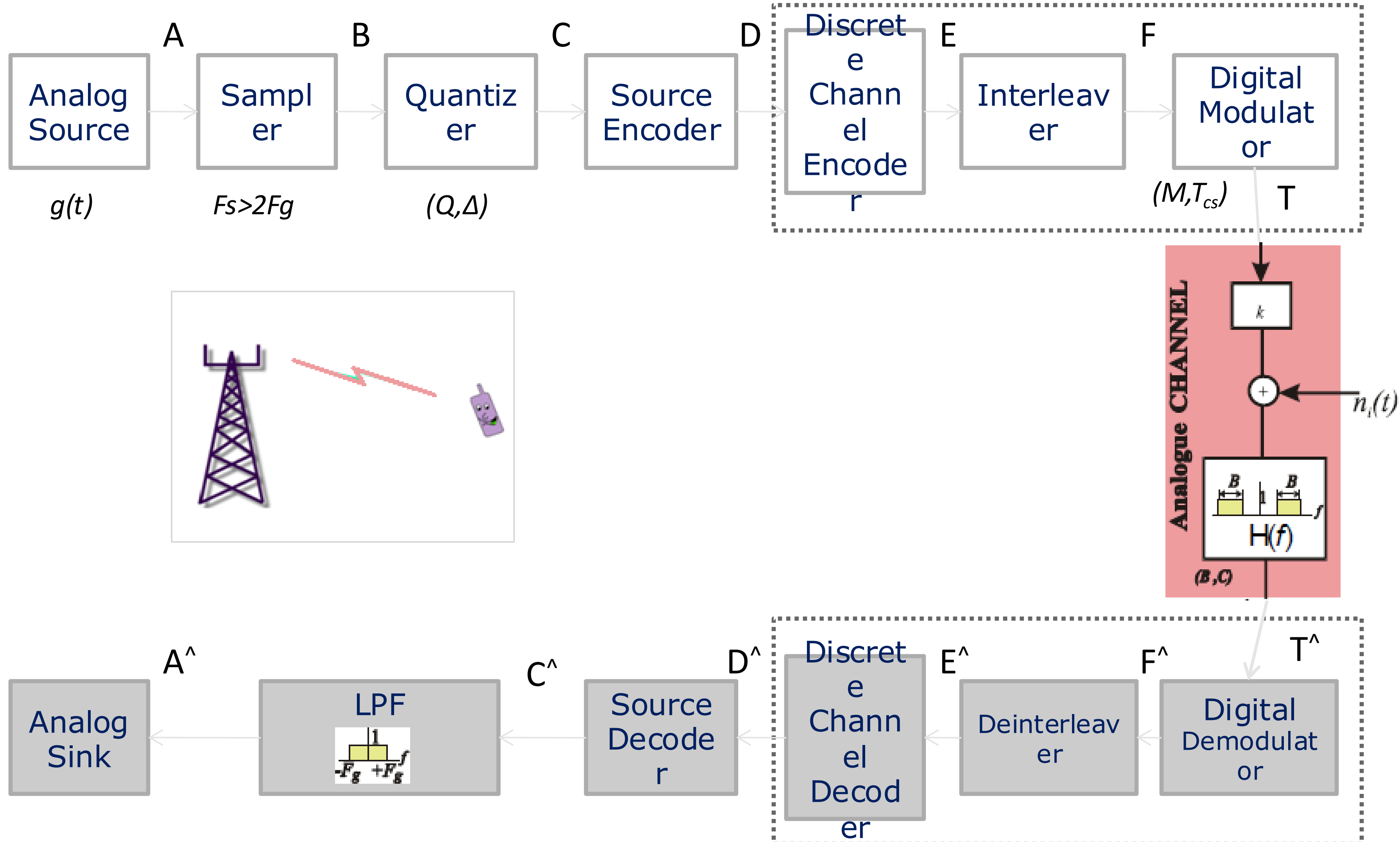


General Block Structure of a DCS

- **Channel**
  - A transmission medium used to convey an information signal from one or several senders (or transmitters) to one or several receivers
  - Adds noise $n_{(t)}$ to the transmitted signal $s_{i(t)}$
  - Output of the channel = received signal = $r_{(t)} = ks_{i(t)} + n_{(t)}$
  - Wireless Channels are much more difficult and hostile than wired channels because of interference, noise, multipath, multiple access …etc

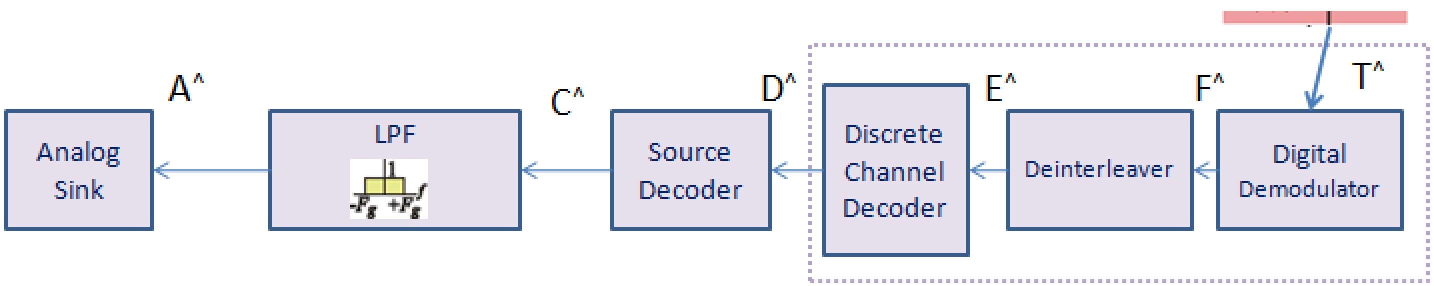


General Block Structure of a DCS



General Block Structure of a DCS

- **Receiver** (Reverse Processes)
  - Digital Demodulator ←→ Digital Modulator
  - Deinterleaver ←→ Interleaver
  - Discrete Channel Decoder ←→ Discrete Channel Encoder
  - Source Decoder ←→ Source Encoder
  - Low-Pass Filter (+Quantization Error) ←→ Sampler + Quantizer
  - Analog Sink (Destination) ←→ Analog Source
    - Discrete Sink ←→ If discrete Source



Radio Frequency Fundamentals

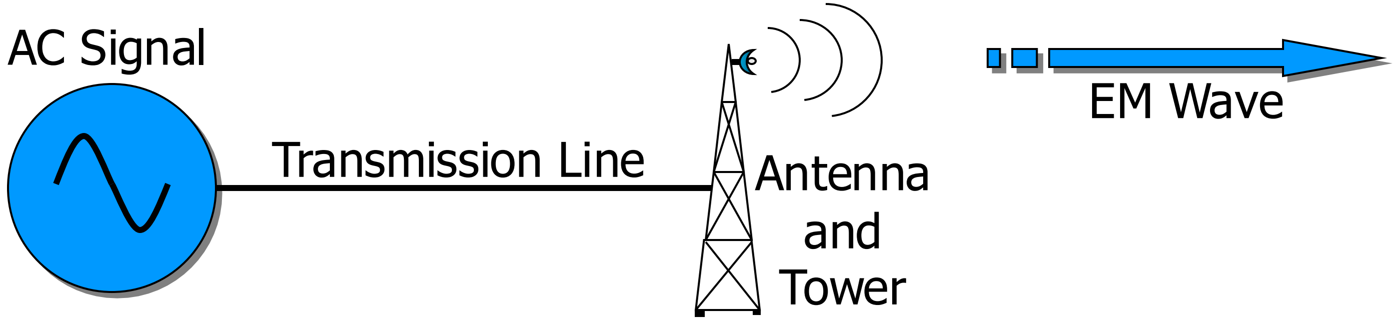
Signals

- Physical representation of data
- Function of time and location
- Signal parameters: parameters representing the value of data
- Classification
  - continuous time/discrete time
  - continuous values/discrete values
  - analog signal = continuous time and continuous values
  - digital signal = discrete time and discrete values
- Signal parameters of periodic signals:
  period T, frequency f=1/T, amplitude A, phase shift φ
  - sine wave as special periodic signal for a carrier:

$$s(t) = A_t \sin(2 \pi f_t t + \varphi_t)$$

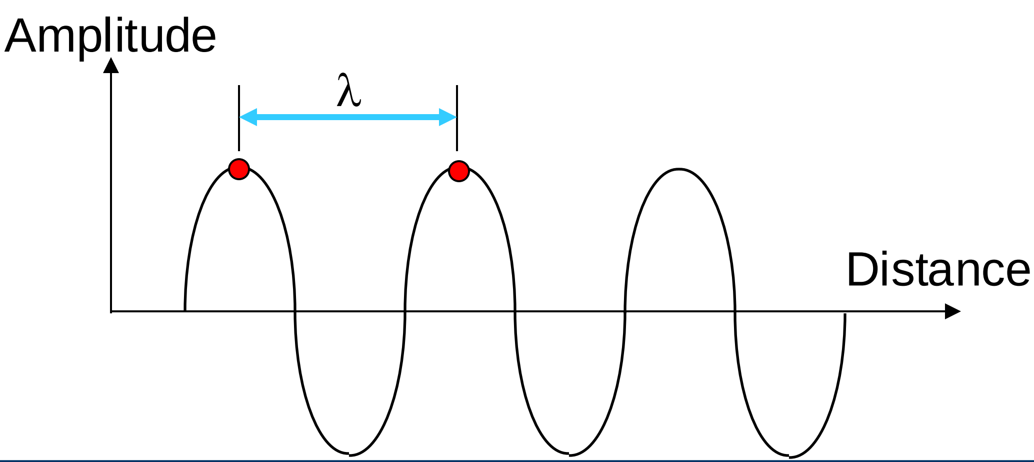
Radio Frequency

- Radio frequency, (RF) is a term that refers to alternating current, (AC) having characteristics such that, if the current is input to an antenna, an electromagnetic (EM) field/wave is generated suitable for wireless communications.



RF Properties

- Wavelength, λ -The distance that a wave travels in the time it takes to go through one full 360 degree phase change, or one cycle.
  - The wavelength dictates the optimum size of the receiving antenna, and it determines how the RF wave will interact with its environment. For example, an RF wave will react differently when it strikes an object that is large in comparison to the wavelength from when it strikes an object that is small in comparison to the wavelength.

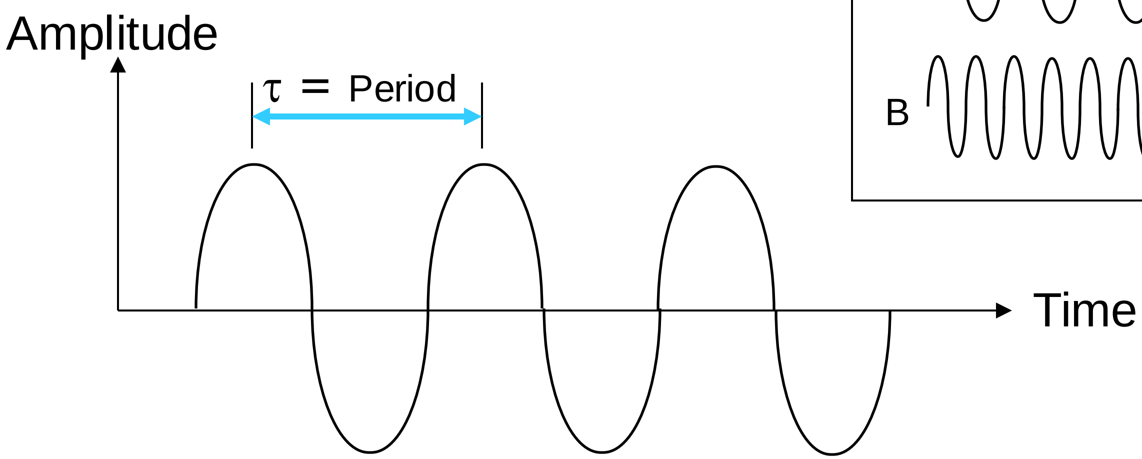


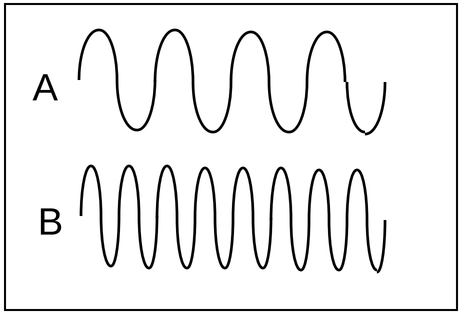
$$\lambda = \frac{300{,}000{,}000 \text{ m/s}}{\text{Frequency (Hz)}}$$

RF Properties

- Frequency -The number of repetitions per unit time of a complete waveform, measured in Hertz. The number of complete oscillations per second of electromagnetic radiation.
  - Wavelength, frequency, and medium are interdependent. Higher frequencies have shorter wavelengths, and lower frequencies have longer wavelengths.

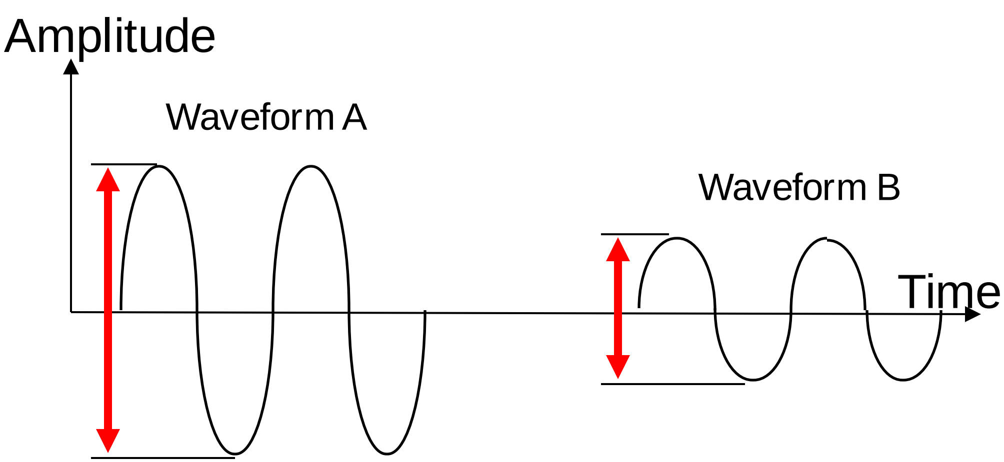
$F = 1/\tau$





RF Properties

- Amplitude - The amount of a signal. Amplitude is measured by determining the amount of variations in air pressure for sound or the voltage of an electrical signal.
  - Measure the energy of an RF signal.
  - The amplitude of an RF signal is analogues to a voltage level in an electrical signal.
  - While the frequency affects the distance a sound wave can travel, the amplitude affects the ability to detect (hear) the sound wave at that distance.

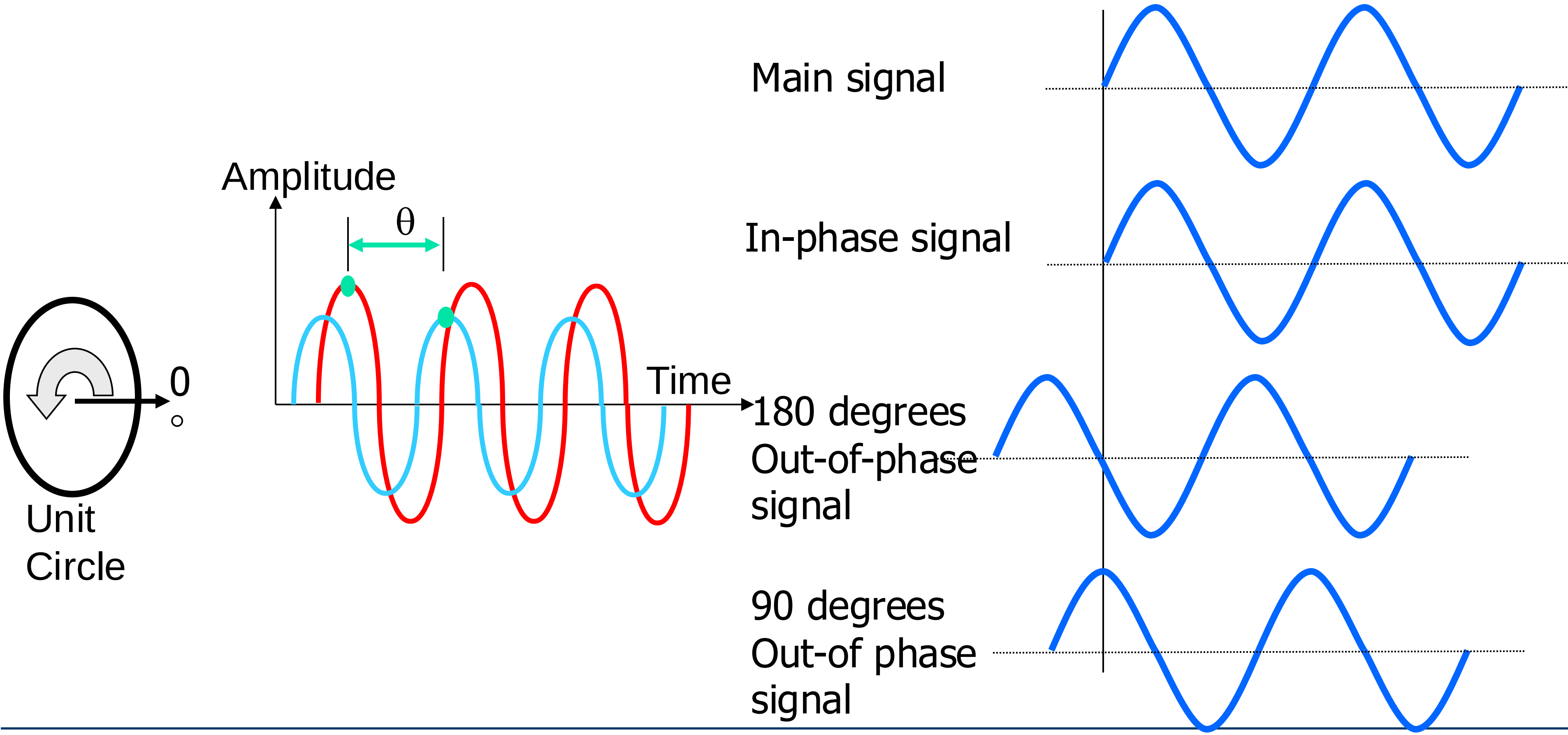


Example power levels include:

- FM radio station: 6000 to 10,000W
- Microwaves ovens: ~ 700 to 1000W
- Cellular phones: 1 to 10W
- 802.11 NICs: 1 to 200mW

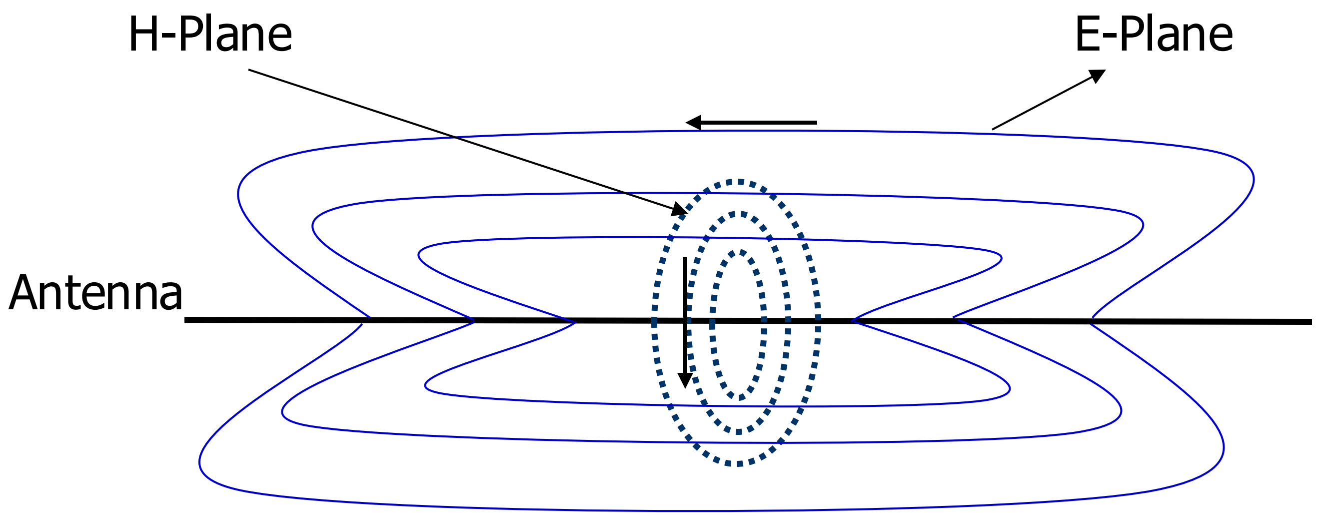
RF Properties

- Phase, θ - Time based relationship between a periodic function and a reference. In electricity, it is expressed in angular degrees to describe the voltage or current relationship of two alternating waveforms.



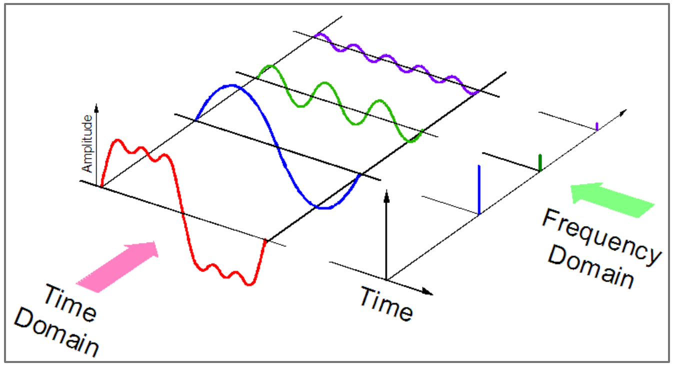
RF Properties

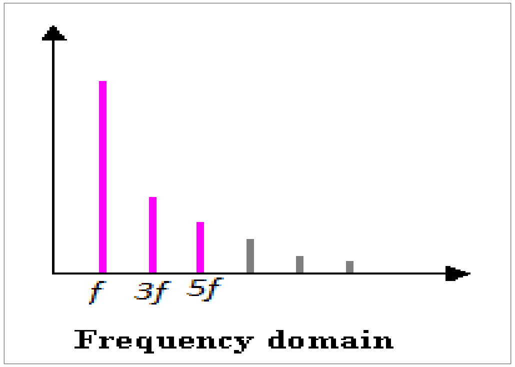
- Polarization
  - Radio waves = one electric field (E-Plane) + one magnetic field (H-Plane). These fields are on planes perpendicular to each other.
  - Polarization: Polarization – By convention the orientation of the electric field, (E) with respect to the earth's surface. Vertical, Horizontal, and Circular/Elliptical polarization.



