Lecture 2: Wireless Transmission Fundamentals

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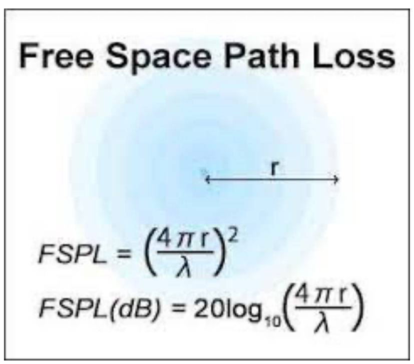
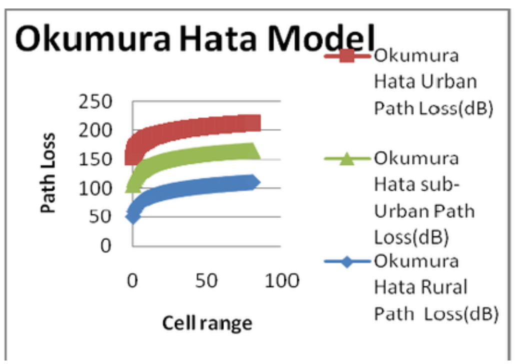
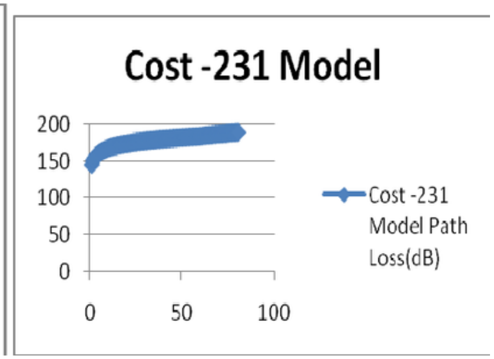
2.1. Wireless Propagation Models and Channel Characteristics

2.1.1. Path Loss Models

- Path loss refers to the reduction in signal strength as it travels through space.
- Free-Space Path Loss (FSPL) is a basic model that calculates path loss in free space and is based on the inverse square law.
    - Free-Space Path Loss (FSPL) is calculated using the formula FSPL (dB) = 20 * log10(d) + 20 * log10(f) + 20 * log10(4π/c), where d is the distance, f is the frequency, and c is the speed of light.
    - This formula estimates the loss of signal power due to spreading as it travels through space.
- Log-distance path loss models consider factors like distance, frequency, and terrain to provide more accurate predictions of path loss in real-world scenarios.
- Empirical models, such as Okumura-Hata and COST 231 models, consider factors like frequency, distance, and environment (urban, suburban, rural) to provide more accurate path loss predictions in real-world scenarios.

