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WIFI ASSIGNMENT 3

1. What are the different 802.11 PHY layer standards? Compare their characteristics.

The IEEE 802.11 standard includes several physical layer (PHY) specifications that define how data is transmitted over wireless networks. Each version improves performance, range, and efficiency in different scenarios.

- **802.11a** operates in the 5 GHz frequency band and supports data rates up to 54 Mbps using Orthogonal Frequency Division Multiplexing (OFDM). It offers better performance in less congested bands but has a shorter range compared to 2.4 GHz standards.
- **802.11b**, introduced alongside 802.11a, uses the 2.4 GHz band with Direct Sequence Spread Spectrum (DSSS) modulation, providing maximum data rates of 11 Mbps. Although it has a longer range and better wall penetration, it suffers from more interference due to crowding in the 2.4 GHz band.
- **802.11g** combines the benefits of 802.11a and b by using OFDM modulation over the 2.4 GHz band, achieving speeds up to 54 Mbps. It is backward compatible with 802.11b devices and offers better performance while still facing the same interference issues.
- **802.11n** was a major enhancement that supports both 2.4 GHz and 5 GHz bands. It introduced Multiple Input Multiple Output (MIMO) technology, allowing simultaneous data streams to increase throughput up to 600 Mbps. It also allowed wider channels of 40 MHz for better bandwidth.
- **802.11ac** builds on 802.11n, operating exclusively in the 5 GHz band. It supports wider channels (up to 160 MHz), multi-user MIMO (MU-MIMO), and beamforming for directional signal enhancement. These features enable theoretical speeds up to 6.9 Gbps, significantly boosting network performance.
- **802.11ax**, also known as Wi-Fi 6 (and Wi-Fi 6E for 6 GHz support), is the most advanced standard, working across 2.4 GHz, 5 GHz, and 6 GHz bands. It introduces Orthogonal Frequency Division Multiple Access (OFDMA), BSS Coloring to reduce interference, and improved MU-MIMO. Theoretical data rates can reach up to 9.6 Gbps. This standard is designed for high-density environments and supports more concurrent users efficiently.

Each new 802.11 standard builds upon the previous, enhancing speed, capacity, and reliability to meet the growing demands of modern wireless communication.

2. What are DSSS and FHSS? How do they work?

DSSS (Direct Sequence Spread Spectrum) and FHSS (Frequency Hopping Spread Spectrum) are two modulation techniques used in wireless communication to reduce interference and improve signal reliability.

DSSS:

DSSS works by spreading the original data signal over a wider frequency band using a pseudo-random code called a chipping code. Each bit of data is represented by multiple chips, which makes the signal more resistant to noise and interference. Even if parts of the signal are lost or corrupted, the receiver can still reconstruct the original data using the known spreading code. DSSS is used in IEEE 802.11b and offers good data integrity and resistance to jamming.

FHSS:

FHSS works by rapidly switching (hopping) the carrier frequency over a wide range of channels in a pseudo-random sequence. Both the transmitter and receiver follow the same hopping pattern, allowing them to stay synchronized. If interference occurs at one frequency, the system quickly moves to another, reducing the chance of signal degradation. FHSS was used in early wireless technologies like Bluetooth and early 802.11 versions.

DSSS spreads the data over a wide band continuously, while FHSS transmits the data over different frequencies at different times, both improving communication reliability and resistance to interference.

3. How do Modulation Schemes Work in the PHY Layer?

Modulation schemes in the PHY layer convert digital data into radio signals suitable for wireless transmission. These techniques encode data by varying signal characteristics like amplitude, frequency, or phase. The choice of modulation affects speed, range, and reliability.

Common Modulation Schemes:

- BPSK (Binary Phase Shift Keying): Uses two phases to represent binary 0 and 1. It is very robust against noise but supports lower data rates.
- QPSK (Quadrature Phase Shift Keying): Uses four different phase shifts to represent two bits per symbol, offering higher data rate than BPSK with moderate reliability.
- 16-QAM (Quadrature Amplitude Modulation): Combines amplitude and phase variations to represent 4 bits per symbol. It provides higher throughput but is more susceptible to noise.
- 64-QAM: Represents 6 bits per symbol, enabling faster data rates. Requires a stronger signal with less interference.
- 256-QAM: Encodes 8 bits per symbol, used in advanced Wi-Fi standards for maximum throughput in ideal conditions.

- 1024-QAM / 4096-QAM: Used in Wi-Fi 6/6E for extremely high data rates, but only effective in very clean, high-signal environments.