Frequency Domain Concepts

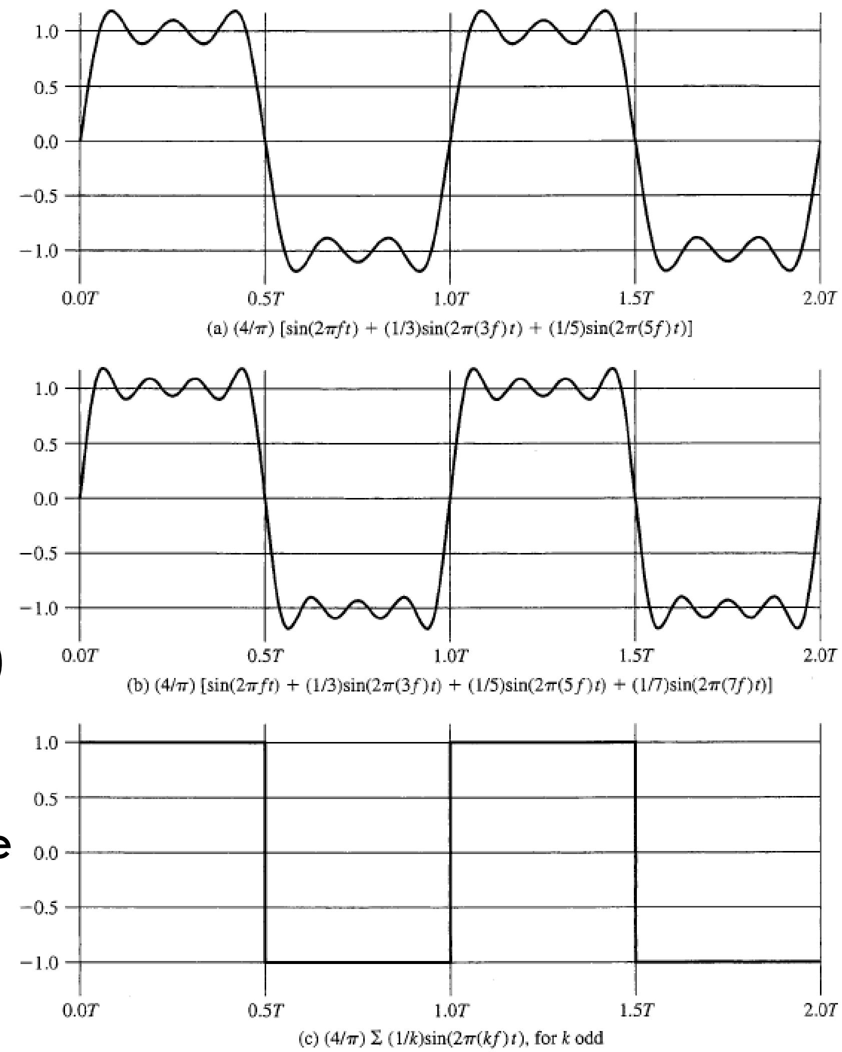
- **Spectrum** - range of frequencies that a signal contains
- **Absolute Bandwidth** - width of the spectrum of a signal = f_{MAX} - f_{Min}
  - Many Signals have an infinite bandwidth but most of the energy is contained in a relatively narrow band of frequencies
- **Effective Bandwidth** (or just bandwidth) - narrow band of frequencies that most of the signal's energy is contained in.
  - e.g. Voice Signal (20 Hz to 20 kHz) we use only (300Hz to 3.4 KHz)





Relationship Between Data Rate and Bandwidth

- **Data Rate -** rate at which data can be communicated (bps = bits per second)
- Consider the square wave shown in the figure
- Suppose that the positive pulse represent binary 0, and the negative pulse represent binary 1.
- The data rate = $2 \times f$ bits per second (bps)
- This waveform consists of infinite number of frequency components and hence an infinite bandwidth.



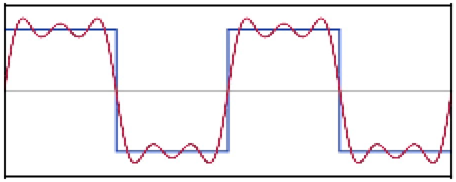
(a) $(4/\pi)$ [$\sin(2\pi ft)$ + $(1/3)\sin(2\pi(3f)t)$ + $(1/5)\sin(2\pi(5f)t)$]

(b) $(4/\pi)$ [$\sin(2\pi ft)$ + $(1/3)\sin(2\pi(3f)t)$ + $(1/5)\sin(2\pi(5f)t)$ + $(1/7)\sin(2\pi(7f)t)$]

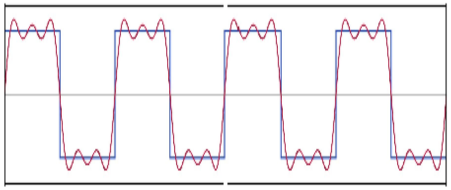
(c) $(4/\pi)\ \Sigma\ (1/k)\sin(2\pi(kf)t)$, for k odd

Relationship Between Data Rate and Bandwidth

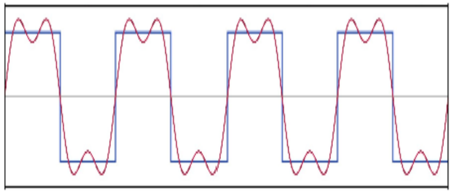
- Case-I
  - Assume a signal has the following components: ***f***, ***3f***, ***5f***; ***f= 1 MHz***
  - *What is the BW?* *BW= 5f-f = 4f = 4MHz*
  - *What is the Data Rate?* *Data Rate = 2 Mbps*



- Case-II
  - Assume a signal has the following components: ***f***, ***3f***, ***5f***; ***f= 2 MHz***
  - *What is the BW?* *BW= 5f-f = 4f = 8MHz*
  - *What is the Data Rate?* *Data Rate = 4 Mbps*



- Case-III
  - Assume a signal has the following components: ***f***, ***3f***; ***f= 2 MHz***
  - *What is the BW?* *BW= 3f-f = 2f = 4MHz*
  - *What is the Data Rate?* *Data Rate = 4 Mbps*



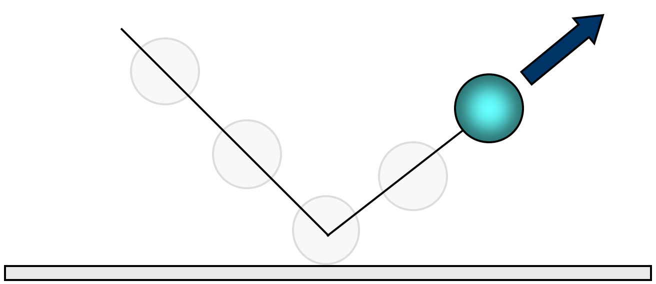
- Conclusions
  - Any digital waveform will have infinite bandwidth
  - BUT the transmission system will limit the bandwidth that can be transmitted
  - AND, for any given medium, the greater the bandwidth transmitted, the greater the cost
  - HOWEVER, limiting the bandwidth creates distortions

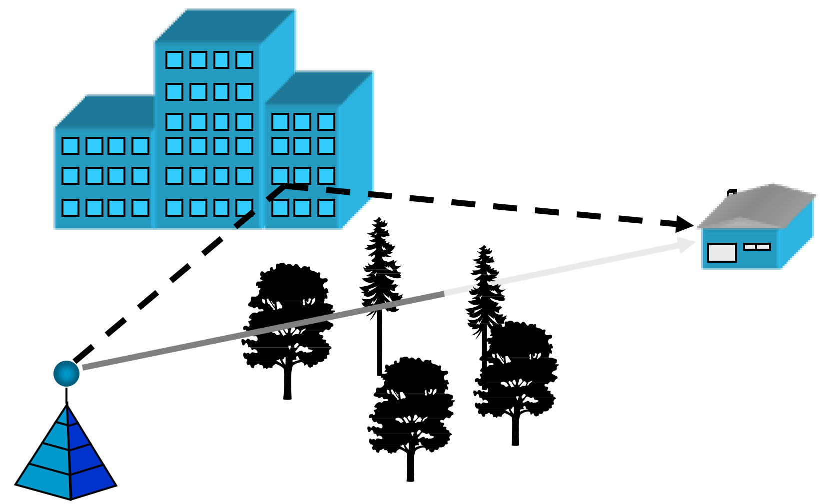
Signal Propagation

- Attenuation/Loss - A decrease in signal level, amplitude, or magnitude of a signal.
  - Propagation in free space always like light (straight line)
  - Receiving power proportional to $1/d^2$ (d = distance between sender and receiver)
  - Receiving power additionally influenced by
    - fading (frequency dependent)
    - shadowing
    - reflection at large obstacles
    - refraction depending on the density of a medium
    - scattering at small obstacles
    - diffraction at edges

Basic Properties of EM waves

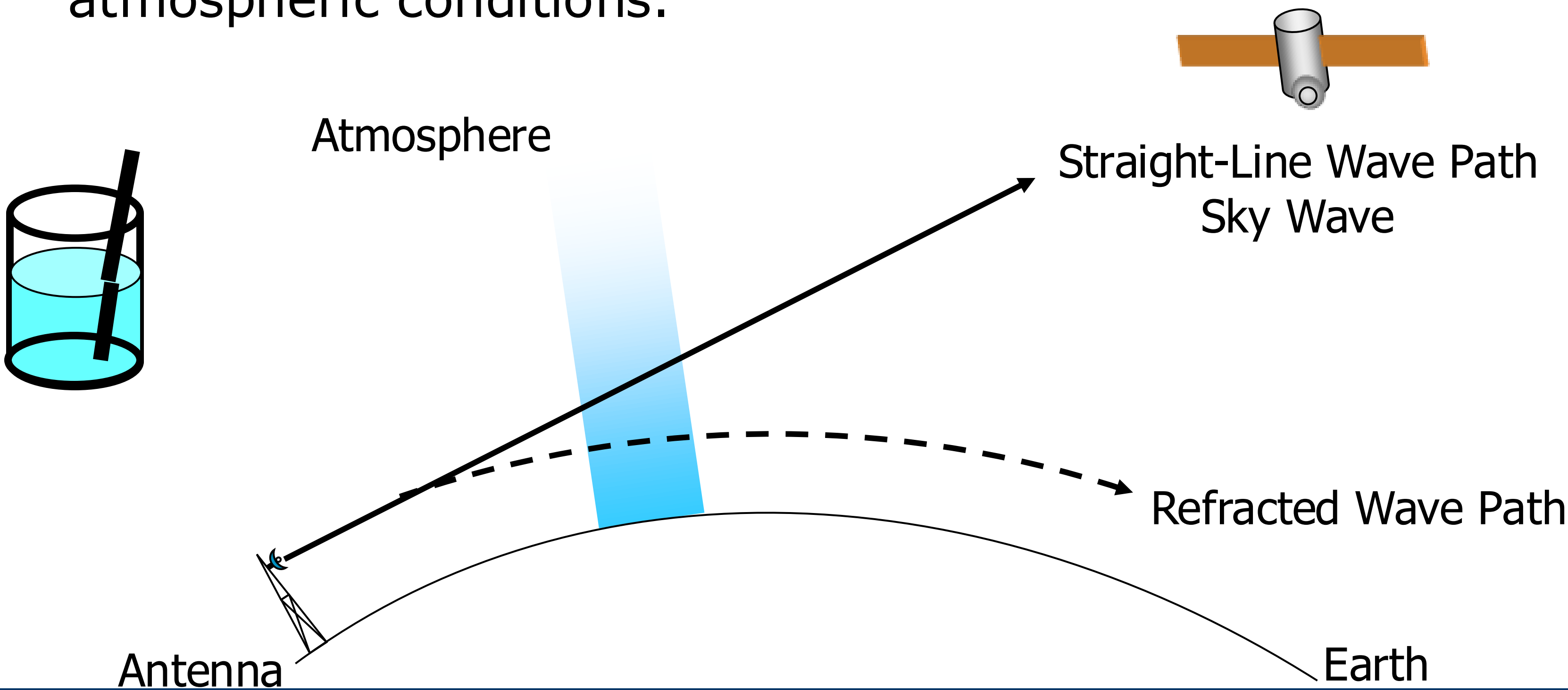
- Reflection – cast off or turn back, (bouncing).
  - RF signals reflect off objects that are smooth and larger than the waves that carry the signals
  - The reflected signal has a greater distance to transverse and that at the reflection point there will be signal absorption and losses





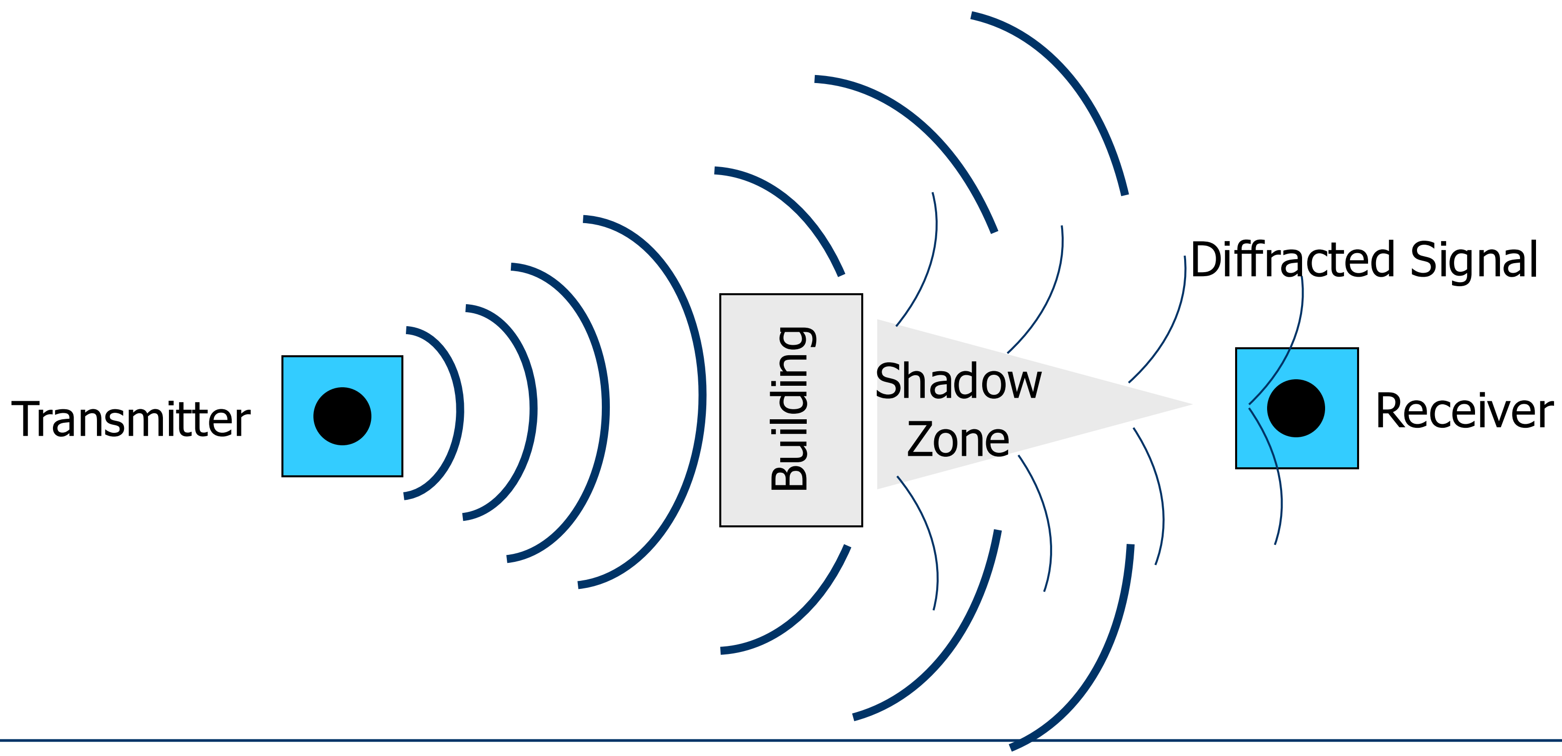
Basic Properties of EM waves

- Refraction - deflection from a straight path, (bending through a medium).
  - Refraction occurs when an EM passes from one medium density to another.
  - RF signal refraction is usually the result of a change in atmospheric conditions.



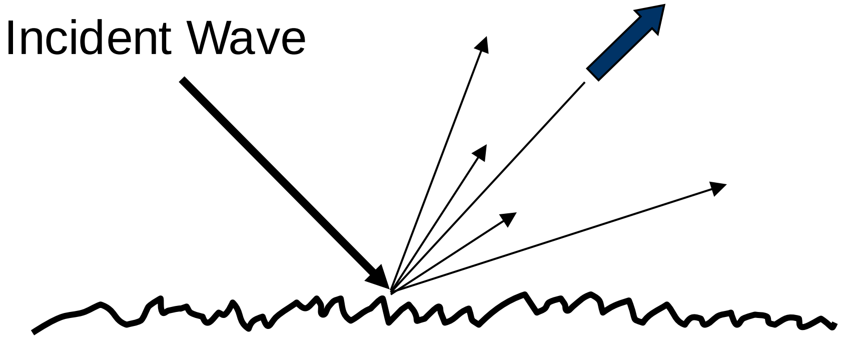
Basic Properties of EM waves

- Diffraction – Change in the directions and intensities of a group of waves when they pass near the edge of an EM *dense* object, (bending around object).



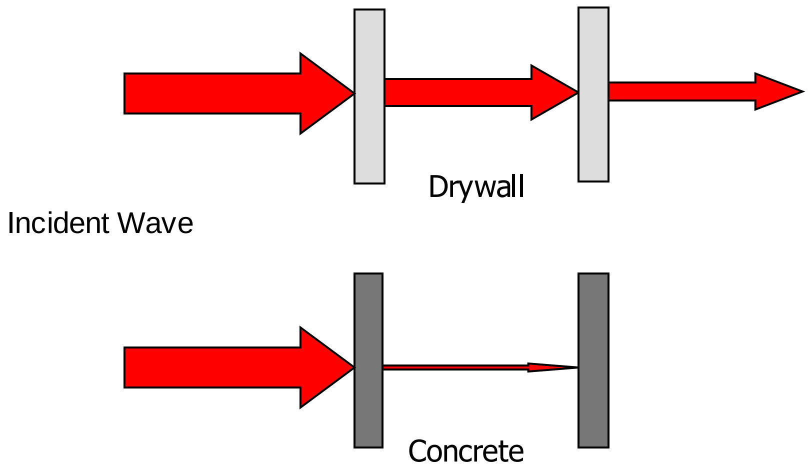
Basic Properties of EM waves

- Scattering – A specification of the angular distribution of the electromagnetic energy scattered by a particle or a scattering medium, (dispersion).
  - The change in direction, frequency, or polarization of electromagnetic waves. dispersion of electromagnetic radiation as a result of it's interaction with molecules in the atmosphere.
  - The sky appears blue as a result of the blue region of the visual spectrum being scattered more than the red region.



Basic Properties of EM waves

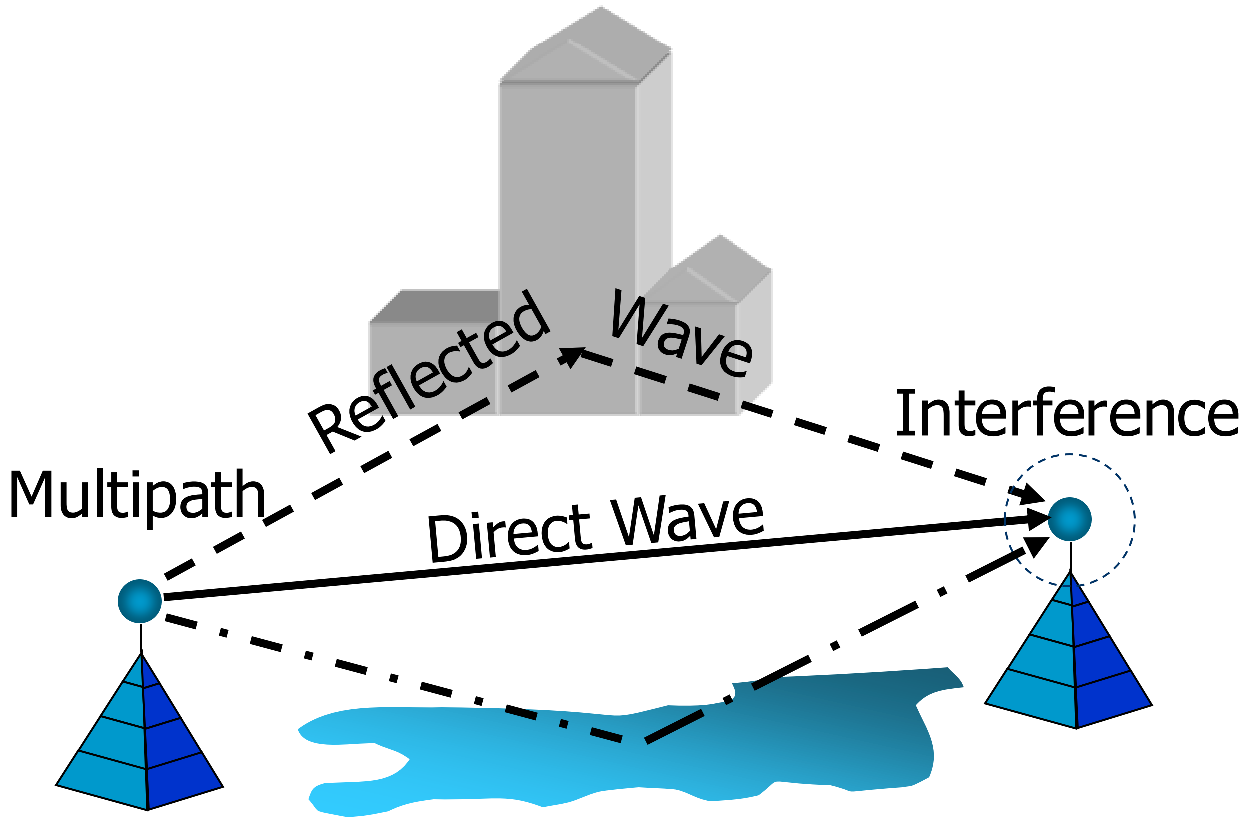
- Absorption – The process in which incident radiant energy is retained by a substance by conversion to some other form of energy.
  - The microwave oven works because RF waves are absorbed well by materials that have moisture (molecular electric dipoles) in them. This absorption converts the RF wave energy into heat energy and therefore heats your food.