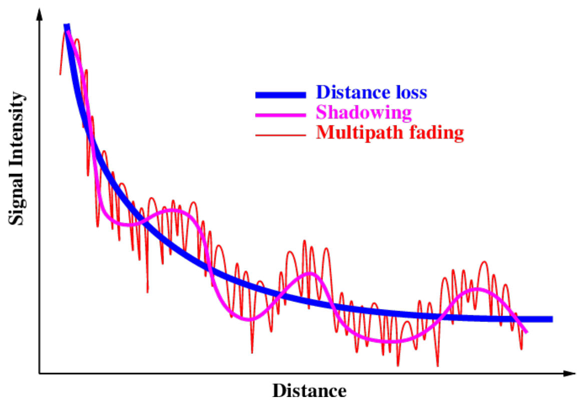


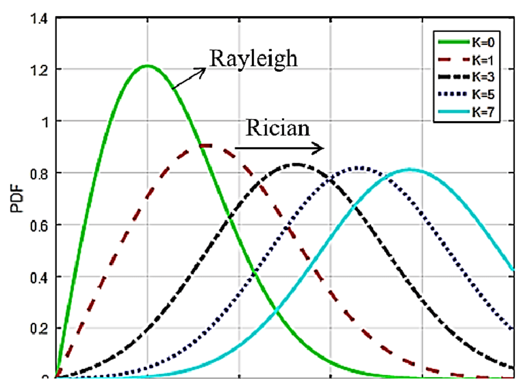




2.1.2. Shadowing and Fading

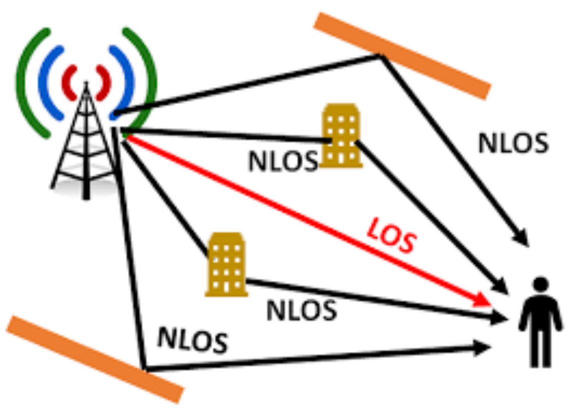
- Shadowing occurs due to obstructions like buildings, trees, and terrain, leading to localized variations in signal strength.
    - Shadowing is characterized by a log-normal distribution of signal variations.
    - The standard deviation of shadowing effects quantifies signal variations from the mean path loss.
- Fading is the rapid fluctuation of signal strength caused by multipath propagation.
    - Fading models, such as Rayleigh and Rician fading, characterize signal variations and their statistical properties.
    - Rayleigh fading is commonly used to model fading,
    - while Rician fading models scenarios with a dominant line-of-sight path.

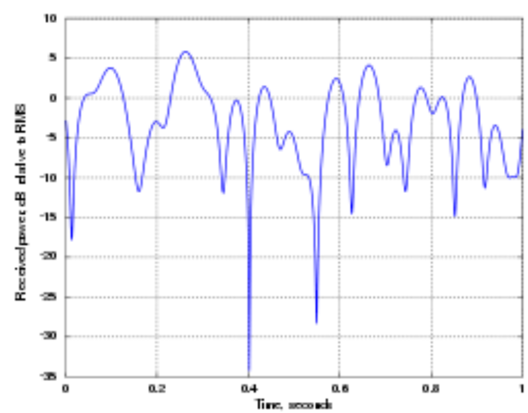




2.1.3. Multipath Propagation

- Multipath propagation happens when signals take multiple paths to reach the receiver due to reflections and scattering.
- Multipath can lead to constructive or destructive interference, causing signal fading, affecting signal quality.
- Mitigation techniques include diversity reception and equalization to combat fading effects.
- Diversity reception techniques, such as selection diversity and maximal ratio combining, mitigate fading effects by combining multiple received signal paths.





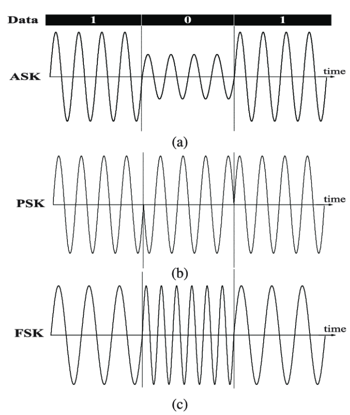
2.1.4. Channel Models

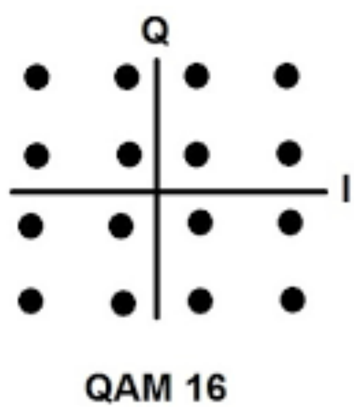
- Channel models describe the characteristics of wireless communication channels.
- The Additive White Gaussian Noise (AWGN) channel model considers the presence of noise in the channel.
- MIMO (Multiple Input, Multiple Output) channel models account for multiple antennas at both the transmitter and receiver, offering spatial diversity and increased data rates.

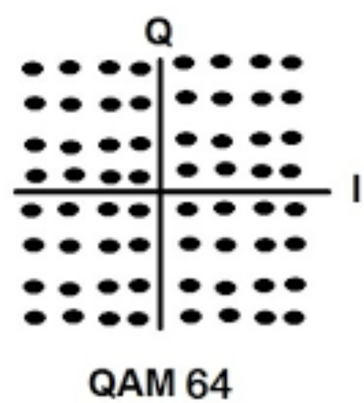
2.2. Signal Encoding and Modulation Techniques

2.2.1. Digital Modulation

- Digital modulation schemes encode digital data onto carrier signals for transmission.
- Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), and Phase Shift Keying (PSK) are common modulation schemes.
- Quadrature Amplitude Modulation (QAM) combines amplitude and phase modulation for higher data rates.
  - Quadrature Amplitude Modulation (QAM) is a widely used digital modulation scheme. For example, 16-QAM encodes four bits per symbol.
  - Higher-order QAM schemes, such as 64-QAM or 256-QAM, offer higher data rates but are more susceptible to noise and interference.

