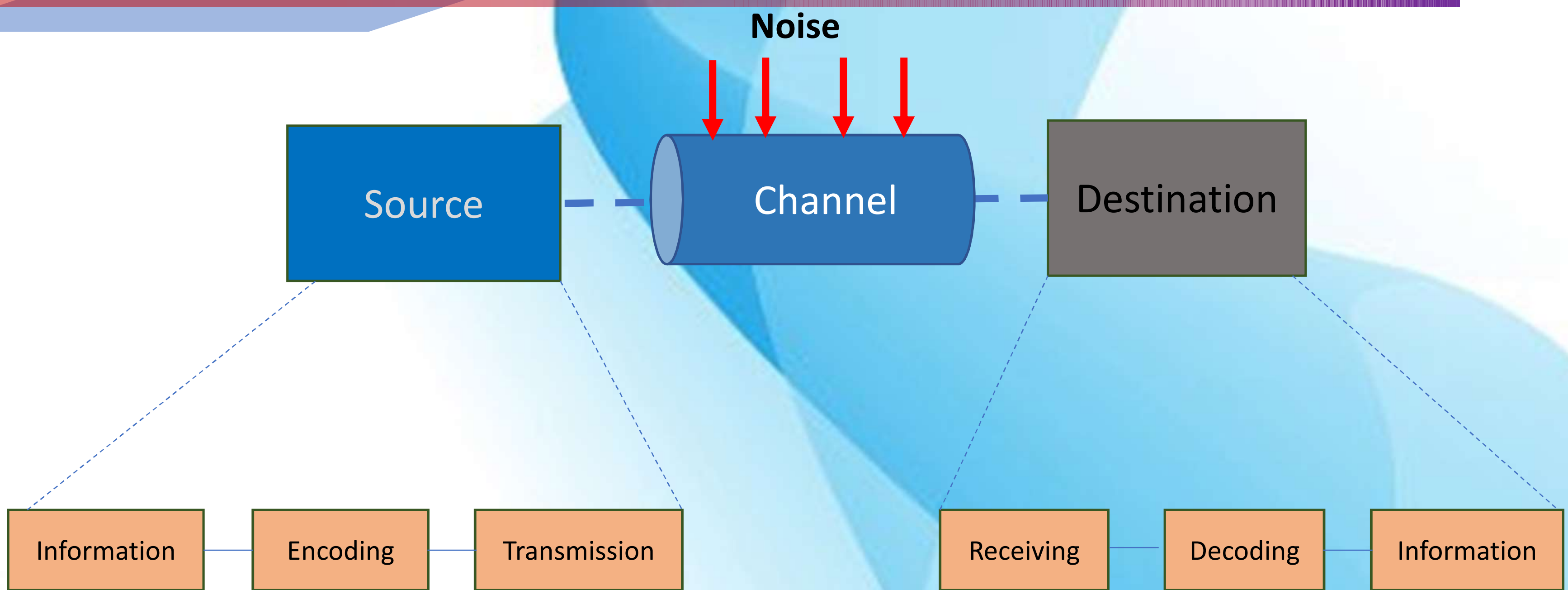
FUNDAMENTAL : Communication Transmission

Week 2 day 2

by

Xerandy

Channel Capacity



- Channel Capacity : the maximum rate at which data can be transmitted over a given communication path, or channel, under given conditions

Concepts Related to Channel Capacity

- Data rate - rate at which data can be communicated (bps)
- Bandwidth - the bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (Hertz)
- Noise - average level of noise over the communications path
- Error rate - rate at which errors occur
  - Error = transmit 1 and receive 0; transmit 0 and receive 1
    - Implying the probability of one bit error
    - Example : Bit error rate of 10^{-3} means probability of a single bit flipped, or in other words, in every 1000 bit, one bit error is found

Concepts Related to Channel Capacity

- Channel Capacity
  - Channel can be thought as a pipe, which certain maximum water (bit) can flow (propagate) through
  - Channel capacity infer the maximum number of bit per unit time that can transmitted through a channel with a very small bit error rate.
- Wireless channel capacity
  - Transmitting digital data using analog signal
  - Shannon Channel Capacity
    - Upper bound channel capacity, with present of noise regardless channel coding scheme,
    - Never being reached in practice

$$C = B\log_2(1 + SNR)$$

Where C is the channel capacity (in bit/second), B is the channel bandwidth (Hz), and SNR is signal to noise ratio quantity (It is in linear scale)