Material	Absorption Rate
Plasterboard/drywall	3–5 dB
Glass wall and metal frame	6 dB
Metal door	6–10 dB
Window	3 dB
Concrete wall	6–15 dB
Block wall	4–6 dB

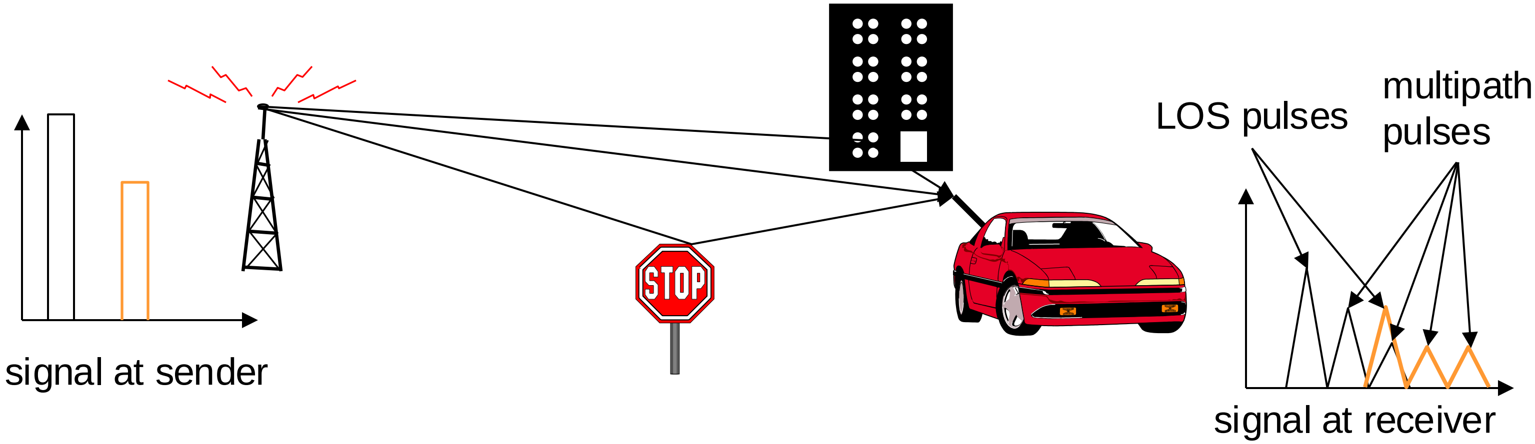
Basic Properties of EM waves

- Interference - hinders, obstructs, or impedes. When two or more wave fronts meet.



Multipath propagation

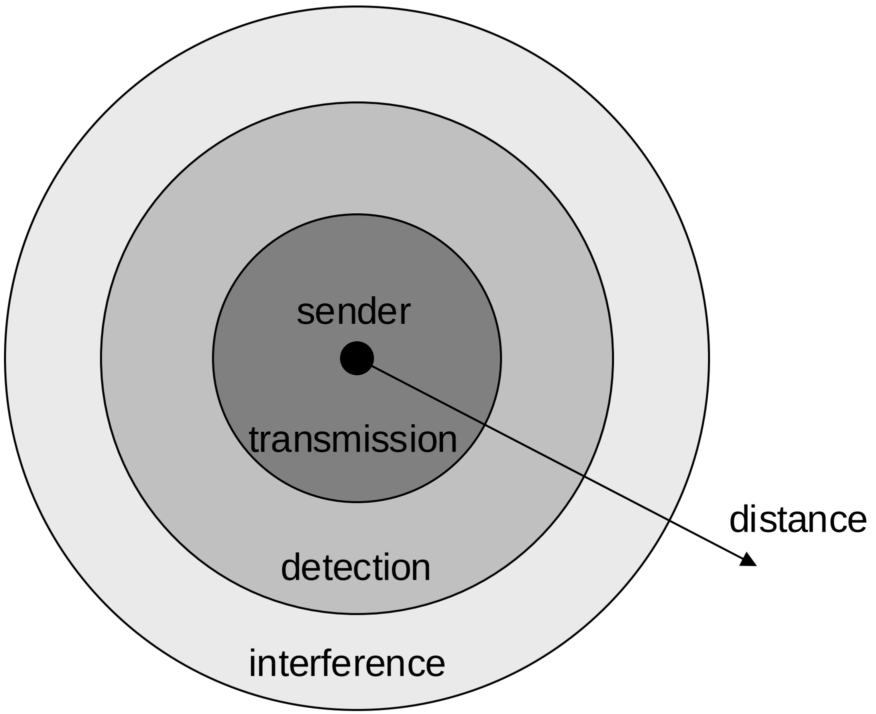
- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction



- Time dispersion: signal is dispersed over time
  - interference with “neighbor” symbols, Inter Symbol Interference (ISI)
- The signal reaches a receiver directly and phase shifted
  - distorted signal depending on the phases of the different parts

Signal propagation ranges

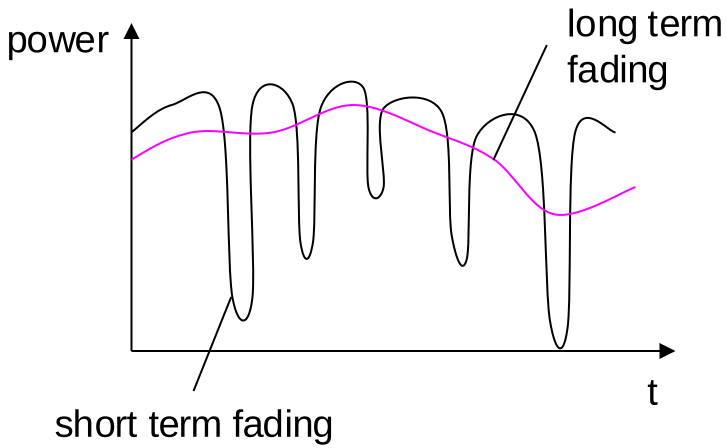
- Transmission range
  - communication possible
  - low error rate
- Detection range
  - detection of the signal possible
  - no communication possible
- Interference range
  - signal may not be detected
  - signal adds to the background noise



Effects of mobility

- Channel characteristics change over time and location
  - signal paths change
  - different delay variations of different signal parts
  - different phases of signal parts
  - ➔ quick changes in the power received (short term fading)

- Additional changes in
  - distance to sender
  - obstacles further away
  - ➔ slow changes in the average power received (long term fading)

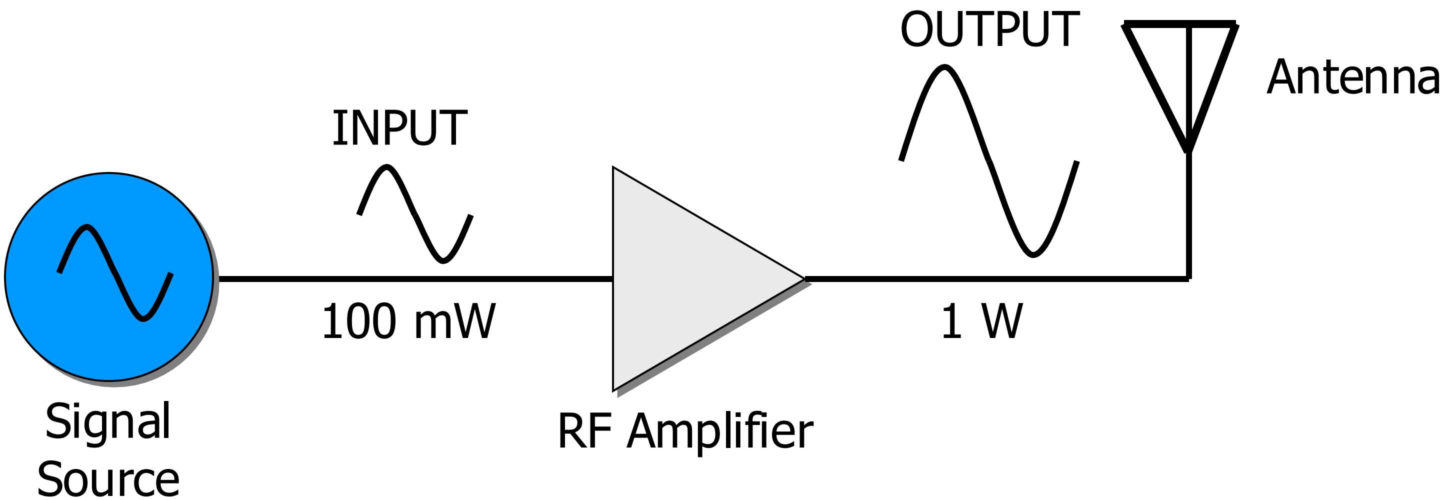


Amplification and Attenuation

- Amplification/Gain - An increase in signal level, amplitude or magnitude of a signal. A device that does this is called an amplifier.
  - *Gain is defined as the positive relative amplitude difference between two RF wave.*
  - *Amplification is* an active process used to increase an RF signal's amplitude and, therefore, results in gain.

- Attenuation/Loss - A decrease in signal level, amplitude, or magnitude of a signal. A device that does this is called an attenuator.
  - *Loss is defined as the negative relative amplitude difference between two RF signals.*

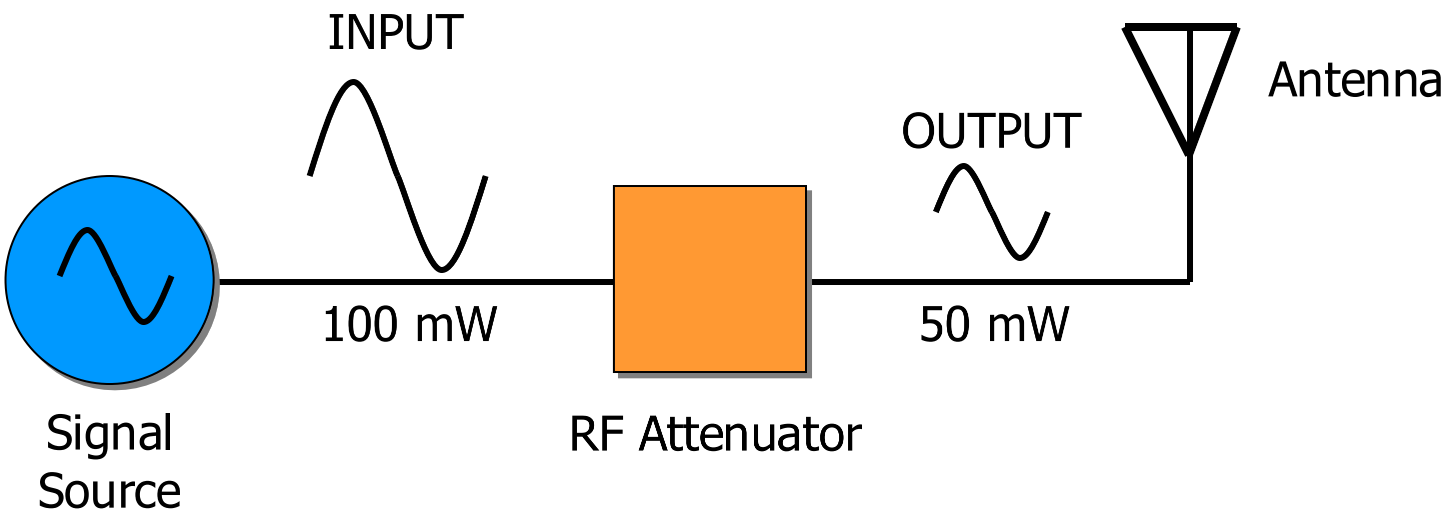
Amplification



The power gain of the RF amplifier is a power ratio.

$$\text{Power Gain} = \frac{\text{Power Output}}{\text{Power Input}} = \frac{1\ \text{W}}{100\ \text{mW}} = 10 \text{ no units}$$

Attenuation



The power loss of the RF attenuator is a power ratio.

$$\text{Power Loss} = \frac{\text{Power Output}}{\text{Power Input}} = \frac{50\ \text{mW}}{100\ \text{mW}} = 0.5 \text{ no units}$$

Decibels

- The decibel is defined as one tenth of a bel where one bel is a unit of a logarithmic power scale and represents a difference between two power levels.
  - The *decibel is a comparative measurement value. In other words, it is a* measurement of the difference between two power levels.
  - It is common to say that a certain power level is 6 dB stronger than another power level or that it is 3 dB weaker.
    - These statements mean that there has been 6 dB of gain and 3 dB of loss, respectively.

$$dB = 10 \log_{10} \frac{P_X}{P_{Ref}}$$

The numerator has P_x which is a power level that you are comparing to power reference P_{ref} which is in the denominator.

Relative and Absolute dB

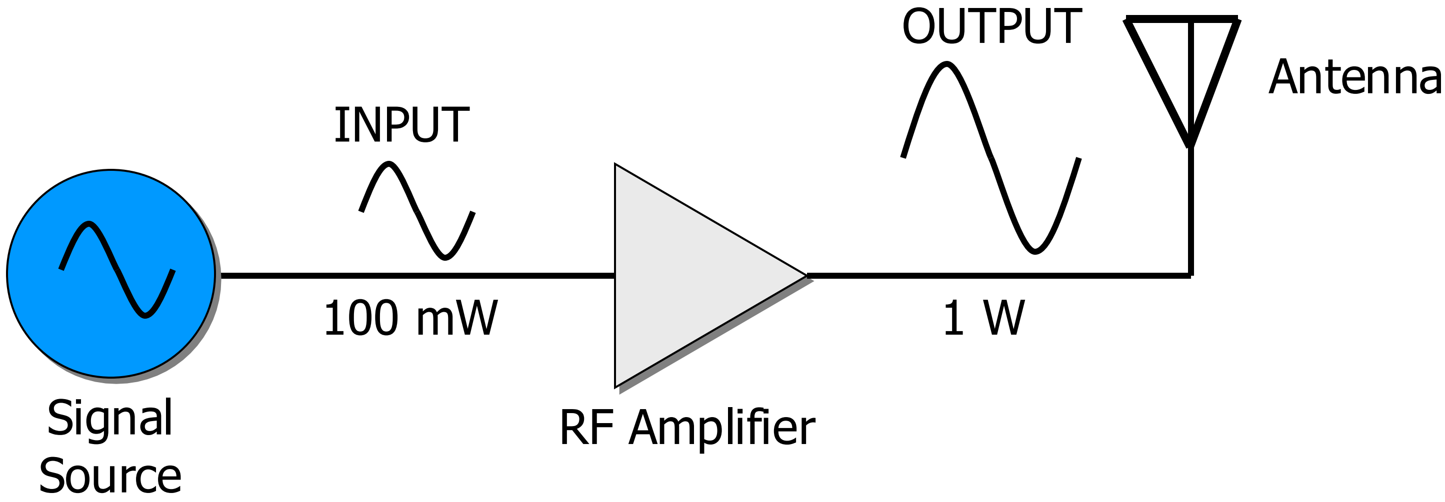
- Relative dB is selecting any value for P_{Ref}

dB

- Absolute dB is selecting a *standard* value for P_{Ref} and identifying the *standard* value with one or more letter following the dB variable.

dBm dBw dBi dBd

dB gain Sample Problem

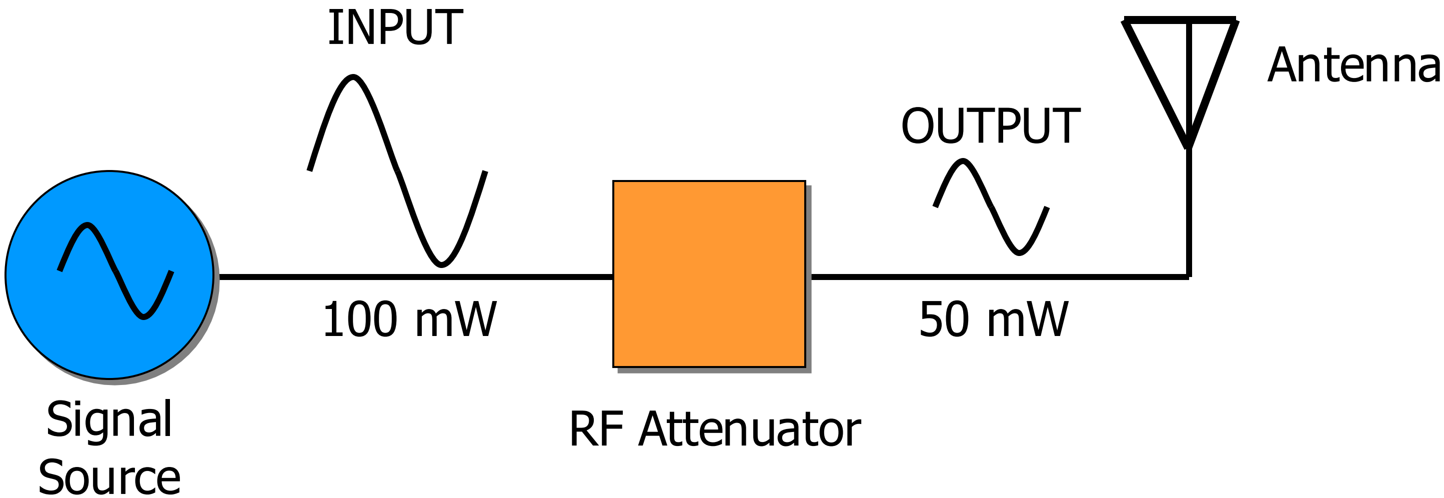


Compute the relative power gain of the RF Amplifier in dB.

$$dB = 10 \log_{10} (1W / \underset{\uparrow P_{Ref}}{100\ mW}) = 10 \log_{10} (10) = 10 (1) = 10\ dB$$

log$_{10}$ (10) = ?, What power must 10 be raised to so that it equals 10? $10^1 = 10$, therefore the log$_{10}$ (10) = 1

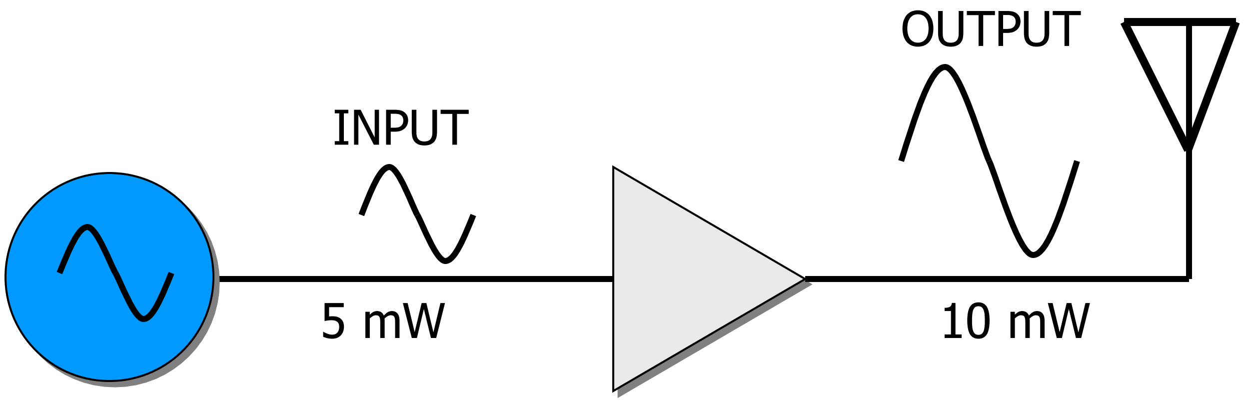
dB loss Sample Problem



Compute the relative power loss of the RF Amplifier in dB.

$$dB = 10 \log_{10} (50 \text{ mW} / \underset{\uparrow \atop P_{Ref}}{100} \text{ mW}) = 10 \log_{10} (.5) = 10 (-0.3) = -3.0 \text{ dB}$$

dB Gain Sample Problem



Compute the absolute dBm power level at the output of the RF Amplifier.

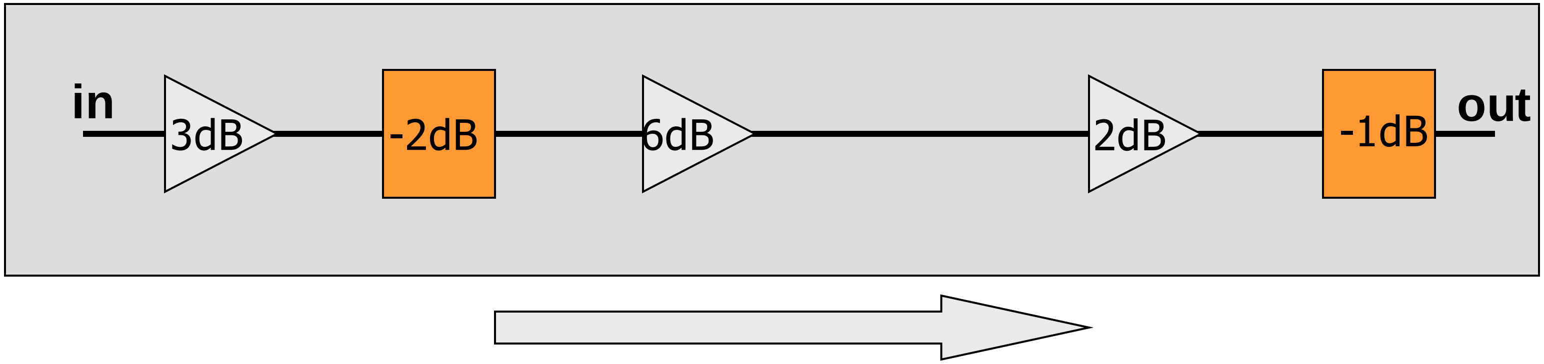
$$\text{dBm} = 10 \log_{10} (\ 10 \text{ mW} / \underset{\uparrow \atop P_{Ref}}{1 \text{ mW}}) = 10 \log_{10} (\ 10\ ) = 10 (\ 1\ ) = 10 \text{ dBm}$$

$$\text{dB} = 10 \log_{10} (\ 10 \text{ mW} / \underset{\uparrow \atop P_{Ref}}{5 \text{ mW}}) = 10 \log_{10} (\ 2\ ) = 10 (\ 0.3\ ) = 3 \text{ dB}$$

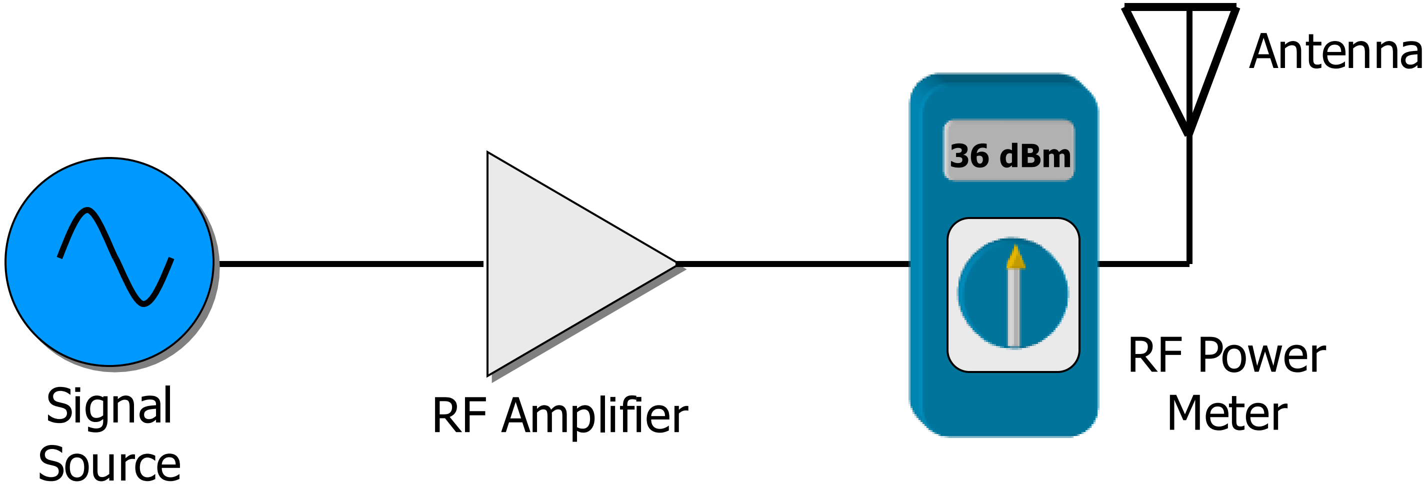
Helpful Hints

1. A gain of 3 dB magnifies the output power by two.
2. A loss of 3 dB equals one half of the output power.
3. A gain of 10 dB magnifies the output power by 10.
4. A loss of 10 dB equals one-tenth of the output power.
5. dB gains and losses are cumulative.