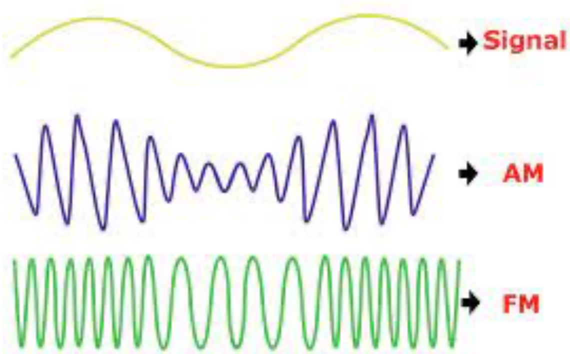






2.2.2. Analog Modulation

- Analog modulation is used for transmitting analog signals, such as voice or video.
- Amplitude Modulation (AM) involves varying the amplitude of a carrier signal to transmit information. AM is used in broadcasting and has variations like double-sideband AM and single-sideband AM.
- Frequency Modulation (FM) varies the frequency of the carrier signal based on the information signal's instantaneous frequency. FM is known for its resistance to amplitude noise.
- Analog modulation is less common in modern wireless communication but is used in broadcasting.



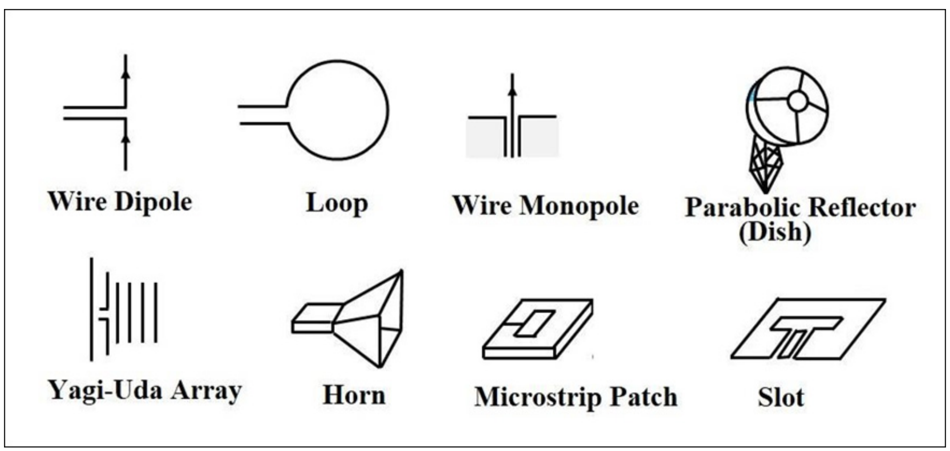
2.2.3. Carrier and Symbol Rates

- Carrier frequency refers to the frequency of the carrier wave used for modulation.
- Symbol rate, or baud rate, determines how many symbols (data elements) are transmitted per second.
- The relationship between symbol rate and bit rate depends on the modulation scheme used.
    - For example, 16-QAM transmits four bits per symbol, so the bit rate is four times the symbol rate.

2.3. Antennas and Radio Frequency (RF) Systems

2.3.1. Antenna Types

- Antennas come in various types, including dipole antennas, Yagi-Uda antennas, parabolic antennas, and patch antennas.
- The choice of antenna depends on factors like radiation pattern, gain, and application (e.g., directional or omnidirectional coverage).
- Patch antennas are commonly used in Wi-Fi routers and have a flat, compact design suitable for integration into devices with limited space.
- Parabolic antennas are highly directional and used for long-range point-to-point communication, such as satellite dishes.
- Yagi-Uda antennas are known for their gain and directionality and are used in TV reception and amateur radio.