Signal-to-Noise Ratio

- Ratio of the power in a signal to the power contained in the noise that's present at a particular point in the transmission
  - Typically measured at a receiver
- Signal-to-noise ratio (SNR, or S/N)

$$(SNR)_{\mathrm{dB}} = 10\log_{10}\frac{\text{signal power}}{\text{noise power}}$$

or

$$SNR = \frac{\text{signal power}}{\text{noise power}}$$

- SNR is a essential parameter that shows signal quality
  - A high SNR means a high-quality signal, low number of required intermediate repeaters
  - A low SNR means low quality signal, may require further signal processing to recover original signal

Channel Noise

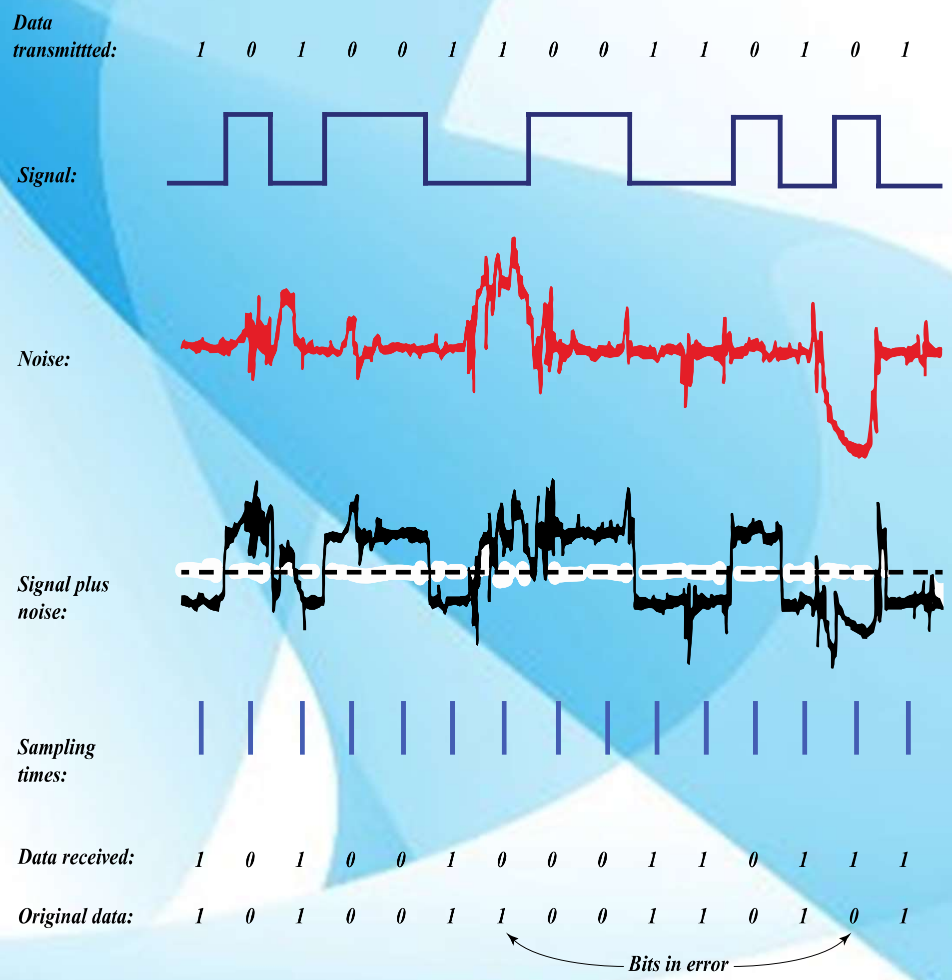
- Noise power is also expressed in Watt
- Type of noise
  - Thermal Noise
    - Thermal noise due to agitation of electrons, Present in all electronic devices and transmission media
    - Cannot be eliminated, function of temperature
    - Particularly significant for satellite communication
  - Intermodulation noise
    - Occurs if signals with different frequencies share the same medium
    - Interference caused by a signal produced at a frequency that is the sum or difference of original frequencies
  - Crosstalk
    - Unwanted coupling between signal paths
  - Impulse Noise
    - Short duration and of relatively high amplitude
    - Caused by external electromagnetic disturbances, or faults and flaws in the communications system

Additive Gaussian White Noise

- Since noise is a random signal in nature, noise signal is described as random process
  - It is usually modelled based on particular probability distribution function (abbr: pdf)
  - The very common yet simple model is Additive Gaussian White Noise
    - It is additive because the received signal is the sum of original signal and the noise signal
    - The noise signal uses Gaussian (or Normal) distribution
    - The spectral density is flat : i.e. the signal power for every frequency is flat (remember about Fourier transformation)
  - However, the use of this model sometime doesn’t fit to represent real-valued noise signal in practice