Gain in dB	Expression in 10s and 3s
1	+ 10 – 3 – 3 – 3
2	+ 3 + 3 + 3 + 3 – 10
3	+ 3
4	+ 10 – 3 – 3
5	+ 3 + 3 + 3 + 3 + 3 – 10
6	+ 3 + 3
7	+ 10 – 3
8	+ 10 + 10 – 3 – 3 – 3 – 3
9	+ 3 + 3 + 3
10	+ 10



dB Sample Problem



Compute the power level in watts at the output of the RF Amplifier.

$36\text{ dBm} = 10 \log_{10} (P_X / 1\text{ mW})$ ⇨ $3.6 = \log_{10} (P_X / 1\text{ mW})$

$\text{antilog } (3.6) = \text{antilog } \log_{10}(P_X / 1\text{ mW})$ ⇨ $3{,}980 = (P_X / 1\text{ mW})$

$3{,}980 \times 1\text{ mW} = P_X$ ⇨ $P_X = 3.98\text{ W} \cong 4\text{ W}$

36 dBm = (10 + 10 + 10 + 3 +3)dB, 1 mW x 10 x 10 x 10 = 1W x 2 x 2 = 4 W

Channel Capacity

- **Channel Capacity:** the maximum rate at which data can be transmitted over a given channel, under given conditions.
- **Noise:** any unwanted signal that combines with and hence distorts the signal intended for transmission and reception.
- **Error Rate:** This is the rate at which errors occur, where an error is the reception of a 1 when a 0 was transmitted or the reception of a 0 when a 1 was transmitted.
- **The Nyquist Limit**
  - A noiseless channel of bandwidth *B Hz* can at most transmit a binary signal at a capacity

    $$C = 2B \quad bps$$

    - e.g. a 3000 Hz channel can transmit data at a rate of at most 6000 bits/second
  - What if the number of signal levels is more than 2 (*M* levels):

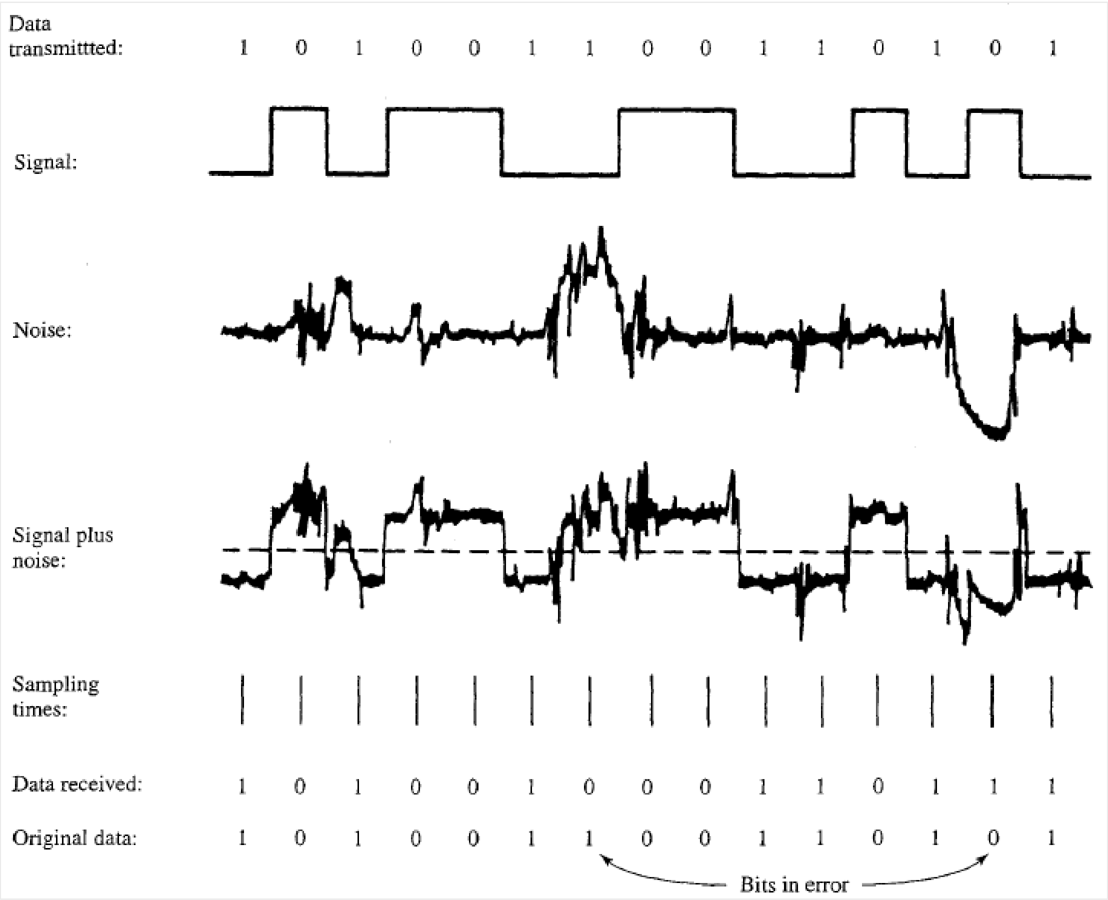
    $$C = 2B \log_2(M) \quad bps$$

    - e.g. a 3000 Hz channel, with **8** discrete signal elements, can transmit data at a rate of at most 18000 bits/second
    - For a given bandwidth, the capacity can be increased by increasing the number of different signal elements (*M*)
    - Increasing *M*, increases receiver sensitivity to noise and other channel impairments.

Channel Capacity

- The presence of noise can corrupt one or more bits. If the data rate is increased, then the bits become "shorter" in time, so that more bits are affected by a given pattern of noise. Thus, at a given noise level, the higher the data rate, the higher the error rate.

- For a given level of noise, we would expect that a greater signal strength would improve the ability to receive data correctly in the presence of noise



Channel Capacity

- **Shannon Capacity Formula**

$$C = B \log_2(1 + SNR) \text{ bps}$$

$$SNR = \text{Signal to Noise Ratio} = \frac{\text{Siganl Power}}{\text{Noise Power}}$$

$$SNR_{dB} = 10 \log_{10}\left(\frac{\text{Siganl Power}}{\text{Noise Power}}\right)$$

SNR: typically measured at a receiver.

- Represents theoretical maximum that can be achieved
- In practice, only much lower rates can be achieved
  - Formula assumes white noise (thermal noise)
  - Impulse noise is not accounted for
  - Attenuation distortion or delay distortion not accounted for
- We can also use Shannon's theorem to calculate the noise that can be tolerated to achieve a certain rate through a channel.

Channel Capacity

Example 2.1 Let us consider an example that relates the Nyquist and Shannon formulations. Suppose that the spectrum of a channel is between 3 MHz and 4 MHz and $SNR_{dB} = 24$ dB. Then

$$B = 4\text{ MHz} - 3\text{ MHz} = 1\text{ MHz}$$
$$SNR_{dB} = 24\text{ dB} = 10\log_{10}(SNR)$$
$$SNR = 251$$

Using Shannon's formula,

$$C = 10^6 \times \log_2(1 + 251) \approx 10^6 \times 8 = 8\text{ Mbps}$$

This is a theoretical limit and, as we have said, is unlikely to be reached. But assume we can achieve the limit. Based on Nyquist's formula, how many signaling levels are required? We have

$$C = 2B\log_2 M$$
$$8 \times 10^6 = 2 \times (10^6) \times \log_2 M$$
$$4 = \log_2 M$$
$$M = 16$$

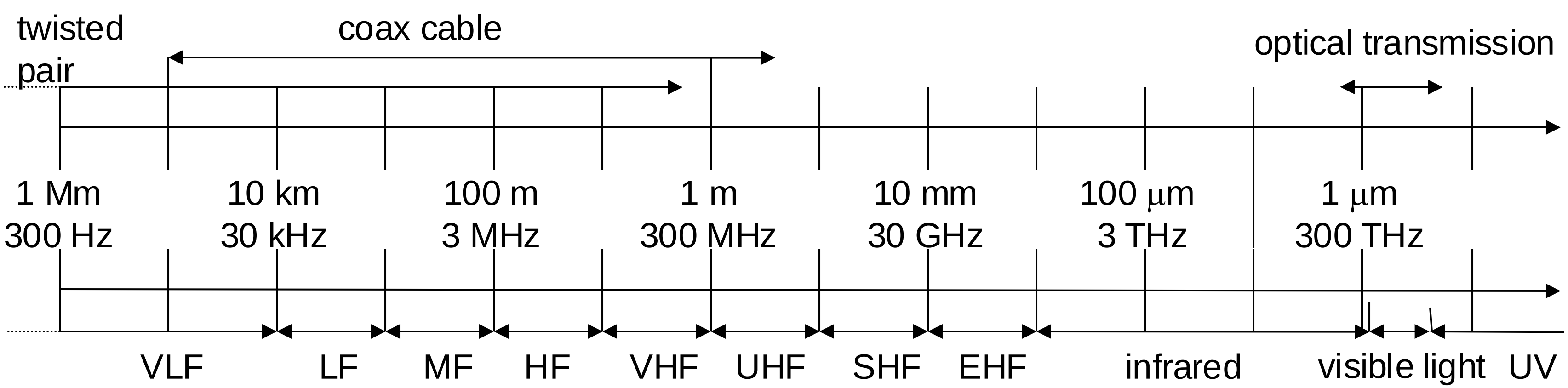
Frequencies & Regulations

Frequencies for communication

- VLF = Very Low Frequency
- LF = Low Frequency
- MF = Medium Frequency
- HF = High Frequency
- VHF = Very High Frequency

UHF = Ultra High Frequency
SHF = Super High Frequency
EHF = Extra High Frequency
UV = Ultraviolet Light

- Frequency and wave length
  - $\lambda = c/f$
  - wave length λ, speed of light $c \cong 3 \times 10^8$ m/s, frequency f



Frequencies for mobile communication

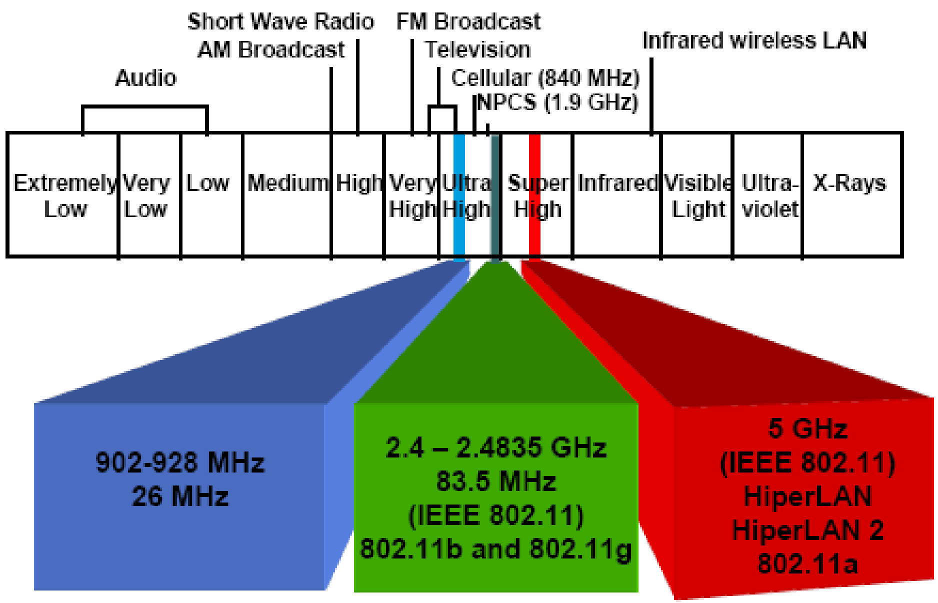
- VHF-/UHF-ranges for mobile radio
  - simple, small antenna for cars
  - deterministic propagation characteristics, reliable connections
- SHF and higher for directed radio links, satellite communication
  - small antenna, beam forming
  - large bandwidth available
- Wireless LANs use frequencies in UHF to SHF range
  - some systems planned up to EHF
  - limitations due to absorption by water and oxygen molecules (resonance frequencies)
    - weather dependent fading, signal loss caused by heavy rainfall etc.

Licensed vs. Unlicensed Spectrum

- **Licensed Spectrum:**
  - Need to buy right to use spectrum allocation in a specific geographic location from the government.
  - Prevents interference – licensee can control signal quality
  - e.g.: GSM Frequency Spectrum.

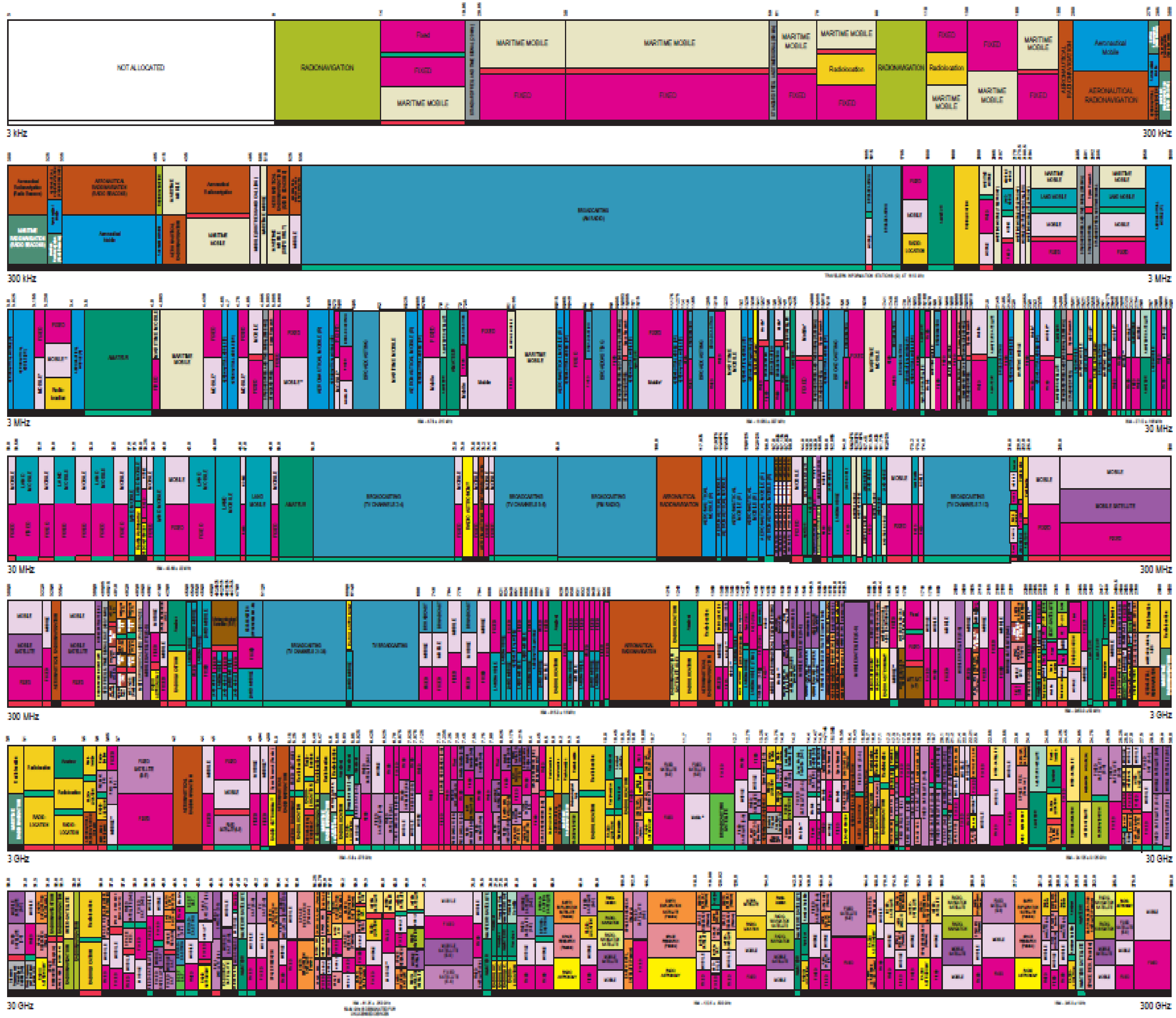
- **Unlicensed Spectrum**
  - Anyone can operate in the spectrum
  - Can have interference problems
  - e.g.: ISM-Band: Industrial, Scientific and Medical frequency band
    - 2.4 GHz
    - e.g. : Wi-Fi uses ISM band

Unlicensed Frequency Bands



UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM



RADIO SERVICES COLOR LEGEND

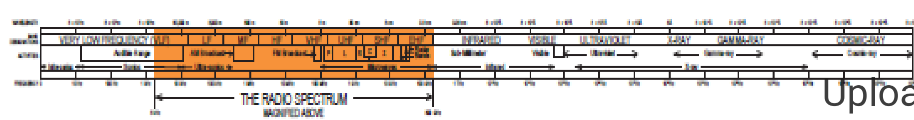
AERONAUTICAL MOBILE	INTER-SATELLITE	RADIO ASTRONOMY
AERONAUTICAL MOBILE SATELLITE	LAND MOBILE	RADIODETERMINATION SATELLITE
AERONAUTICAL RADIONAVIGATION	LAND MOBILE SATELLITE	RADIOLOCATION
AMATEUR	MARITIME MOBILE	RADIOLOCATION SATELLITE
AMATEUR SATELLITE	MARITIME MOBILE SATELLITE	RADIONAVIGATION
BROADCASTING	MARITIME RADIONAVIGATION	RADIONAVIGATION SATELLITE
BROADCASTING SATELLITE	METEOROLOGICAL AIDS	SPACE OPERATION
EARTH EXPLORATION SATELLITE	METEOROLOGICAL SATELLITE	SPACE RESEARCH
FIXED	MOBILE	STANDARD FREQUENCY AND TIME SIGNAL
FIXED SATELLITE	MOBILE SATELLITE	STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE

- GOVERNMENT EXCLUSIVE
- GOVERNMENT/NON-GOVERNMENT SHARED
- NON-GOVERNMENT EXCLUSIVE

ALLOCATION USAGE DESIGNATION

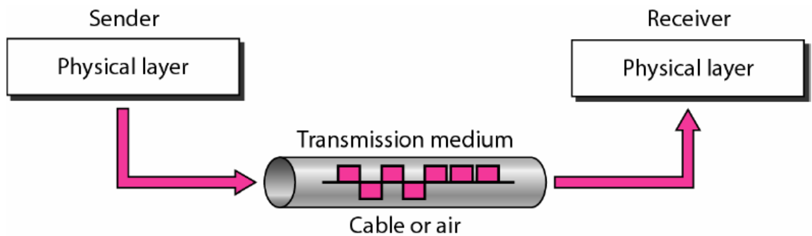
SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters



U.S. DEPARTMENT OF COMMERCE
October 2003

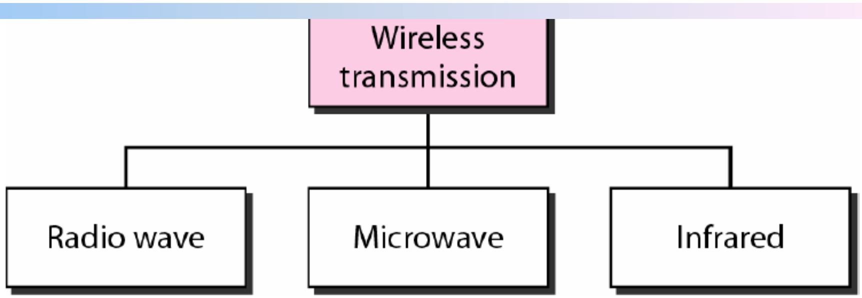
Transmission Media

- **Transmission Medium**
  - Physical path between transmitter and receiver
- **Types:**
  - **Guided Media**
    - Waves are guided along a solid medium
    - e.g., copper twisted pair, copper coaxial cable, optical fiber



  - **Unguided Media**
    - Provides means of transmission but does not guide electromagnetic signals
    - Usually referred to as wireless transmission
    - e.g., atmosphere, outer space
    - Transmission and reception are achieved by means of an antenna
    - Configurations for **wireless transmission**
      - Directional
      - Omni-directional

Transmission Media

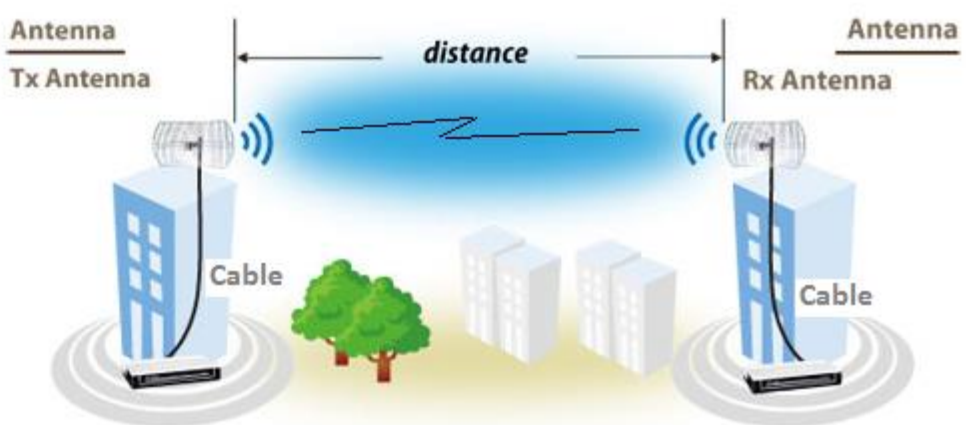


- **Microwave frequency** range
  - 1 GHz to 40 GHz
  - Directional beams possible
  - Suitable for point-to-point transmission
  - Used for satellite communications
- **Radio frequency** range
  - 30 MHz to 1 GHz
  - Suitable for omni-directional applications
- **Infrared frequency** range
  - Roughly, 3×10^{11} to 2×10^{14} Hz
  - Useful in local point-to-point applications within confined areas

Antennas

What is Antenna

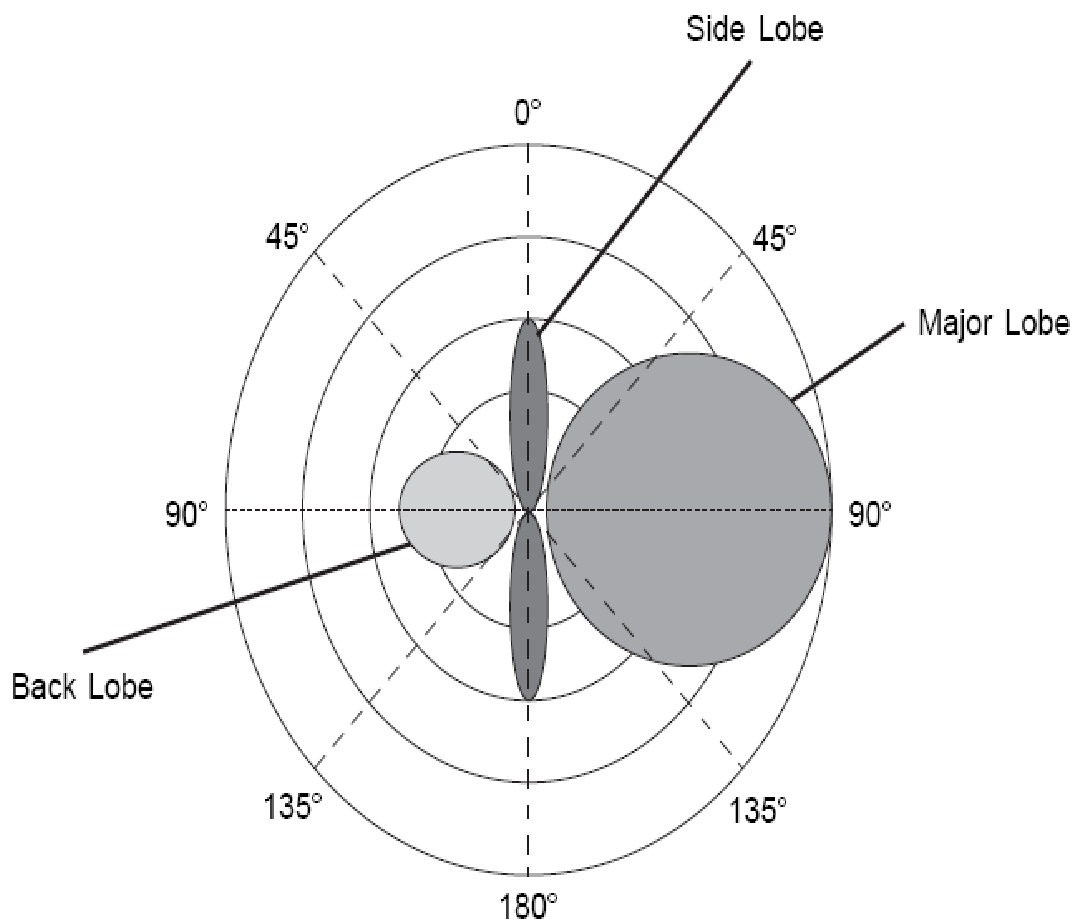
- **Antenna:** is an electrical conductor or system of conductors used either for radiating electromagnetic energy or for collecting electromagnetic energy.
  - Transmission - radiates electromagnetic energy into space
  - Reception - collects electromagnetic energy from space
- In two-way communication, the same antenna can be used for transmission and reception.