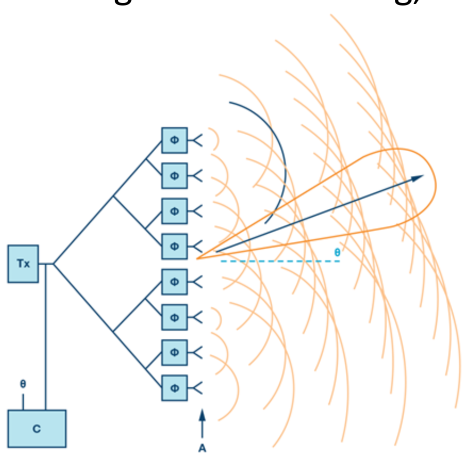


2.3.2. Antenna Gain and Directivity

- Antenna gain quantifies the ability to focus energy in a particular direction.
    - Antenna gain is often measured in decibels relative to an isotropic radiator (dBi) or a dipole (dBd). Higher gain antennas concentrate more energy in a specific direction.
- Directivity is a measure of how strongly an antenna radiates in a specific direction.
    - Directivity quantifies the degree to which an antenna focuses energy in a particular direction. High directivity antennas have narrow radiation patterns.
- High-gain and directional antennas are used for long-range communication, while omnidirectional antennas provide 360-degree coverage.

2.3.3. Beamforming and Phased Array

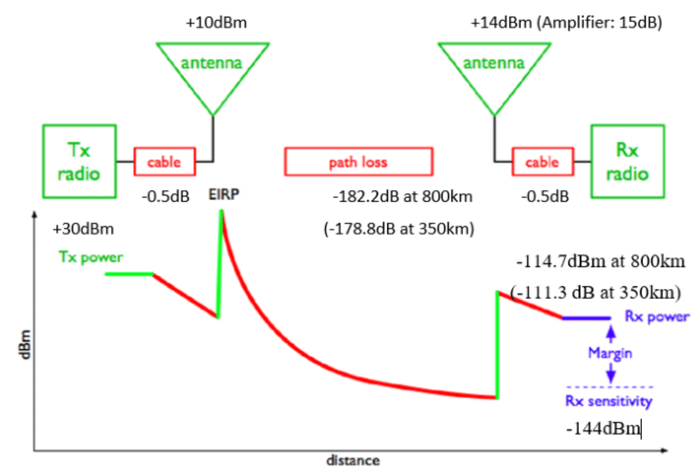
- Beamforming and phased arrays are both based on phase array antenna technology.
    - Beamforming is a technique that uses an array of antennas and a combiner to form a spatial filter.
    - Phased arrays are groups of sensors located at different spatial locations.
- Beamforming can be used to
    - Improve the signal-to-noise ratio of received signals
    - Eliminate interference sources
    - Focus transmitted signals to specific locations
- Phased arrays can be used to:
    - Reinforce the effective propagation pattern of the array in a desired direction
    - Suppress the effective propagation pattern of the array in undesired directions
- In analog beamforming, a single input data stream is provided to a set of feedlines leading into the phased array. A phase shift is intentionally applied to the input signals leading to each antenna.
- In digital beamforming, different signals are designed for each antenna in the digital baseband.



2.4. Link Budget Analysis and System Capacity Planning

2.4.1. Link Budget Components

- A link budget analysis calculates the power budget of a wireless link, considering factors like transmitter power, antenna gains, path loss, and receiver sensitivity.
- Components of a link budget include transmit power, free-space path loss, antenna gains, and receiver sensitivity.
- Transmit power includes the power generated by the transmitter's amplifier and any antenna gains. It's essential for calculating the power available at the receiver.
- Receiver sensitivity represents the minimum signal power required for the receiver to decode and recover data reliably.
- The link budget helps determine whether a communication link will meet its performance requirements.



2.4.2. System Capacity Planning

- System capacity planning involves designing and optimizing wireless networks for a specific level of capacity, coverage, and quality of service (QoS).
- Factors like user density, data rate requirements, and network architecture influence capacity planning.
- User density is a key factor in capacity planning. Higher user densities require more base stations or access points to meet capacity demands.
- Techniques like frequency reuse, cell splitting, and sectorization are used to increase network capacity.
- Sectorization divides a cell into sectors, each served by its own antenna and base station, increasing capacity and reducing interference.
- Load balancing techniques distribute user traffic across multiple cells or access points to prevent network congestion.