Channel Capacity

- Impact due to noise



Signal Power

- Power
  - Commonly denoted as P
  - Amount of energy spent per unit time
  - Measurement standard unit is Watt (w)

    Variant :
    - Kilowatt (kW) = 1000 times of 1 Watt
    - Megawatt (MW) = 1,000,000 times of 1 Watt
    - Milliwatt (mW) = 10^{-3} times of 1 Watt
    - Microwatt (uW) = 10^{-6} times of 1 Watt

  - Sometime it is also expressed in decibel scale, which is denoted as decibel-Watt (dBW)
    - Formulated as follows:

$$P_{(dBW)} = 10\log_{10}\left(\frac{P_{(W)}}{1\ W}\right)$$

  - Another common unit is decibel-milliWatt (dBm)

$$P_{(dBm)} = 10\log_{10}\left(\frac{P_{(mW)}}{1\ mW}\right)$$

Basic of Logarithm : Revisit

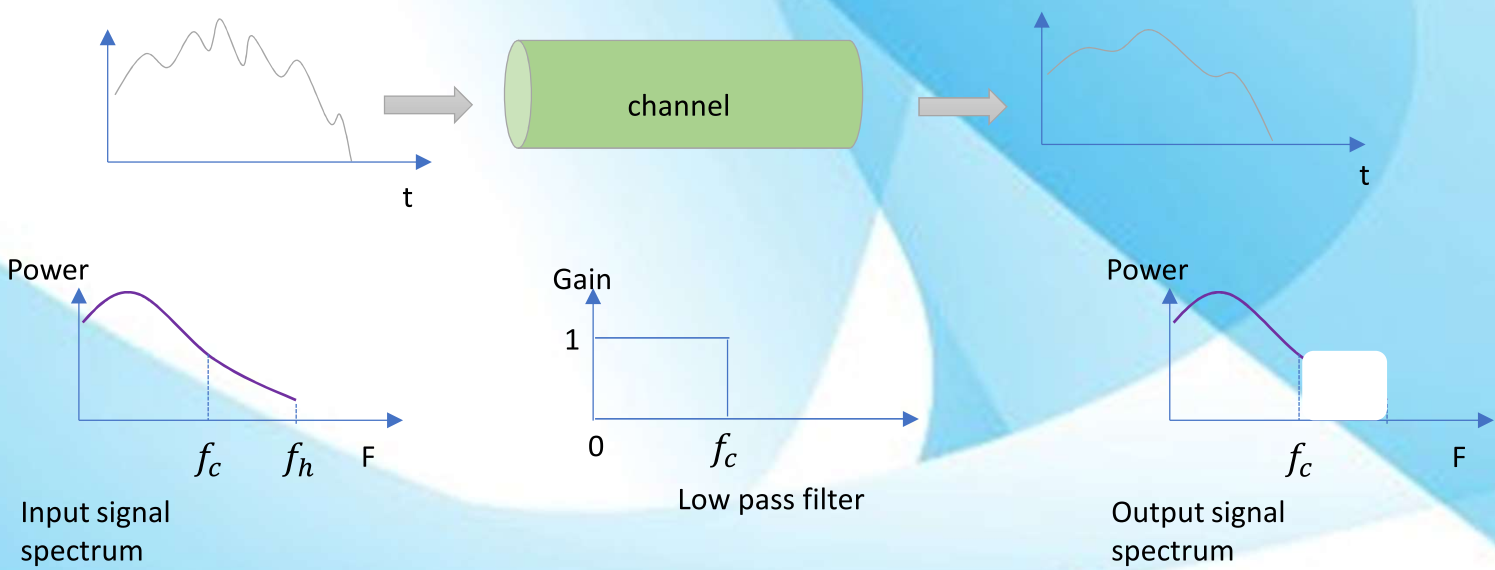
- $C = x^B \quad \leftrightarrow \log_x(C) = B$ for any x > 0
  - example : $100 = 10^2$ then $\log_{10}(100) = 2$
  - Do you know the outcome of $\log_x(x)$ = ?
- $C = A \times B \leftrightarrow \log_x(C) = \log_x(A) + \log_x(B)$
  - example : If $12 = 3 \times 4$; then $\log_2(12) = \log_2(3)$+ $\log_2(4)$
  - Do you know the outcome of $\log_2(4)$?
- $C = \frac{A}{B} \leftrightarrow \log_x(C) = \log_x(A) - \log_x(B)$
  - example : If $3 = 24 \div 8$; then $\log_2(3) = \log_2(24)$- $\log_2(8)$
  - Do you know the outcome of $\log_2(8)$?
- $C = A^B \leftrightarrow \log_x(C) = B \times \log_x(A)$