Performance Across Wi-Fi Standards:

- **802.11b** uses BPSK and QPSK (with DSSS), offering low speeds (up to 11 Mbps) but high reliability.
- **802.11a/g** use BPSK, QPSK, 16-QAM, and 64-QAM with OFDM, achieving up to 54 Mbps.
- **802.11n** expands on previous modulation with MIMO and 64-QAM to reach up to 600 Mbps.
- **802.11ac** introduces 256-QAM and wider channels, allowing up to several Gbps.
- **802.11ax (Wi-Fi 6/6E)** uses up to 1024-QAM or even 4096-QAM with OFDMA and MU-MIMO for efficient, high-throughput communication in dense environments.

4. What is the Significance of OFDM in WLAN? How Does It Improve Performance?

OFDM (Orthogonal Frequency Division Multiplexing) is a digital modulation technique that divides a high-speed data stream into multiple lower-speed sub-streams and transmits them simultaneously over several closely spaced, orthogonal subcarriers. Each subcarrier is modulated with a conventional modulation scheme (like BPSK, QPSK, or QAM).

These subcarriers are mathematically orthogonal to each other, meaning they can overlap in frequency without interfering with each other, thus maximizing spectral efficiency.

Significance of OFDM in WLAN:

OFDM plays a foundational role in modern wireless standards such as IEEE 802.11a, g, n, ac, and ax. Its inclusion transformed WLAN communication in the following ways:

- Better utilization of bandwidth
- Enabler for High-Speed Data Transmission
- Supports Complex Modulations

This technique significantly improves performance by:

1. High Data Rates: By transmitting data in parallel across multiple subcarriers, OFDM increases overall throughput efficiently.
2. Resistance to Interference: Each subcarrier operates at a lower data rate, making the signal more robust against noise and interference.
3. Multipath Handling: OFDM mitigates the effects of multipath fading, which is common in indoor environments, by allowing delayed signals to be received without distortion.

4. Spectral Efficiency: Subcarriers are orthogonal (non-overlapping yet close), which maximizes the use of available bandwidth.
5. Scalability: OFDM supports adaptive modulation—different subcarriers can use different modulation schemes based on channel quality, optimizing performance dynamically.

5. How Are Frequency Bands Divided for Wi-Fi? Explain Different Bands and Their Channels

Wi-Fi operates on multiple frequency bands to allow flexible, high-speed wireless communication. These bands are divided into specific ranges and further split into **channels** that devices use to transmit and receive data.

1. <u>2.4 GHz Band:</u>

- Range: 2.400 GHz to 2.4835 GHz
- Total Channels: 14 channels (each 20 MHz wide, but only 1–13 are commonly used globally)
- Channel Spacing: 5 MHz apart, leading to overlap between adjacent channels
- Non-overlapping Channels: Only 3 non-overlapping channels — 1, 6, and 11 — are commonly used to reduce interference
- Use Case: Longer range, better wall penetration, but more interference from devices like Bluetooth, microwaves, etc.

2. <u>5 GHz Band:</u>

- Range: 5.150 GHz to 5.825 GHz (varies by country and regulatory domain)
- Total Channels: Over 20 channels, including UNII-1, UNII-2, UNII-2 Extended, and UNII-3 ranges
- Channel Widths: Supports 20, 40, 80, and 160 MHz channels for higher throughput
- Less Congestion: More non-overlapping channels and less interference make it suitable for high-performance applications
- DFS : Some channels require DFS to avoid interference with radar systems

3. <u>6 GHz Band (Wi-Fi 6E):</u>

- Range: 5.925 GHz to 7.125 GHz
- Total Channels: Up to 59 new 20 MHz channels, or 14+ channels at 80/160 MHz widths
- No Legacy Devices: Only accessible by Wi-Fi 6E devices
- Benefits: Ideal for ultra-high-speed connections, VR, 4K/8K streaming, and enterprise environments

6. What is the Role of Guard Intervals in WLAN Transmission? How Does a Short Guard Interval Improve Efficiency?

In WLAN transmission, a Guard Interval (GI) is a short time gap inserted between successive data symbols to prevent interference caused by multipath propagation. When a transmitted signal reflects off surfaces like walls or furniture, delayed copies may arrive at the receiver. Without a guard interval, these delayed signals (echoes) can interfere with the next symbol—this is known as Inter-Symbol Interference (ISI).

The Guard Interval provides a buffer period that allows these delayed reflections to die out before the next symbol starts, ensuring accurate data decoding at the receiver.