Antennas Samples

Radiation pattern of an antenna.

- The shape of the pattern describes the directionality of the antenna. The direction for maximum power is referred to as the primary beam or main lobe, whereas secondary beams are called the minor lobes
- The pattern of the antenna has two desired effects: concentration of the power in a desired direction to improve the signal strength at the receiver and weakening the power in an undesired direction to reduce interference from or to other receivers.

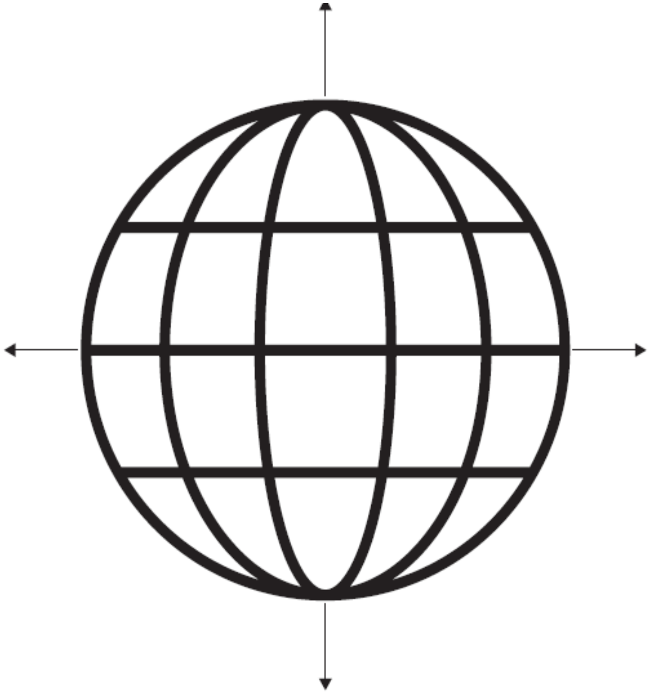


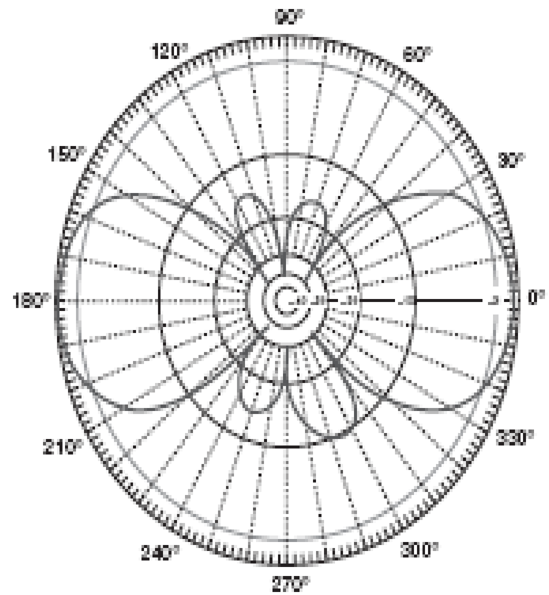
Antennas Radiation Patterns

- Along with the type of antenna there is the relative pattern of the antenna, indicating in which direction the energy emitted or received will be directed.

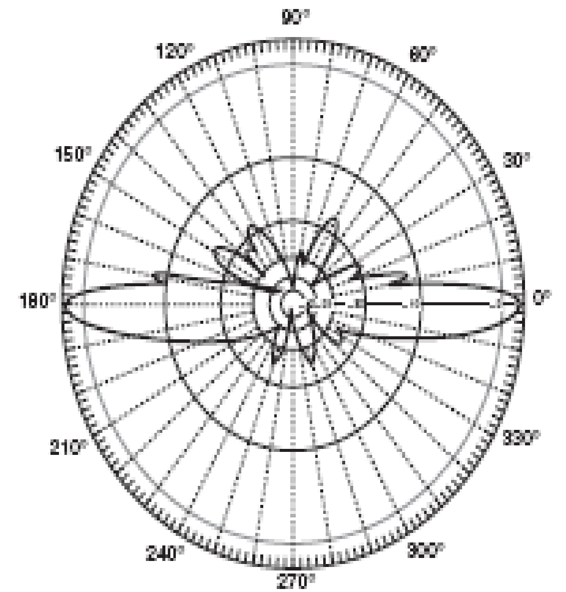
- Radiation Patterns: measurement of radiation around an antenna
  - **Isotropic radiator**: equal radiation in all directions (three dimensional) - only a theoretical reference antenna
    - The most popular type being the dipole antenna, antennas with a 360-degree horizontal propagation pattern.
    - The omnidirectional antenna is most commonly used indoors to provide coverage throughout an entire space; however, they have become more and more popular in outdoor usage for either hotspots or central antennas.

Radiation Patterns: Isotropic radiator





4 dBi

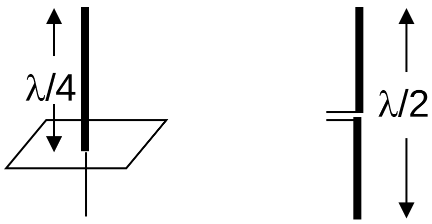


15 dBi

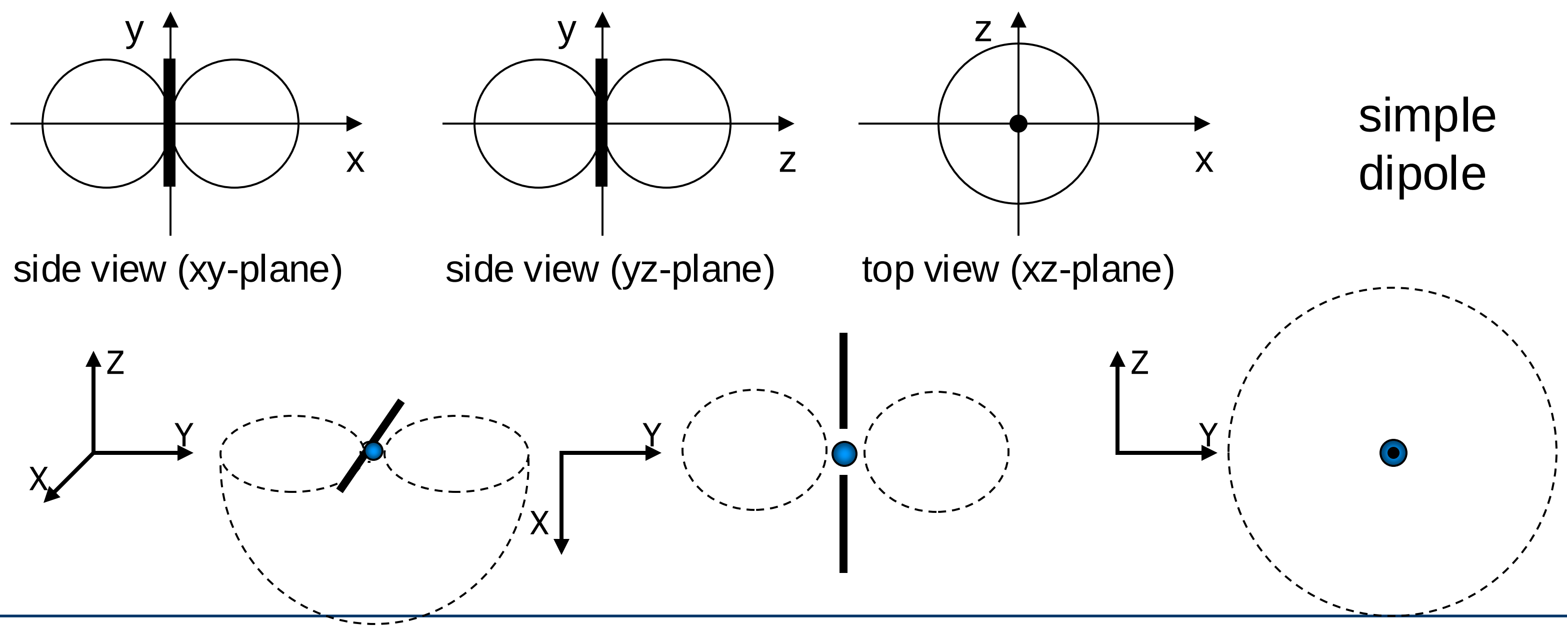
- devices directly above or below the omnidirectional antenna may have a very weak signal or even be unable to detect the signal. This is due to the primary signal being focused outwardly on a horizontal plane.

Radiation Patterns: simple dipoles

- Real antennas are not isotropic radiators but, e.g., dipoles with lengths λ/4 on car roofs or λ/2 as Hertzian dipole
  ➔ shape of antenna proportional to wavelength

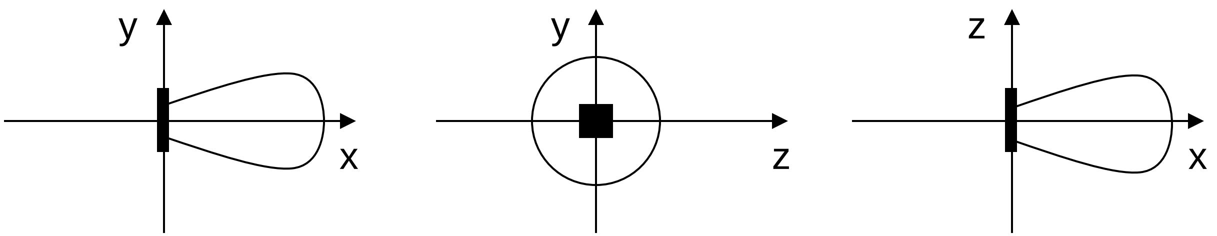


- Example: Radiation pattern of a simple Hertzian dipole



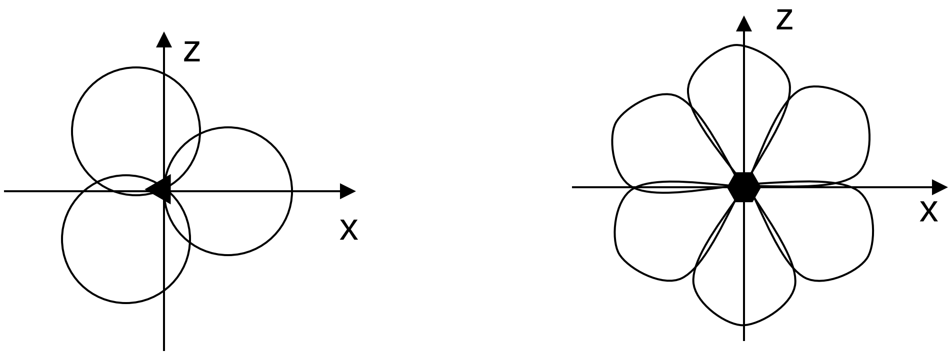
Radiation Patterns: directed and sectorized

- Often used for microwave connections or base stations for mobile phones (e.g., radio coverage of a valley)
- Semi-directional antennas are most useful for providing RF coverage down long hallways



side view (xy-plane) side view (yz-plane) top view (xz-plane)

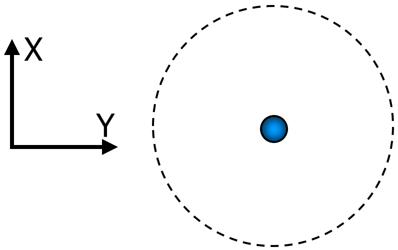
directed antenna



top view, 3 sector top view, 6 sector

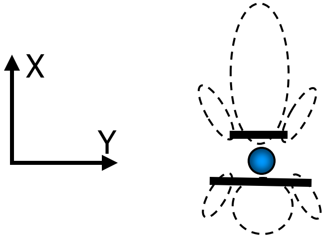
sectorized antenna

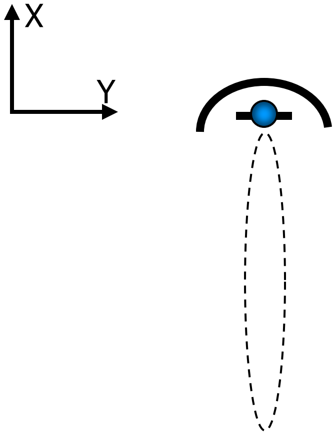
Radiation Patterns: Summery



Omni-Directional

Semi-Directional

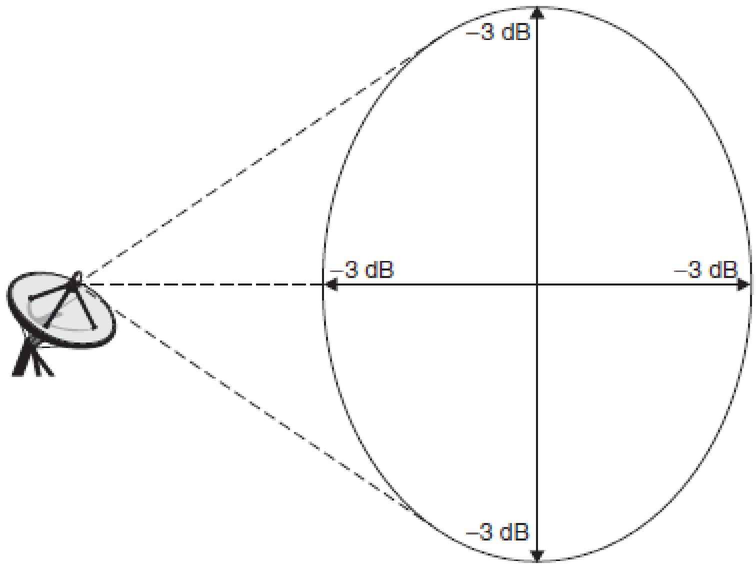


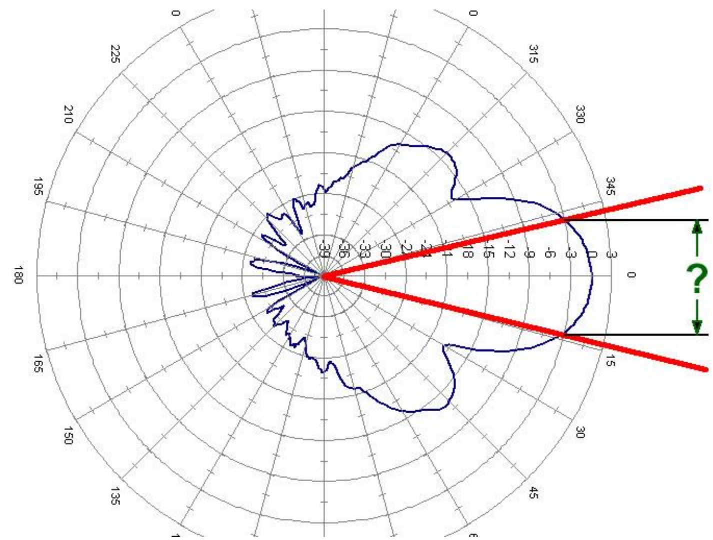


Highly-Directional

Beamwidths

- Beamwidth is the measurement of how broad or narrow the focus of the RF energy is as it propagates from the antenna along the main lobe.
  - The main lobe is the primary RF energy coming from the antenna.
- Beamwidth is measured both vertically and horizontally
- The beamwidth is a measurement taken from the center of the RF signal to the points on the vertical and horizontal axes where the signal decreases by 3 dB or half power. (or 0.707 of the voltage maximum.)





- Beamwidth measurements give us an idea of the propagation pattern of an antenna

Various Beamwidths for Antenna Types

- Beam-width – the angular separation between the two half-power points on the major lobe of one of the radiation planes of an antenna.

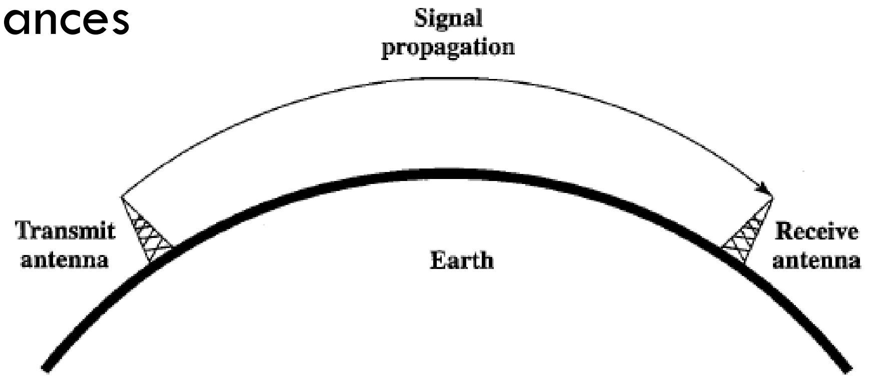
- Various Beamwidths for Antenna Types

Antenna Type	Horizontal Beamwidth	Vertical Beamwidth
Omnidirectional	360 degrees	7–80 degrees
Patch/panel	30–180 degrees	6–90 degrees
Yagi	30–78 degrees	14–64 degrees
Sector	60–180 degrees	7–17 degrees
Parabolic dish	4–25 degrees	4–21 degrees

Propagation Modes

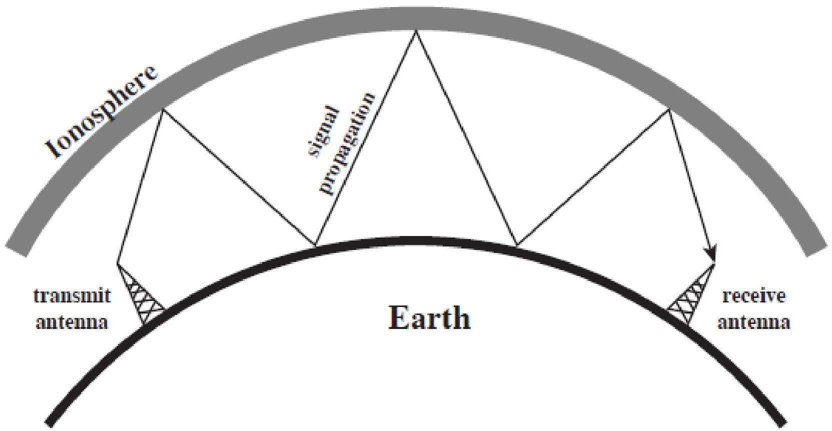
- **A signal radiated from an antenna travels along one of three routes: ground wave, sky wave, or line of sight (LOS)**
- **Ground Wave Propagation**
  - Follows the earth's curvature
  - Factors:
    - The electromagnetic wave induces a current in the earth's surface, the result of which is to slow the wavefront near the earth, causing the wavefront to tilt downward and hence follow the earth's curvature
    - Diffraction
  - Can propagate considerable distances
  - Frequencies up to 2 MHz
  - Example:
    - AM Radio

diffraction



Propagation Modes

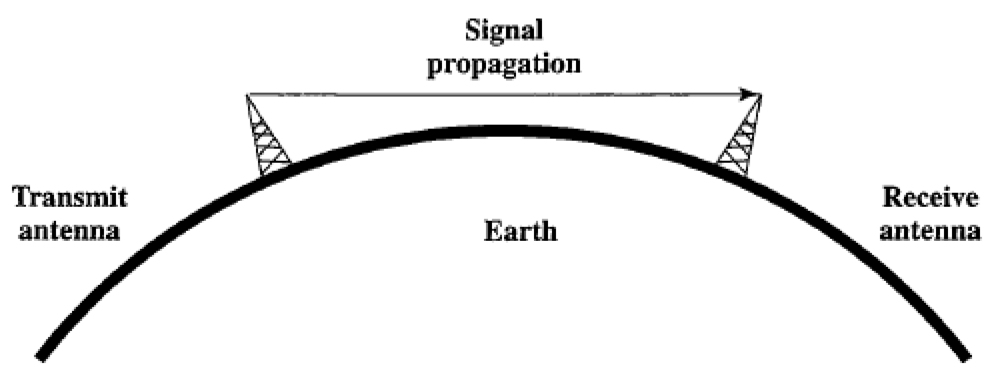
- **Sky Wave Propagation**
  - Signal is reflected from the ionized layer of atmosphere (Ionosphere) back down to earth.
  - Signal can travel a number of hops, back and forth between ionosphere and earth's surface
  - Reflection effect caused by refraction
  - Frequencies: 2 MHz to 30 MHz
  - Examples:
    - International Radio Broadcast
    - Long distance aircraft and ship navigation