Signal Power

- Power expressions examples
  - Linear scale
    - 1 W = mW
    - 100 W = kW
    - 0.5 kW = W
    - 75 mW = W
    - 15 W = mW
    - 0.5 mW = uW
  - In decibel
    - 1 W = dBW
    - 0.5 W = dBW
    - 1 mW = dBm
    - 0.25 mW = dBm
    - 50 mW = dBm = dBW
    - 1 kW = dBW= dBm

Channel Bandwidth

- Channel bandwidth in Shannon capacity formulation
  - In most cases, it is defined as the highest frequency that a wireless channel can support, which is imposing a low-pass filter
    - Low pass filter : If the supported highest frequency is f_c, then any frequency higher than f_c will be rejected.



Shannon's Channel Capacity : Example

- Spectrum of a channel between 3 MHz and 4 MHz ; SNR_{dB} = 24 dB

$$B = 4\ \text{MHz} - 3\ \text{MHz} = 1\ \text{MHz}$$

$$\text{SNR}_{\text{dB}} = 24\ \text{dB} = 10\log_{10}(\text{SNR})$$

$$\text{SNR} = 251$$

- Using Shannon's formula

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

FUNDAMENTAL : SIGNAL TRANSMISSION

University of Pittsburgh

Transmission Media

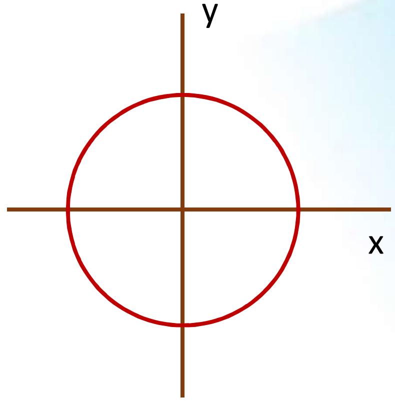
- Transmission Medium
  - Physical path between transmitter and receiver
- Guided Media
  - Waves are guided along a solid medium
  - E.g., copper twisted pair, copper coaxial cable, optical fiber
- Unguided Media
  - Provides means of transmission but does not guide electromagnetic signals
  - Usually referred to as wireless transmission
  - E.g., atmosphere, outer space
  - Transmission and reception in wireless transmission are achieved by means of an antenna

Antenna in Wireless Communication

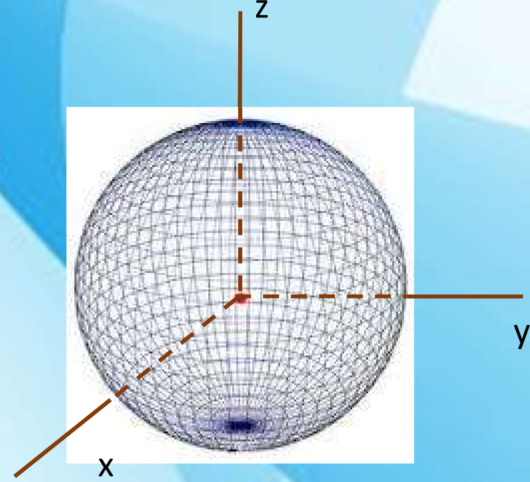
- An antenna is an electrical conductor or system of conductors
  - Transmission - radiates electromagnetic energy into space
  - Reception - collects electromagnetic energy from space
- In two-way communication, the same antenna can be used for transmission and reception.
- Radiation pattern
  - Graphical representation of radiation properties of an antenna
  - Depicted as two-dimensional cross section, however, it is a 3D description
  - The patterns shows the amount and direction of power radiated with respect to relative distance from antenna position
  - The radiation pattern also describes the direction from which antenna can receive the signal in the best manner.

Antenna Radiation Pattern

- Sphere pattern : Isotropic antenna

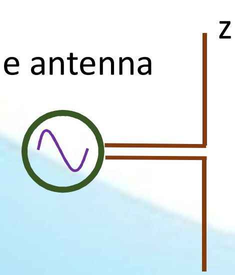


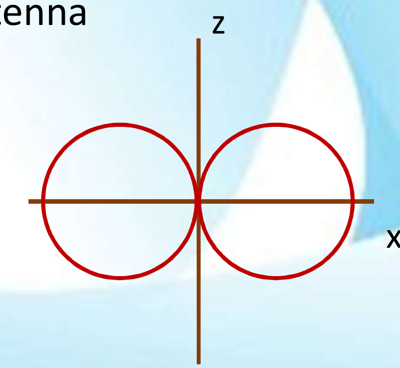
2D x-y plane

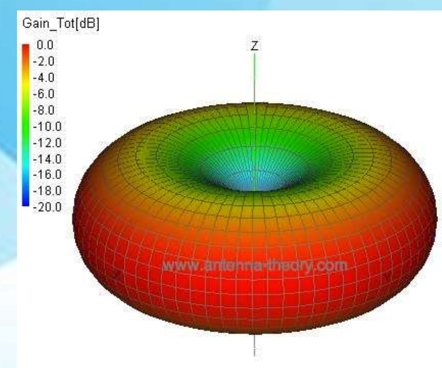


- Omni-directional pattern : Dipole antenna

Dipole antenna







Antenna Radiation Pattern

- Directional antenna

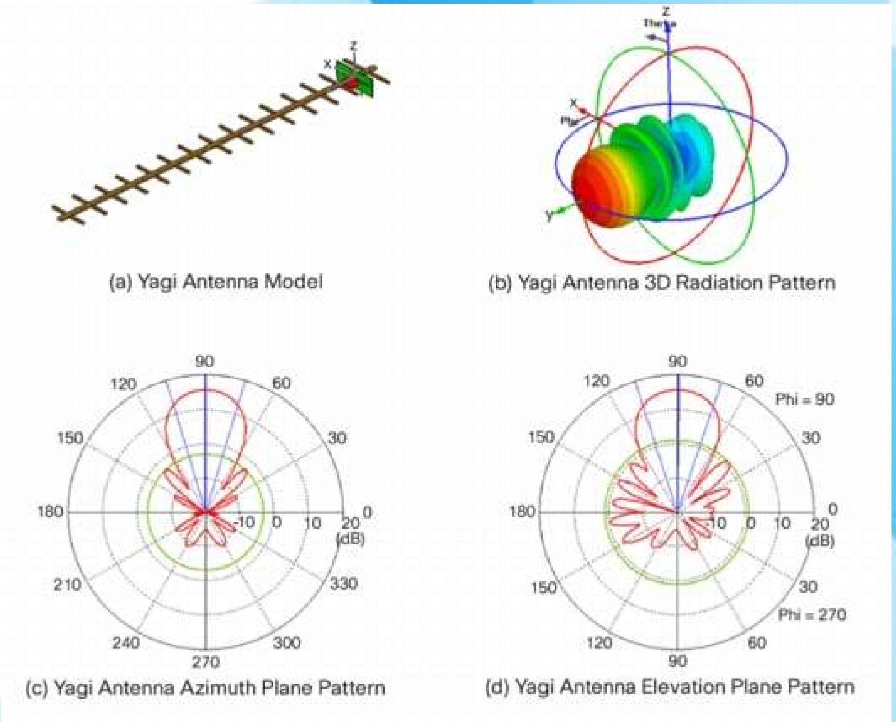


Image credit : http://www.cisco.com/c/en/us/products/collateral/wireless/aironet-antennas-accessories/prod_white_paper0900aecd806a1a3e.html

Wireless Transmission : Impairments

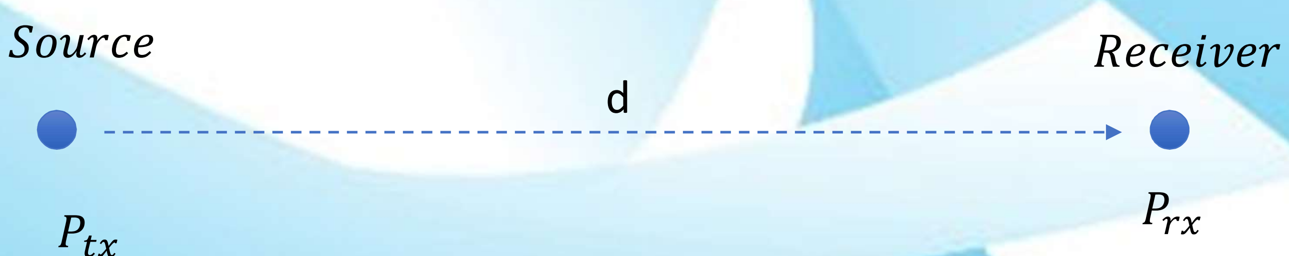
- Transmission loss
  - Mainly by signal attenuation
- Noise
  - Unwanted external signal that can impair original signal
- Multipath
  - caused by reflection, refraction, and scattering
- Doppler spread
  - Signal distortion that is caused by the movement of mobile unit