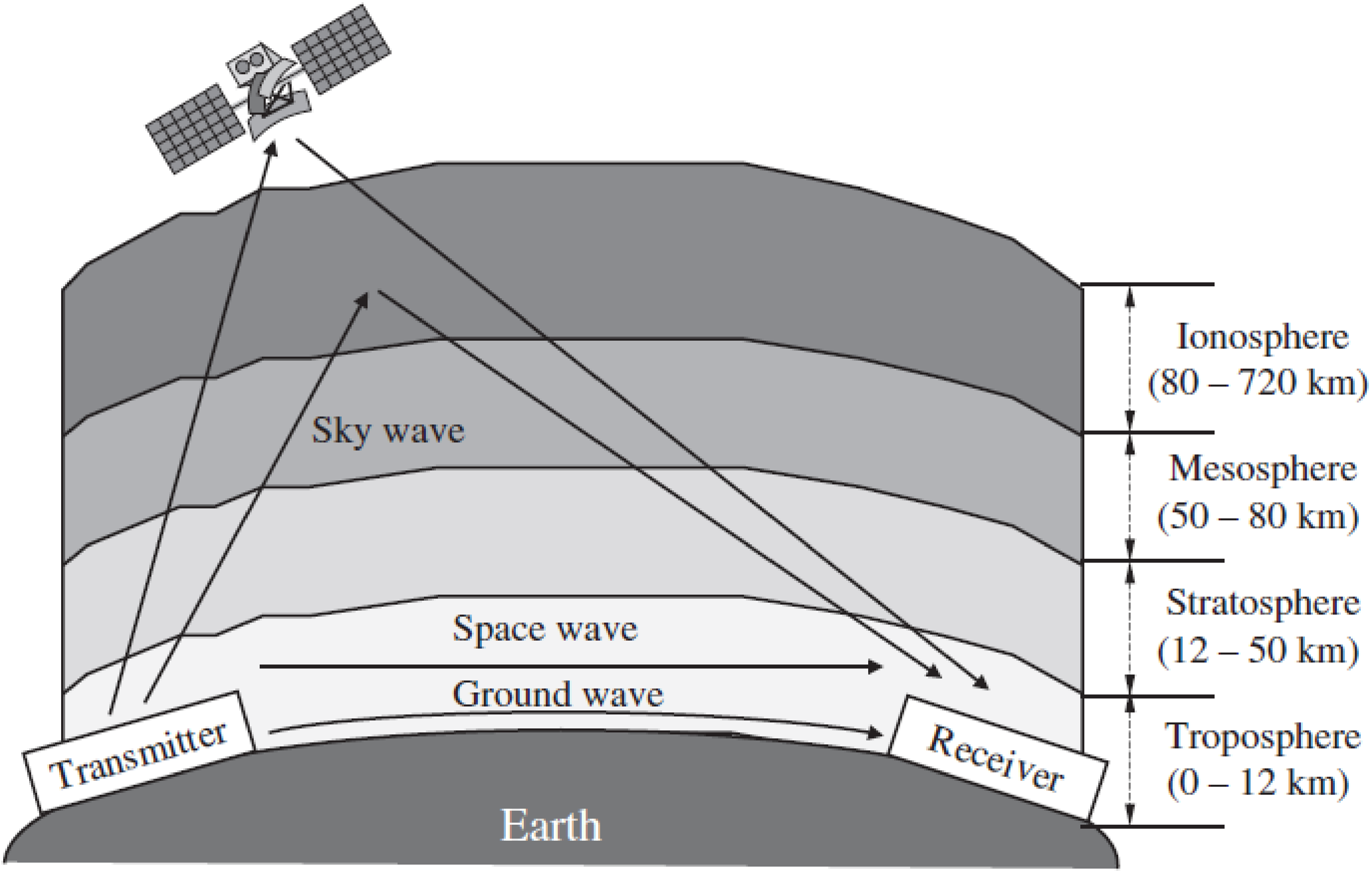
Propagation Modes

- **Line-of-Sight (LOS) Propagation**
  - Transmitting and receiving antennas must be within line-of-sight
    - Satellite communication – signal not reflected by ionosphere
    - Ground communication – antennas within ***effective*** *line-of-site* due to refraction
  - Frequencies: Above 30 MHz
  - Examples:
    - Mobile Communication
    - Satellite Communication
    - Wi-Fi, Wi-MAX ....

Note: *in practice, this mode can be used for non-line of sight communication because the signal can penetrate some obstacles and because of signal reflections.*



Propagation Modes



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

Antenna Gain

- Antenna Gain - is a measure of the ability of the antenna to **focus** radio waves in a particular direction.
  - **Antenna gain**
    - Power output, in a particular direction, compared to that produced in any direction by an isotropic antenna
  - **Active Gain**
    - Active gain is achieved by placing an amplifier in-line between the RF signal generator (such as an access point) and the propagating antenna.
  - **Effective area**
    - Related to physical size and shape of antenna

Antenna Gain

- Relationship between 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 (» 3 ´ 10^8 m/s)
  - λ = carrier wavelength

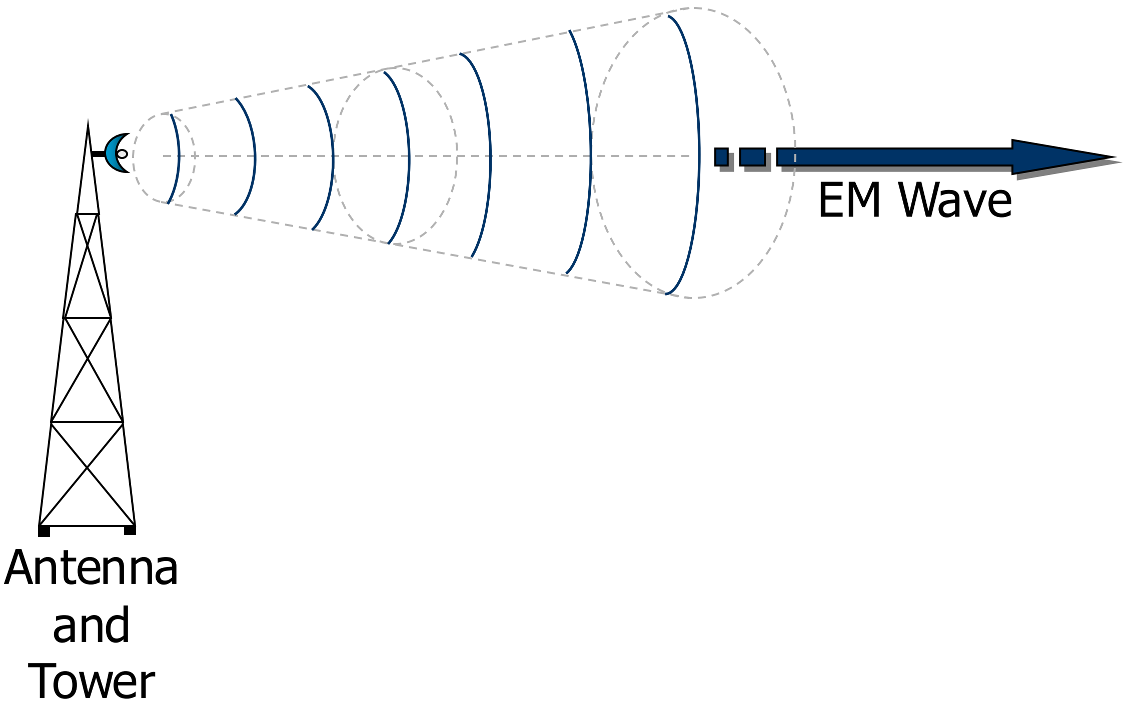
- The term dBi is used to refer to the antenna gain with respect to the isotropic antenna. The term dBd is used to refer to the antenna gain with respect to a half-wave dipole.

Attenuation

- Strength of signal falls off with distance over transmission medium
- Attenuation factors for unguided media:
  - Received signal must have sufficient strength so that circuitry in the receiver can interpret the signal
  - Signal must maintain a level sufficiently higher than noise to be received without error
  - Attenuation is greater at higher frequencies, causing distortion
- Signal with higher frequencies have shorter wavelengths and therefore shorter optimum antenna sizes. The result is that the smaller antenna has a greater difficulty gathering–sufficient RF energy because of its smaller receiving surface.
  - The receiver is the actual locus of the problem rather than the attenuated signal strength.

Free Space Path Loss

- Free Space Path Loss – Loss caused by an EM wave as it propagates in a straight path through a vacuum with no other losses.



Free Space Loss

- 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 (» 3 ´ 10 8 m/s)

where d and λ are in the same units (e.g., meters)

Free Space Loss

- Free space loss equation can be recast:

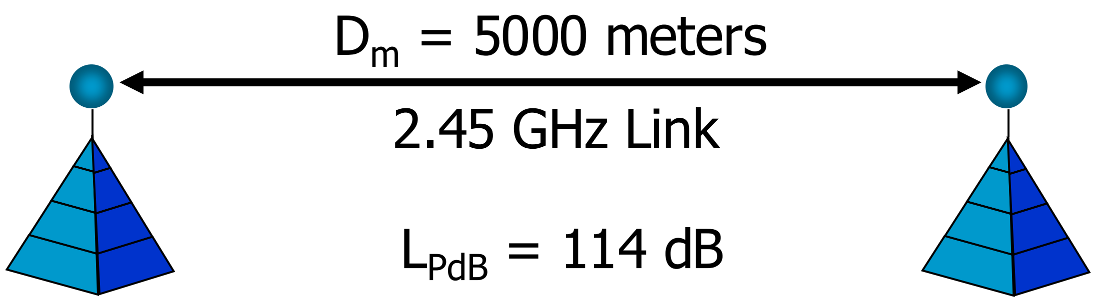
$$L_{dB} = 10\log\frac{P_t}{P_r} = 20\log\left(\frac{4\pi d}{\lambda}\right)$$

$$= -20\log(\lambda) + 20\log(d) + 21.98\text{ dB}$$

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

Free Space Path Loss

$$\text{Path Loss}_{dB} = L_{PdB} = 20 \log_{10}\left(\frac{4\pi D_m}{\lambda_m}\right)$$



20log ((4x3.14x5000)/(300000000/2450000000) = 114 dB

Free Space Loss

- Free space loss accounting for gain of other antennas

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

- G_t = gain of transmitting antenna
- G_r = gain of receiving antenna
- A_t = effective area of transmitting antenna
- A_r = effective area of receiving antenna

Free Space Loss

- Free space loss accounting for gain of other antennas can be recast as

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

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

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

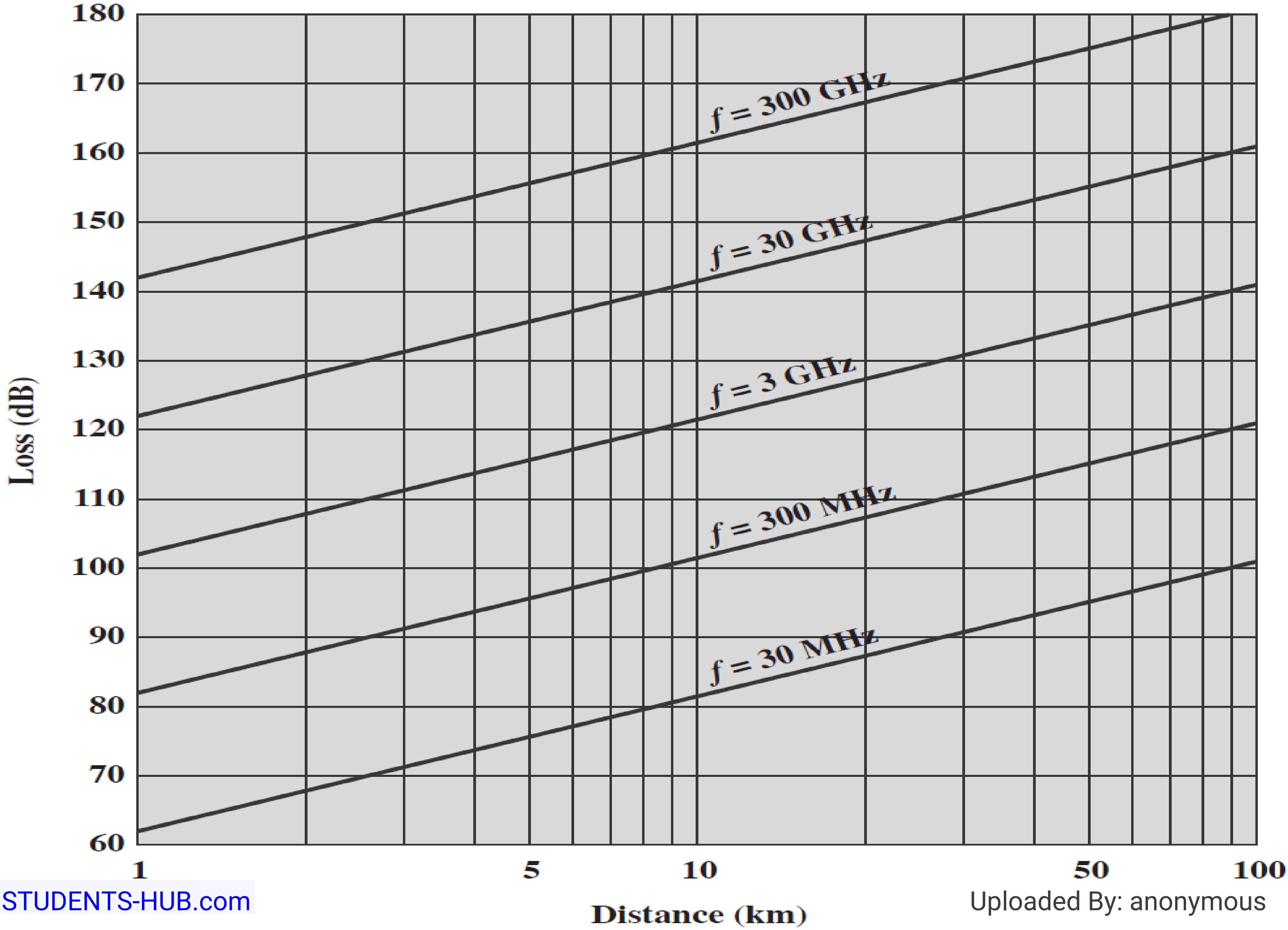
Free Space Path Loss Table

Path Attenuation

Distance Meters	Loss dB	Distance Meters	Loss dB
100	80.3	1000	100
200	86.3	2000	106
500	94.3	5000	114

f = 2.45 GHz

Free Space Path Loss Graph



Path Loss with other losses

- If other losses are also present, such as atmospheric absorption or ohm losses of the waveguides leading to antennas, then:

$$\frac{P_R}{P_T} = \left[\frac{\lambda}{4\pi d}\right]^2 \cdot \frac{G_T G_R}{L_0}$$

$$P_R = 20\log\left[\frac{\lambda}{4\pi d}\right] + P_T + G_T + G_R - L_0 \text{ dB}$$

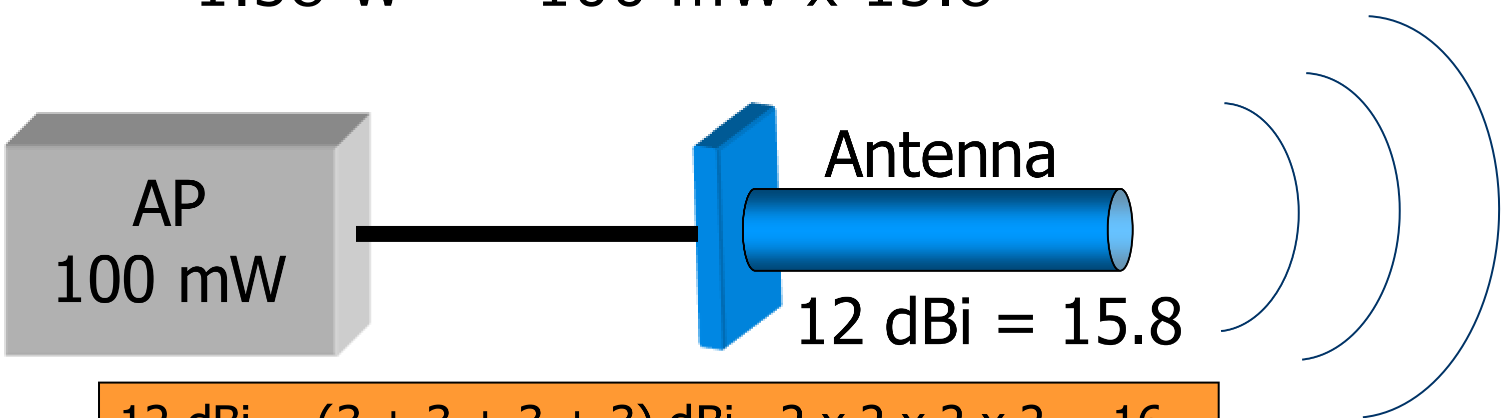
L_0 is the loss factor for additional losses.

EIRP

- Effective Isotropic Radiated Power (EIRP) is a figure of merit for the net radiated power in a given direction.
  - a quantity used to characterize the performance of a device relative to other devices of the same type. It is often used as a marketing tool to convince consumers to choose a particular brand.
- EIRP - The product of the power supplied to the antenna and the antenna gain in a given direction relative to a reference isotropic antenna.

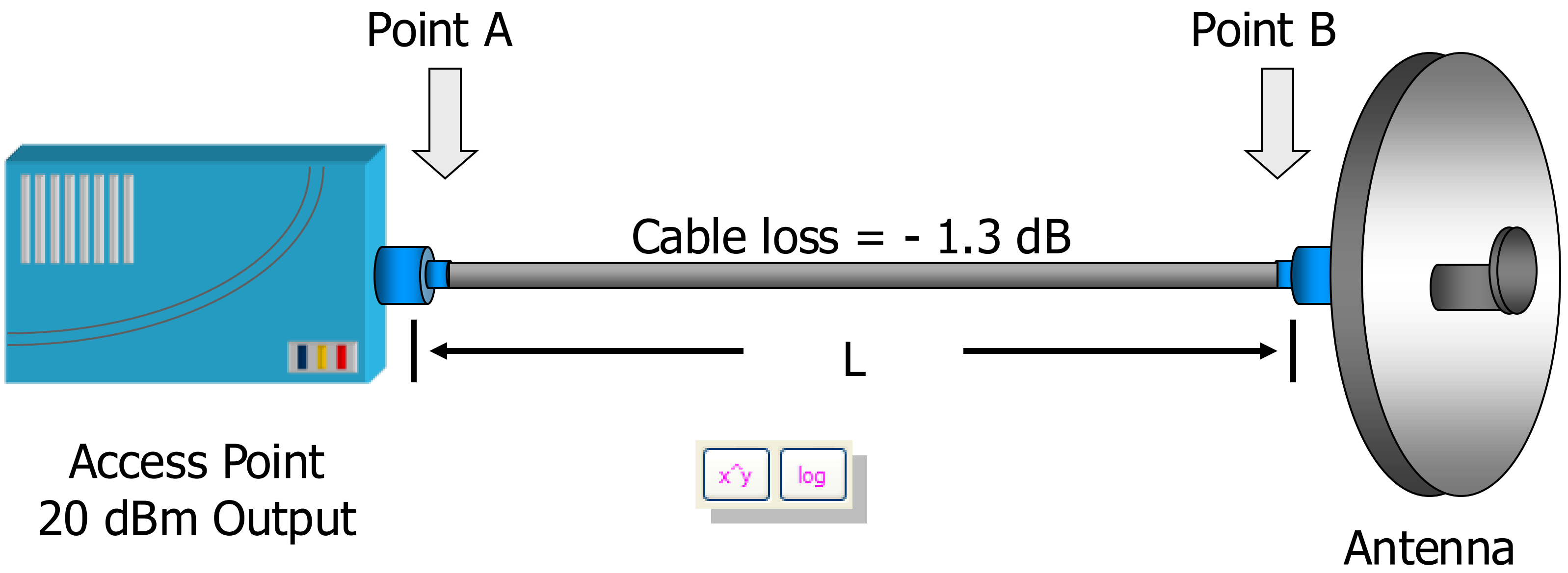
$$\text{EIRP} = P_{in} \times G_i$$

$$1.58\text{ W} = 100\text{ mW} \times 15.8$$



12 dBi = (3 + 3 + 3 + 3) dBi, 2 x 2 x 2 x 2 = 16

dB Sample Problem

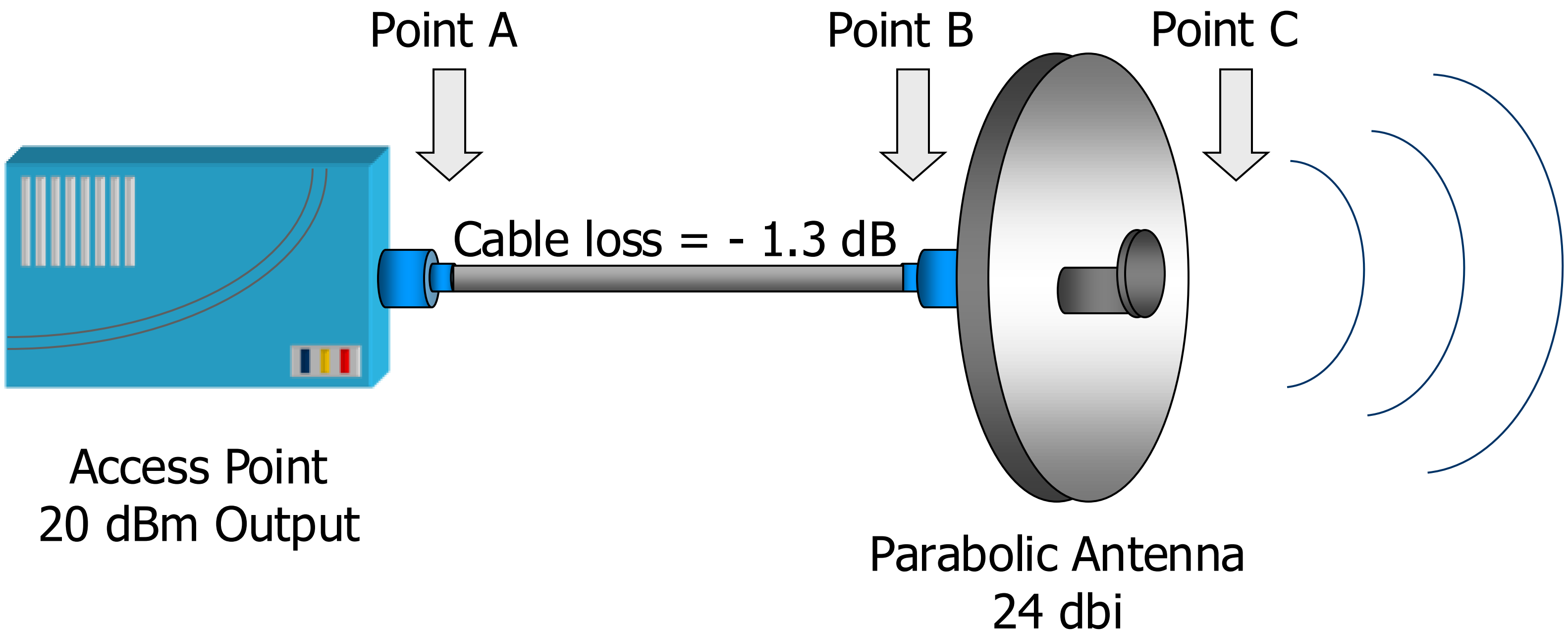


Power at point A is 20 dBm = 100 mW

Power at point B is 20 dBm – 1.3 dB = 18.7 dBm = 74.1 mW

Windows calculator:
Input 10 press x^y
input 1.87 and press
Enter Key = 74.13

EIRP



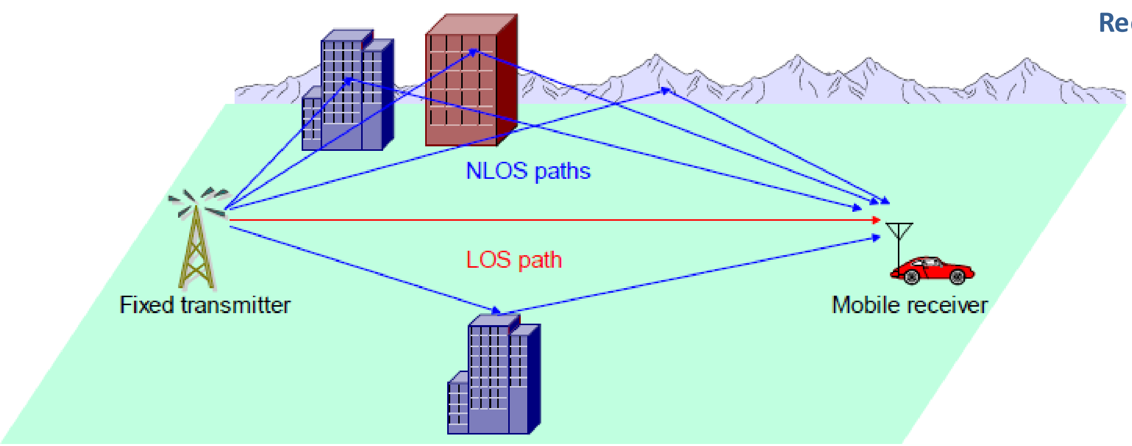
Power at point A is 20 dBm = 100 mW

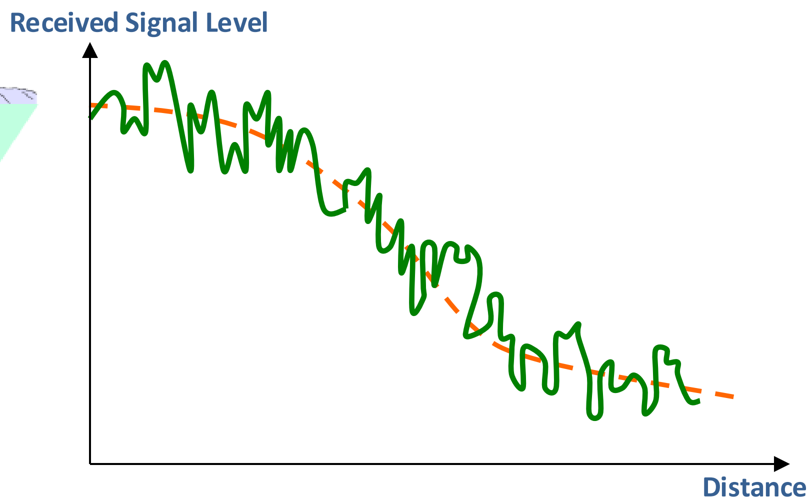
Power at point B is 20 dBm – 1.3 dB = 18.7 dBm = 74.1 mW