Transmission Loss

- Main source of wireless transmission loss is attenuation
  - For a microwave (and radio frequencies), transmitted from a source, with wave length λ (in meter) , and travels with distance *d* (in meter) from source, then the attenuation L is formulated as the ratio between transmitted power and received power, which in simplified case, it is assumed as free space loss, which can be expressed as

$$L = \frac{P_{tx}}{P_{Rx}} = \left(\frac{4\pi d}{\lambda}\right)^2 \quad \text{or}$$

$$L_{dB} = 10\log_{10}\left(\frac{P_{tx}}{P_{rx}}\right) = 10\log_{10}\left(\frac{4\pi d}{\lambda}\right)^2 \quad \text{in dB (decibel)}$$



Transmission Loss

- In decibel, it can be re written as follows

$$L_{dB} = -20\log(\lambda) + 20\log(d) + 21.98\,\text{dB}$$
$$= 20\log\left(\frac{4\pi fd}{c}\right) = 20\log(f) + 20\log(d) - 147.56\,\text{dB}$$

- In real practice, following formula can be used to approximate wireless channel path loss

$$L_{dB} = 20\log(f) + 10n\log(d) - 147.56\ \text{dB}$$

Transmission Loss

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

Transmission Loss

- Example 1 :
  - If transmission power of a radio wave is P_{tx}=100 Watt and the received power is P_{rx}=0.5 Watt.
    - Transmission and receiving power in dBW

$$P_{tx(dBW)} = 10\log_{10}\left(\frac{P_{tx(W)}}{\text{[redacted]}}\right) = 10\log_{10}\left(\frac{100\ W}{\text{[redacted]}}\right) = 20 \quad \text{dBW}$$

$$P_{rx(dBW)} = 10\log_{10}\left(\frac{P_{rx(W)}}{\text{[redacted]}}\right) = 10\log_{10}\left(\frac{0.5\ W}{\text{[redacted]}}\right) = -3 \quad \text{dBW}$$

    - Attenuation L, in decibel

$$L_{dB} = 10\log_{10}\left(\frac{P_{tx(w)}}{P_{rx(w)}}\right) = 10\log_{10}\left(\frac{100}{0.5}\right) = 23 \quad \text{dB}$$

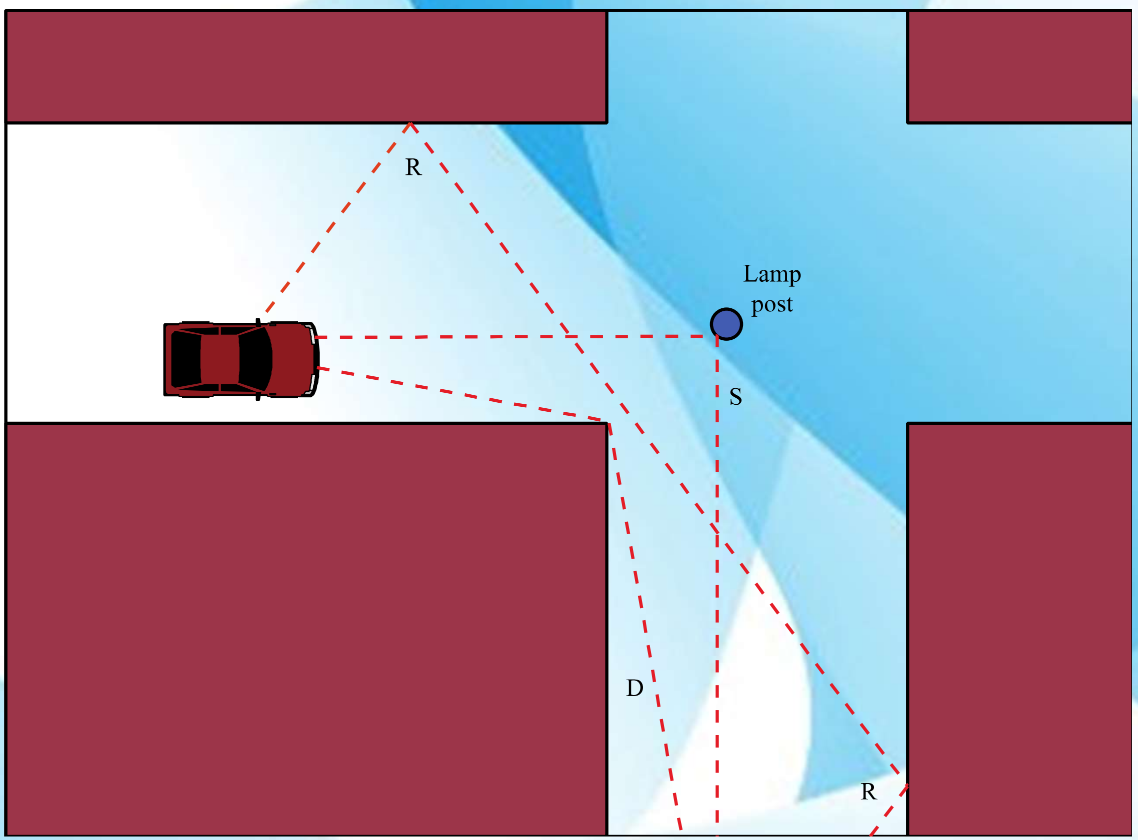
Transmission Loss

- Example 2
  - Using the same values as given in example 1, find the distance that the radio wave would have traveled, if :
    - $\lambda = 4 \quad meter: \quad L = \frac{P_{tx}}{P_{rx}} = \frac{100}{0.5} = \left(\frac{4\pi d}{4}\right)^2$ => d = m
    - $\lambda = 1\, meter: \quad L = \frac{P_{tx}}{P_{rx}} = \frac{100}{0.5} = \left(\frac{4\pi d}{1}\right)^2$ => d = m
    - $\lambda = 0.25\, meter: \quad L = \frac{P_{tx}}{P_{rx}} = \frac{100}{0.5} = \left(\frac{4\pi}{0.25}\right)^2$ => d= m

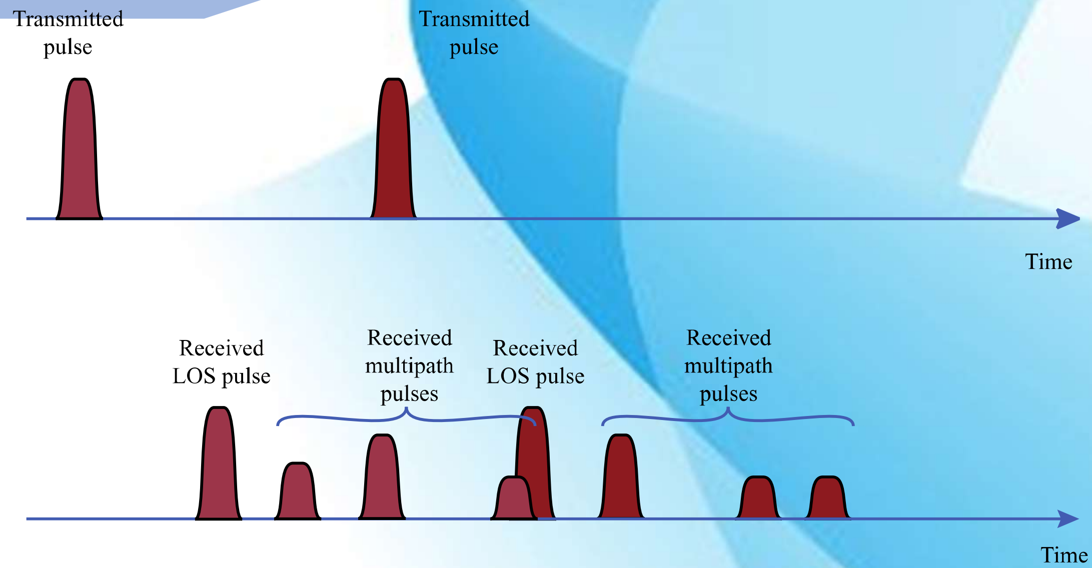
Impairments: Multipath

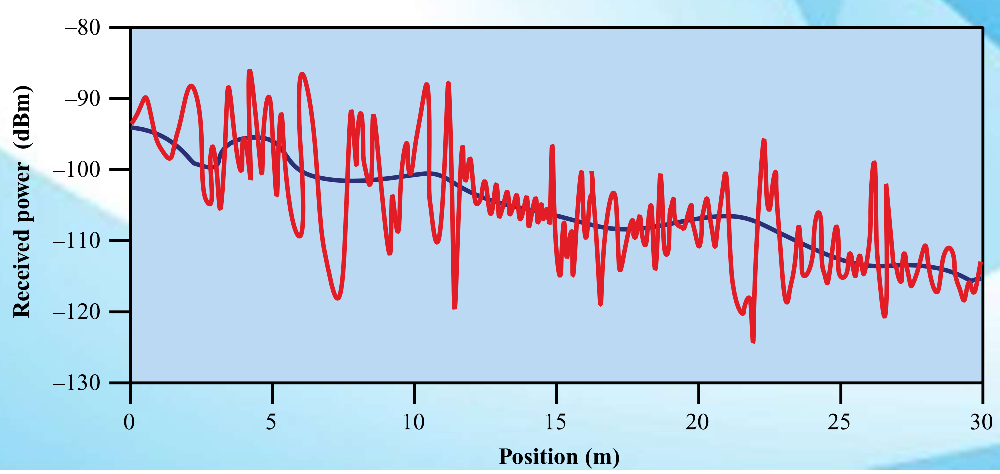
- Can be caused by reflection, diffraction, and scattering
  - Reflection occurs when radio wave encounters a surface that is large relative to the wave length of signal
  - Diffraction occurs at the edge of an impenetrable body that is large compared to the wave length
  - Scattering occurs when the size of obstruction is on the order of the wave length
- 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
- Rapid signal fluctuations
  - Over a few centimeters can cause multipath fading