EIRP at point C is 74.1 mW x 251 = 18.6 W

Fading in the Mobile Environment

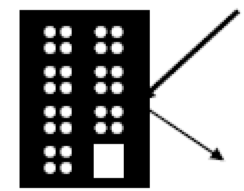
- **Fading: time variation of received signal power caused by changes in the transmission medium or path(s).**
  - *In a fixed environment*, fading is affected by changes in atmospheric conditions, such as rainfall.
  - *In a mobile environment*, where one of the two antennas is moving relative to the other, the relative location of various obstacles changes over time, creating complex transmission effects.
  - The most challenging technical problem facing communications Engineers





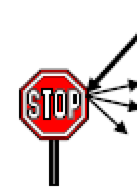
Multipath Propagation

- A phenomenon that results in radio signals reaching the receiving antenna by two or more paths
- Causes:
  - **Reflection -** occurs when signal encounters a surface that is large relative to the wavelength of the signal.
    - e.g.: the surface of the Earth, buildings, walls, etc.
  - **Diffraction** - occurs at the edge of an impenetrable body that is large compared to wavelength of radio wave.
    - Waves propagate in different directions with the edge as the source
  - **Scattering** - occurs when incoming signal hits an object whose size in the order of the wavelength of the signal or less.
    - An incoming signal is scattered into several weaker outgoing signals.
    - e.g.: traffic signs, lamp posts



Reflection

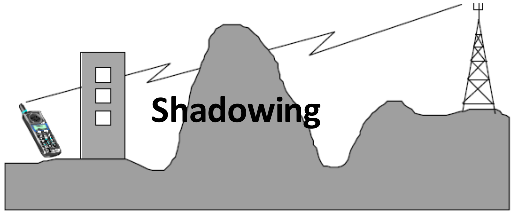
diffraction

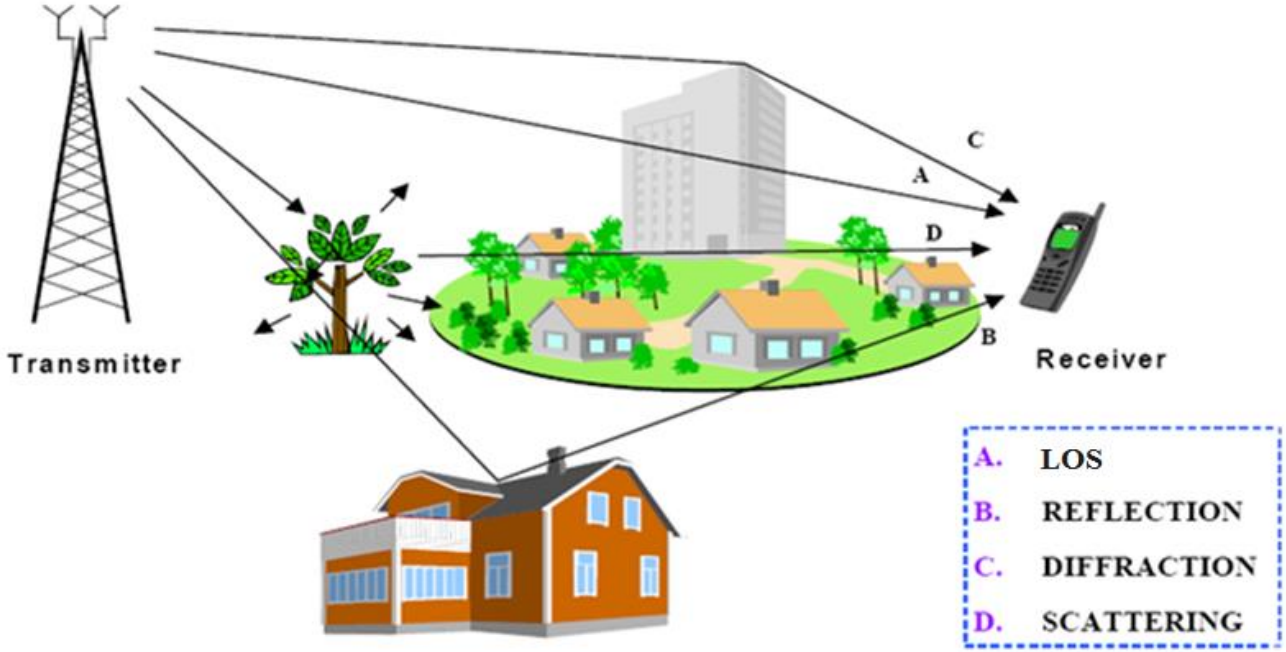


scattering

Multipath Propagation

- **Shadowing** - occurs when there are physical obstacles including hills and buildings between the transmitter and receiver. The obstacles create a shadowing effect which can decrease the received signal strength.





Effects of Multipath Propagation

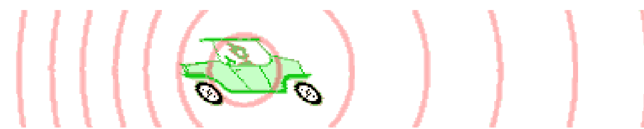
- **Positive:**
  - Helps receive signals even without line of sight.
  - With smart Antennas, can substantially increase the usable received power
- **Negative:**
  - Multiple copies of a signal may arrive at different phases
    - If phases add destructively, the signal level relative to noise declines, making detection more difficult and increases errors.
  - 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

Antenna Diversity

- **Types of Diversity**
  - **Space diversity**: Two antennas separated physically by a short distance **d** can provide two signals with low correlation between their fades.
  - **Frequency diversity**: Signals received on two frequencies, separated by coherence bandwidth are uncorrelated.
  - **Time diversity**
  - **Polarization diversity**
  - **Angle diversity**

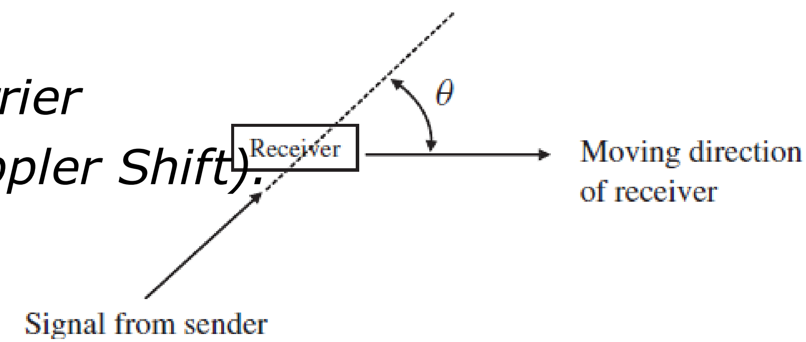
Doppler Shift

- A frequency variation of the received signal due to the relative movement of the receiver with respect to the transmitter.
  - When they are moving toward each other, the frequency of the received signal is higher than the source.
  - When they are moving away from each other, the received frequency decreases.
  - Thus, the frequency of the received signal is



$$f_r = f_c - f_d$$

- ***f_c* is the frequency of source carrier**
- ***f_d* is the Doppler frequency (Doppler Shift).**

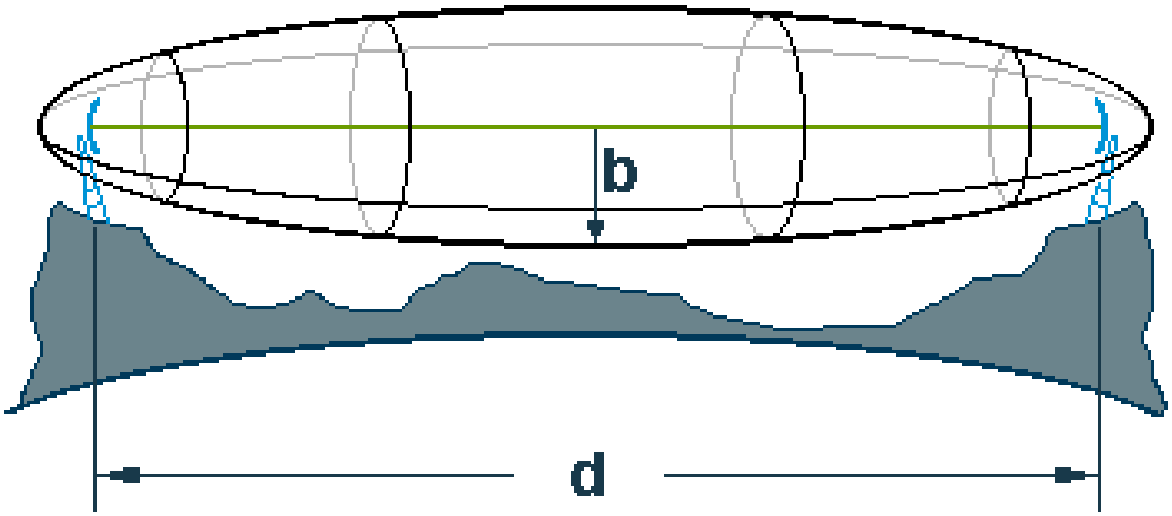


$$f_d = \frac{v}{\lambda} \cos\theta$$

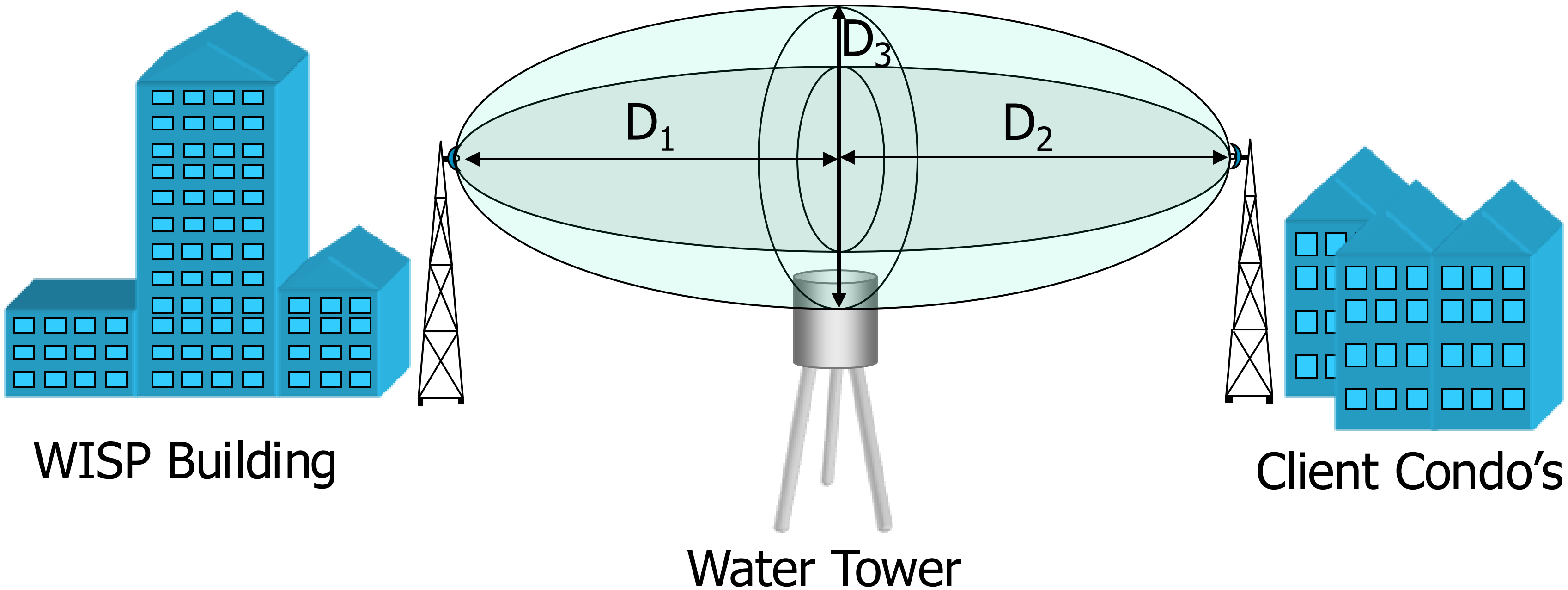
- v is the moving speed, λ is the wavelength of carrier,
- $\cos\theta$ represents the velocity component of the receiver in the direction of the sender.

Fresnel Zone

- Fresnel Zone - one of a (theoretically infinite) number of a concentric ellipsoids of revolution centered around the LOS path. (Pronouced frA-nel)
- Provides a technique to determine the required clearance between the signal and any obstacles along the transmission path.

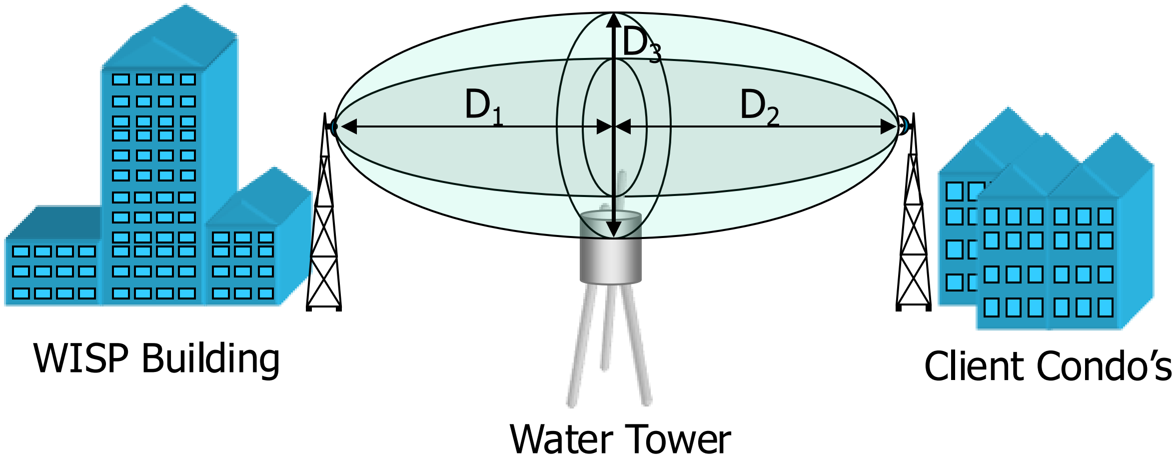


Fresnel Zone



$$D_3 = 72.1\sqrt{\frac{(D_1)\,(D_2)}{f\,(D_1 + D_2)}}$$

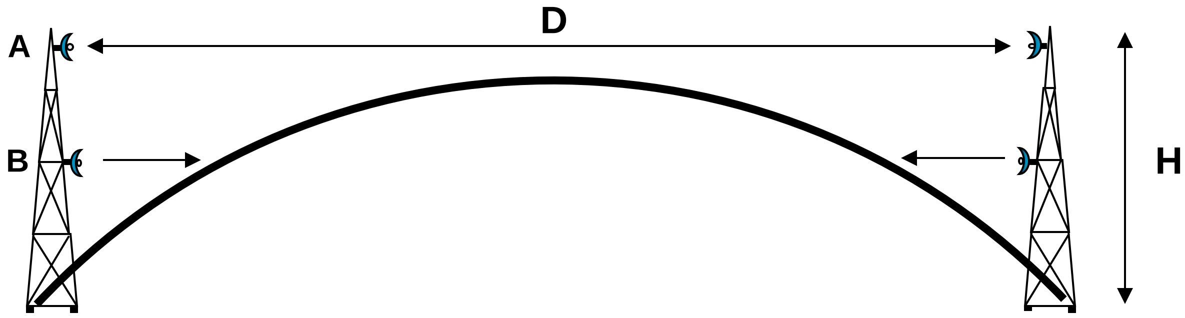
Fresnel Zone calculations



$$D_3 = 72.1 \sqrt{\frac{(D_1)\,(D_2)}{f\,(D_1 + D_2)}}$$

- To compute the diameter in feet of this 60% zone use the equation in the slide
  - where the D's represent the LOS distance in mile and the f is the frequency of interest in GHz.
- For example using a frequency of 2.4 GHz and $D_1 = D_2 = 2$ miles:
  - 1^{st} Fresnel Zone Diameter = 46.5 ft.
  - Finally multiple this Diameter by 60%. Obstruction Diameter = 0.6 x 46.5 ft. = 27.9 ft.
  - Once this is plotted to scale on the drawing it can be seen that the water tower is not in this 60% area.

Earth Curvature



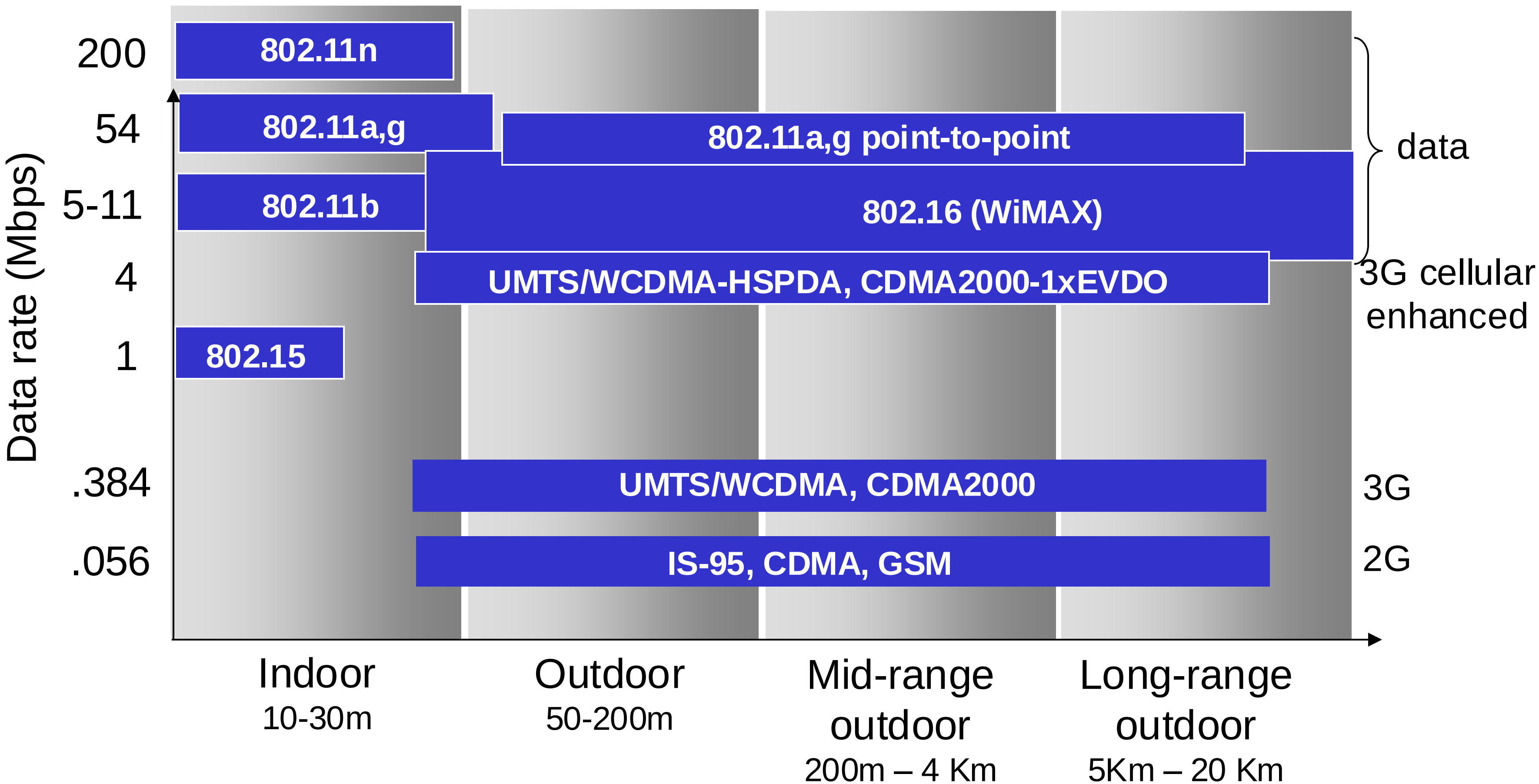
$$H = 43.3\sqrt{\frac{D}{4F}} + \frac{D^2}{8}$$

H → Feet

D → Miles

F → GHz

Characteristics of selected wireless link standards



Example link budget calculation

Let’s estimate the feasibility of a 5 km link, with one access point and one client radio.

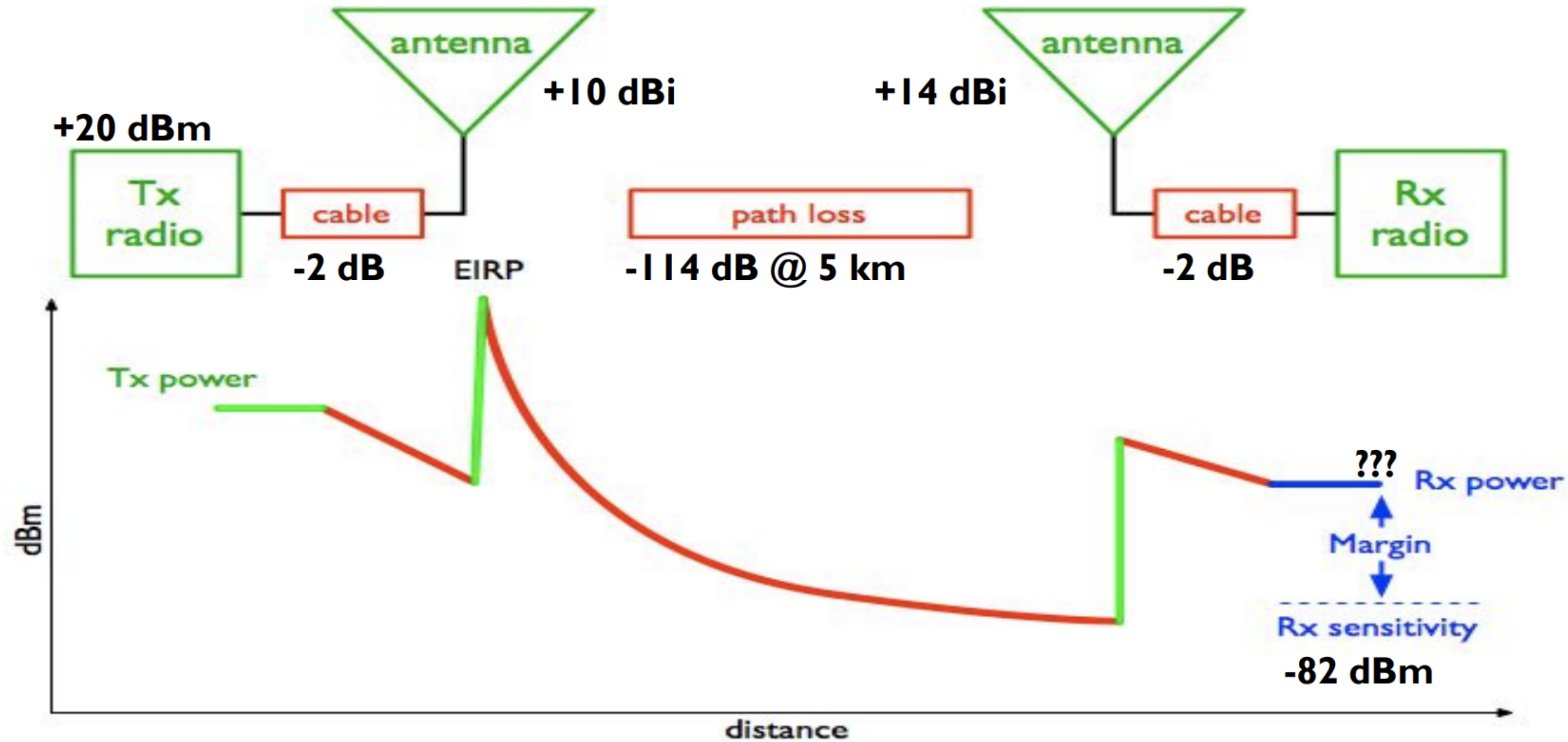
The access point is connected to an antenna with 10 dBi gain, with a transmitting power of 20 dBm and a receive sensitivity of -89 dBm.

The client is connected to an antenna with 14 dBi gain, with a transmitting power of 15 dBm and a receive sensitivity of -82 dBm.

The cables in both systems are short, with a loss of 2dB at each side at the 2.4 GHz frequency of operation.

Example link budget calculation

Link budget: AP to Client link

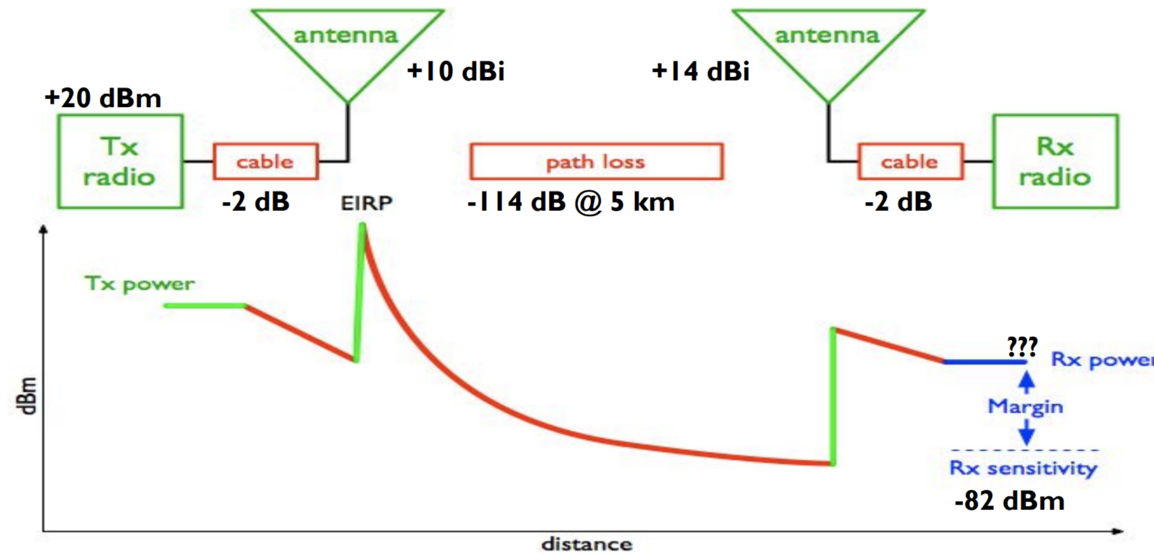


Source: ICTP - Ermanno Pietrosemoli and Marco Zennaro

Example link budget calculation

Link budget: AP to Client link

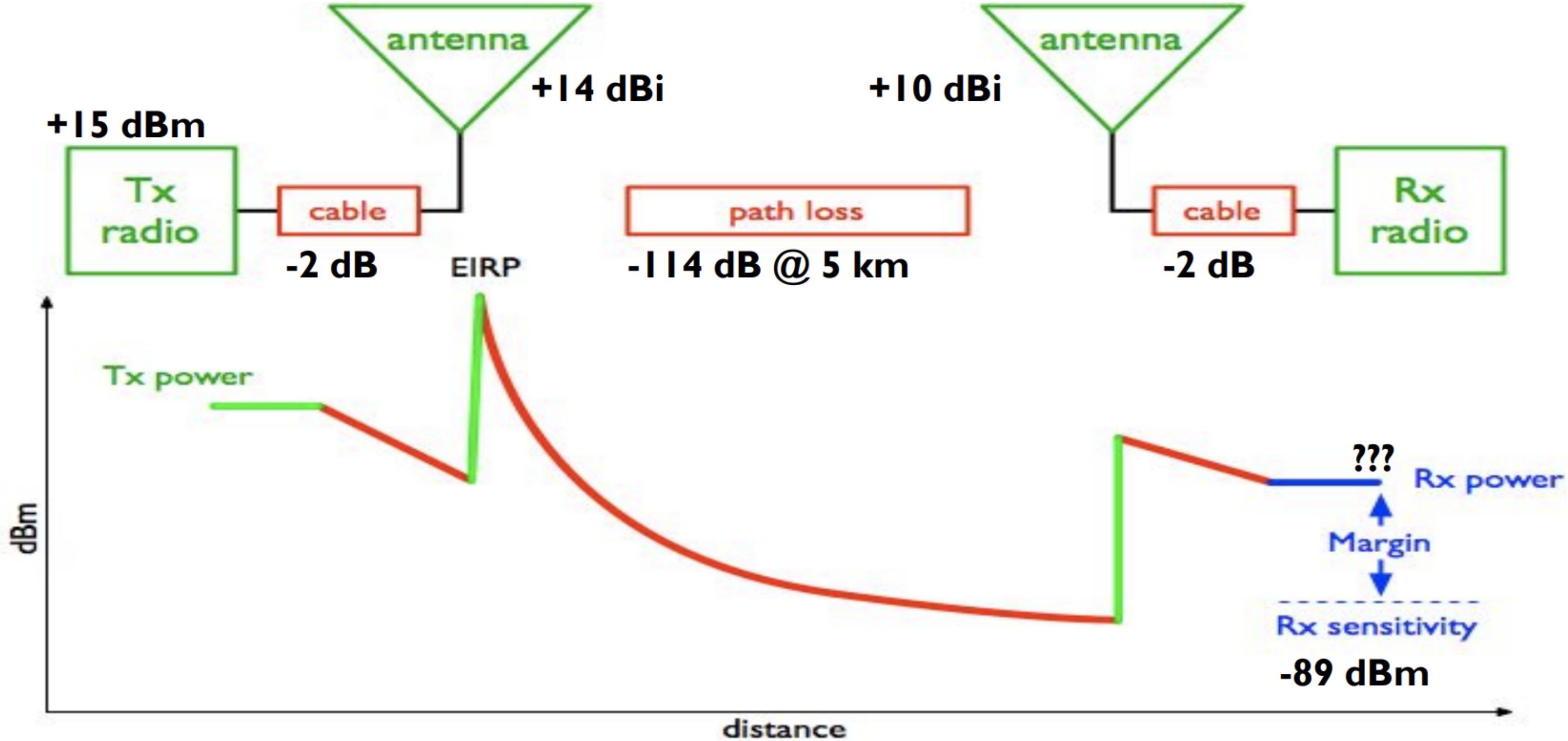
20 dBm	(TX Power AP)
+ 10 dBi	(AP Antenna Gain)
- 2 dB	(AP Cable Losses)
-114 dB	(free space loss @5 km)
+ 14 dBi	(Client Antenna Gain)
- 2 dB	(Client Cable Losses)
-74 dBm	(expected received signal level)
-(-82 dBm)	(sensitivity of Client)
8 dB	(link margin)



Source: ICTP - Ermanno Pietrosemoli and Marco Zennaro

Example link budget calculation

Opposite direction: Client to AP



Source: ICTP - Ermanno Pietrosemoli and Marco Zennaro

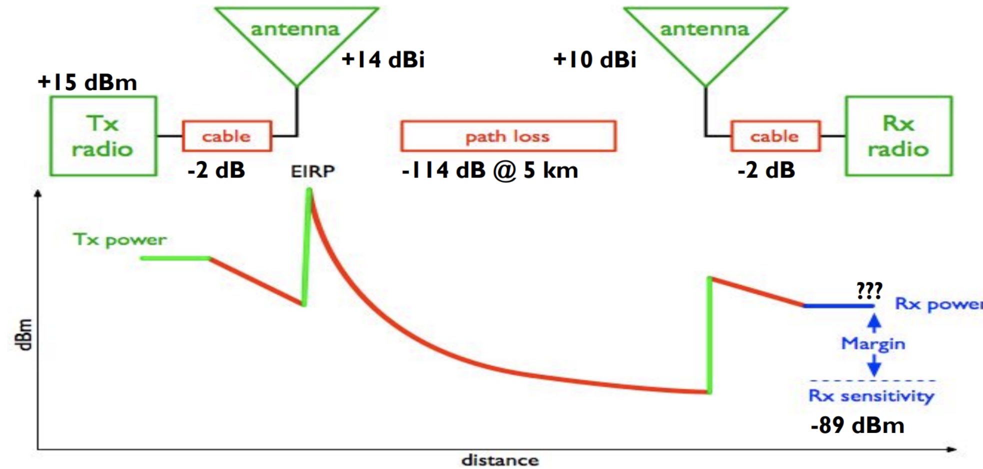
Example link budget calculation

Opposite direction: Client to AP

15 dBm (Client TX Power)
- 2 dB (Client Cable Losses)
+ 14 dBi (Client Antenna Gain)
-114 dB (free space loss @5 km)
+ 10 dBi (AP Antenna Gain)
- 2 dB (AP Cable Losses)

\- 79 dBm (expected received signal level)
-(-89 dBm) (sensitivity of AP)

10 dB (link margin)



Source: ICTP - Ermanno Pietrosemoli and Marco Zennaro

Example link budget calculation

By combining all the factors, we can develop a relation that allows us to calculate the received power (<u>just before the receiver detection circuit</u>):

$$P_r = \frac{P_t G_t G_r A_r}{L_p L_f L_o F_{margin}}$$

- P_t: *transmitted power*
- G_t: *antenna gain at transmitter*
- G_r: *antenna gain at reciver*
- A_r: gain of receiver amplifier
- L_p path losses
- L_f antenna feed line loss
- L_0 other losses
- F_{margin}: fade margin

Receiver Thermal Noise

Receiver thermal noise is generated due to random noise inherent within a receiver's electronics. This increases with temperature. We account for this thermal noise effect with the following:

$$N = kTB_w$$

- k: Boltzmann's constant (1.38×10^{-23} W/Kelvin-Hz)
- T: temperature (or noise temperature) in Kelvin
- B_w: receiver bandwidth(Hz).

Spectral noise density, N_0, is the ratio of thermal noise to receiver bandwidth

$$N_o = \frac{N}{B_W} = kT$$

Quality of the components used in the receiver

- There is an effect on SNR due to the quality of the components used in the receiver's amplifiers, local oscillators (LOs), mixers, etc.
- The most basic description of a component's quality is its noise figure, N_f, which is the ratio of the SNR at the input of the device versus the SNR at its out- put.
- The overall composite effect of several amplifiers' noise figures is cumulative, and can be obtained as:

$$N_{f,total} = N_{f1} + \frac{(N_{f2}-1)}{G_1} + \frac{(N_{f3}-1)}{G_1 G_2} + \ldots$$

N_{fk} is the noise figure in stage *k*

G_k gain of the *k*th stage.

$\frac{E_b}{N_o}$ at Detector Calculation

By combining all the factors, we can develop a relation that allows us to calculate the $\frac{E_b}{N_o}$ at detector:

$$\left(\frac{E_b}{N_o}\right)_{at\ detector} = \frac{P_r}{kTN_{f,total}R}$$

$$= \frac{1}{kTN_{f,total}R} \times \frac{P_t G_t G_r A_r}{L_p L_f L_o F_{margin}}$$

- $\left(\frac{E_b}{N_o}\right)_{at\ detector}$ *: ratio of energy per bit to spectral noise density at detector*
- P_r*: received power*

- *: total noise figure*
- *R: data rate*

Overall Link Margin Calculation

By combining all the factors, we can develop a relation that allows us to calculate the overall link margin:

$$M = \frac{P_r}{kTN_{f,total}R\left(\frac{E_b}{N_o}\right)_{required}}$$

$$= \frac{1}{kTN_{f,total}R\left(\frac{E_b}{N_o}\right)_{required}} \times \frac{P_t G_t G_r A_r}{L_p L_f L_o F_{margin}}$$

- $\left(\frac{E_b}{N_o}\right)_{required}$ *: required ratio of energy per bit to spectral noise density at detector*

Example transmitted power calculation

Given a flat rural environment with a path loss of 140 dB, a frequency of 900 MHz, 8dB transmit antenna gain and 0dB receive antenna gain, data rate of 9.6kbps, 12dB in antenna feed line loss, 20dB in other losses, a fade margin of 8dB, a required Eb/N0 of 10dB, receiver amplifier gain of 24dB, noise figure total of 6dB, and a noise temperature of 290K, find the total transmit power required of the transmitter in watts for a link margin of 8 dB.

$$k = 10\log(1.38 \times 10^{-23}) = -228.6\,\text{dBW}$$

$L_p = 140\,\text{dB}$; $A_g = 24\,\text{dB}$; $N_f = 6\,\text{dB}$; $F_{\text{margin}} = 8\,\text{dB}$; $G_t = 8\,\text{dB}$; $G_r = 0\,\text{dB}$;
$L_0 = 20\,\text{dB}$; $L_{\text{feed}} = 12\,\text{dB}$; $T = 24.6\,\text{dB}$; $R = 39.8\,\text{dB}$; $(E_b/N_0)_{\text{reqd}} = 10\,\text{dB}$;
and $\text{M} = 8\,\text{dB}$

From Equation (3.54)

$$P_t = M - G_t - G_r - A_g + N_{f,\,\text{total}} + T + k + L_p + L_f + L_0 + F_{\text{margin}} + R + (E_b/N_0)_{\text{reqd}}$$

$$P_t = 8 - 8 - 0 - 24 + 6 + (24.6 - 228.6) + 140 + 12 + 20 + 8 + 39.8 + 10$$

$$= 7.8\,\text{dBW}$$

$$\therefore P_t = 10^{0.78} \approx 6\,\text{W}$$

Received power under non-line-of-sight

The received power under non-line-of-sight propagation conditions can be written as:

$$\Pr(d) = P(d_o)\left(\frac{d_o}{d}\right)^{\gamma}$$

Or

$$P_{r,\,dB}(d) = 10\log\big(P(d_o)\big) + \gamma 10\log\left(\frac{d_o}{d}\right)$$

γ: path loss exponent, varying from 2 (free-space) to 5 (urban environment)

$P_{0:}$ power at reference distance d_0

Pr(d): power received at distance d

Received power under non-line-of-sight

- The accuracy of Power received can be improved by accounting for a random shadow effect caused by obstructions such as buildings or mountains.

- Shadow effect is described by a zero-mean Gaussian random variable, X_σ, with standard deviation, $\boldsymbol{\sigma}$ in (dB).

$$\mathrm{P}_{\mathrm{r},\,\mathrm{d}B}(d) = 10\log\big(P(d_o)\big) + \gamma 10\log\left(\frac{d_o}{d}\right) + X_\sigma$$

Example: received power under non-line-of-sight

Calculate the received power at a distance of 3km from the transmitter if the path-loss exponent is 4. Assume the transmitting power of 4 W at 1800 MHz, a shadow effect of 10.5 dB, and the power at reference distance (d_0 = 100 m) of 32 dBm.

$$P_r(d_0) = 32\text{ dBm} - 30 = 2\text{ dB}$$

$$P_t = \ 6\text{ dB}$$

$$P_r(d) = P_r(d_0) - 10n\log_{10}(d/d_0) + X_\sigma$$

$$P_r(3000) = 2 - 10(4)\log_{10}\left(\frac{3000}{100}\right) + 10.5$$

$$P_r(3000) = -46.58\text{ dB}$$

$$\text{Path Loss} = P_t - P_r$$

$$\text{Path Loss} = 6 - (-46.58)$$

$$\text{Path Loss} = 6 + 46.58 = 52.58\text{ dB}$$

Example: received power under non-line-of-sight

A wireless signal experiences path loss according to a log-normal shadowing model. The received power at a reference distance d_0=100 meter is given as 32 dBm. The path-loss exponent is 3.5, and the transmitted power is 5 W at 900 MHz. The shadowing effect follows a Gaussian distribution with a standard deviation of 6 dB. Calculate the probability that the received power at d = 2 km is greater than -20 dBm using a Gaussian table.

$$P_r(d_0)(\text{dB}) = 32 - 30 = 2\ \text{dB}$$

$$P_{th}(\text{dB}) = -20 - 30 = -50\ \text{dB}$$

$$P_r(d) = P_r(d_0) - 10n\log_{10}(d/d_0) + X_\sigma$$

$$P_r(2000) = 2 - 10(3.5)\log_{10}\left(\frac{2000}{100}\right)$$

$$P_r(2000) = 2 - 10(3.5)\log_{10}(20)$$

$$P_r(2000) = -43.54\ \text{dB}$$

$$P(P_r > -50) = P\left(Z > \frac{-50-(-43.54)}{6}\right)$$

$$P(P_r > -50) = P\left(Z > \frac{-6.46}{6}\right)$$

$$P(P_r > -50) = P(Z > -1.08)$$

$$P(Z > -1.08) = P(Z < 1.08) = 0.8599$$

Example: received power under non-line-of-sight

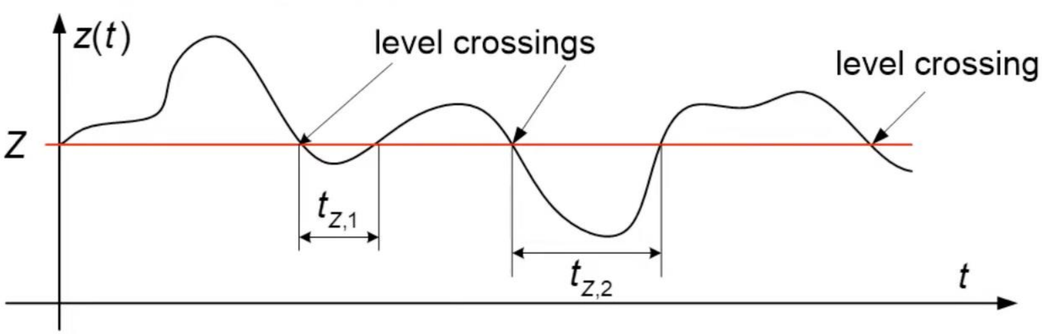
z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
0.0	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.1	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5675	0.5714	0.5753
0.2	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.3	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.4	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.5	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.6	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.7	0.7580	0.7611	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.8	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.9	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.0	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.1	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.2	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.3	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.4	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319
1.5	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.6	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.7	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.8	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706
1.9	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9761	0.9767
2.0	0.9772	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.1	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.2	0.9861	0.9864	0.9868	0.9871	0.9875	0.9878	0.9881	0.9884	0.9887	0.9890
2.3	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.4	0.9918	0.9920	0.9922	0.9925	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936

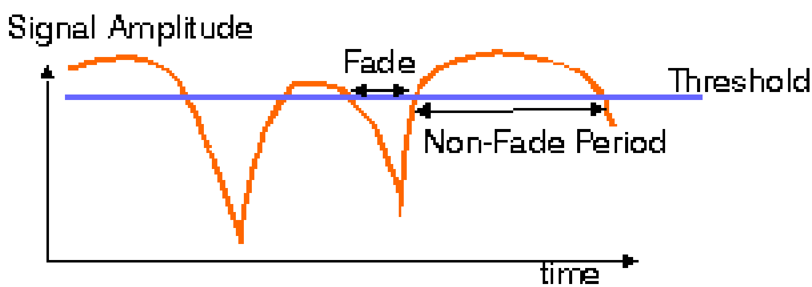
Level Crossing Rate and Average Fade Duration

- **Level crossing rate** is the average number of times a signal crosses a certain level.

- **Average fade duration** is the average time over which the signal below a certain level.

- Bit errors are more likely to occur in bursts on wireless channels because of the fading nature of the channels





Level Crossing Rate and Average Fade Duration

A wireless system operates at 900 MHz. The average fade duration is measured to be 2 ms for an outage threshold of 7 dB. The system now employs a (15,11) BCH code, where each code block (packet) contains 15 bits and can correct up to 2-bit errors per block. Determine the minimum interleaver memory size (in terms of coding blocks/packets) required to spread the errors across different blocks, assuming a bit rate of 100 kbps.