Impairments: Multipath



Impairments: Multipath



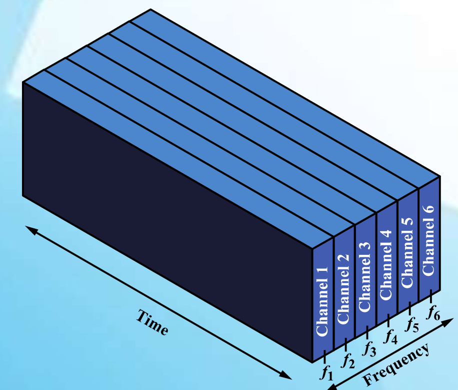


Multiplexing

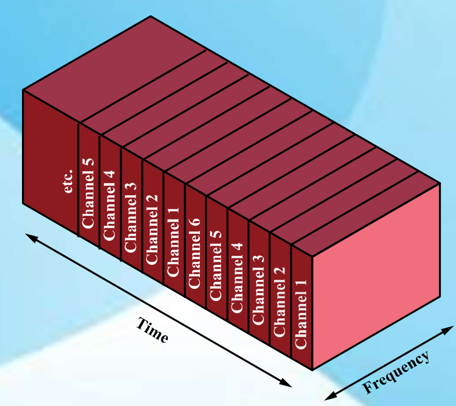
- Capacity of transmission medium usually exceeds capacity required for transmission of a single signal
- Multiplexing - carrying multiple signals on a single medium
  - More efficient use of transmission medium
  - Cost per kbps of transmission facility declines with an increase in the data rate
  - Cost of transmission and receiving equipment declines with increased data rate
  - Most individual data communicating devices require relatively modest data rate support

Multiplexing Techniques

- Frequency-division multiplexing (FDM)
  - Takes advantage of the fact that the useful bandwidth of the medium exceeds the required bandwidth of a given signal
  - Orthogonal FDM is a special case of FDM technique
- Time-division multiplexing (TDM)
  - Takes advantage of the fact that the achievable bit rate of the medium exceeds the required data rate of a digital signal



(a) Frequency division multiplexing



(b) Time division multiplexing

Addressing Channel Impairment

- Adaptive Modulation
  - Can be performed adaptively according to channel condition
- Data Encoding :
  - Error Control Coding
  - Adding extra bit into the data so that error can be detected or corrected
- Equalization
  - Counteract the multipath effect of the channel
- Multiple input – multiple output (MIMO)
  - The use of multiple antenna either for transmitting and receiving
- Direct sequence spread spectrum
  - Signal occupies large bandwidth, so that problems in parts of it are overcome

Error Control Coding

- Coding and Error Control
  - Applied to digital data
    - Data would be a sequence of bits with certain length, called as frame
  - There are two approaches:
    - Error Detection Codes
    - Error Correction Codes
- Error Detection Codes
  - Simply detect the presence of error bit
  - Transmitter
    - For a given frame, an error-detecting code (check bits) is calculated from data bits
    - Check bits are appended to data bits
  - Receiver
    - Separates incoming frame into data bits and check bits
    - Calculates check bits from received data bits
    - Compares calculated check bits against received check bits
    - Detected error occurs if mismatch
      - Automatic repeat request (ARQ) protocols
        - Block of data with error is discarded
        - Transmitter retransmits that block of data

Error Control Coding

- Forward error correction
  - Transmitter adds error-correcting code to data block
    - Block code
    - Convolutional Code
    - Turbo codes
  - Code is a function of the data bits
  - Receiver calculates error-correcting code from incoming data bits
  - If calculated code matches incoming code, no error occurred
  - If error-correcting codes don't match, receiver attempts to determine bits in error and correct