Standard vs. Short Guard Interval:

- **Standard GI:** 800 nanoseconds (ns)
- **Short GI:** 400 nanoseconds (ns), introduced in 802.11n and used in later standards like 802.11ac and 802.11ax

How a Short Guard Interval Improves Efficiency:

1. Increases Data Throughput: Reducing the guard interval shortens the time between symbols, allowing more symbols (and thus more data) to be transmitted per second.
2. Boosts Transmission Rate: A 400 ns GI improves data rates by approximately 10% compared to the standard 800 ns.
3. Optimized for Clean Channels: Short GI is most effective in environments with minimal multipath distortion (e.g., line-of-sight or short-range communication).
4. Better for High-Speed Applications: It helps maximize efficiency in modern WLANs that use higher modulation schemes and wider channels.
5. Trade-Off: While more efficient, short GIs may be more vulnerable to ISI in environments with significant multipath, so dynamic adjustment is often used.

7. Describe the structure of an 802.11 PHY layer frame. What are its key components?

The 802.11 PHY layer frame is structured to prepare data for wireless transmission and ensure proper synchronization, modulation, and decoding. It is made up of three main parts: the Preamble, PHY Header, and PPDU (PLCP Protocol Data Unit).

<u>1. Preamble:</u>

- Used for synchronization, channel estimation, and timing alignment.
- Includes:
  - Short Training Field (STF): Helps the receiver detect the signal and perform coarse frequency offset correction.
  - Long Training Field (LTF): Used for fine channel estimation.
  - Signal Field: Contains modulation, coding rate, and length of the frame.

2. PHY Header:

- Follows the preamble and provides additional transmission parameters.
- Includes:
    - Rate and Length Information
    - Parity and Reserved Bits
    - Helps the receiver understand how to process the data portion of the frame.

3. PPDU (PLCP Protocol Data Unit):

- Contains the actual data payload from the MAC layer.
- Includes:
    - SERVICE Field: Assists in scrambler initialization.
    - DATA Field: Carries the MAC frame (user data).
    - TAIL Field: Helps reset decoder state.
    - PAD Bits (if needed): Used for symbol alignment.

8. What is the Difference Between OFDM and OFDMA?

OFDM (Orthogonal Frequency Division Multiplexing) and OFDMA (Orthogonal Frequency Division Multiple Access) are both digital modulation techniques used in wireless communication, particularly in Wi-Fi. While they are based on the same core principle of dividing bandwidth into multiple subcarriers, they differ in how these subcarriers are utilized.

OFDM (Orthogonal Frequency Division Multiplexing):

- **Used In:** Wi-Fi standards like 802.11a, 802.11g, 802.11n, and 802.11ac.
- **Working:** OFDM divides the channel into multiple orthogonal subcarriers. All subcarriers are used to send data to a **single user at a time**.
- **Efficiency:** Works well at high data rates, but users have to wait for their turn—causing delays in multi-user environments.
- **Latency:** Higher latency in dense networks due to sequential user servicing.

OFDMA (Orthogonal Frequency Division Multiple Access):

- **Used In:** Wi-Fi 6 (802.11ax) and newer.
- **Working:** OFDMA enhances OFDM by allowing multiple users to be served **simultaneously**. It divides subcarriers into smaller units called **Resource Units (RUs)**, each allocated to different users at the same time.
- **Efficiency:** Greatly improves bandwidth utilization and network efficiency, especially in crowded environments.
- **Latency:** Lower latency since multiple devices can transmit and receive concurrently.

9. What is the Difference Between MIMO and MU-MIMO?

MIMO (Multiple Input, Multiple Output) and MU-MIMO (Multi-User MIMO) are wireless technologies that enhance throughput and signal quality by using multiple antennas at both the transmitter and receiver. While both improve data rates and reliability, they differ in how they handle user communication.

MIMO (Single-User MIMO):

- Used In: Wi-Fi standards like 802.11n and 802.11ac (Wave 1).
- Working: MIMO allows the access point to transmit multiple data streams to a single device simultaneously using multiple antennas.
- Benefit: Increases speed and reliability for one user by exploiting spatial multiplexing.
- Limitation: Other users have to wait; only one device benefits from MIMO at any given time.

MU-MIMO (Multi-User MIMO):

- Used In: Wi-Fi 5 (802.11ac Wave 2) and Wi-Fi 6 (802.11ax).
- Working: MU-MIMO allows the access point to transmit multiple data streams to multiple users simultaneously, each with their own stream.
- Benefit: Greatly improves network efficiency and total throughput in multi-device environments.
- Direction: Wi-Fi 5 supports downlink MU-MIMO; Wi-Fi 6 supports both uplink and downlink MU-MIMO.

10. What are PPDU, PLCP, and PMD in the PHY Layer?

In the IEEE 802.11 physical layer, the data transmission process is divided into well-structured sublayers and units to ensure reliable wireless communication. The key components involved are PPDU, PLCP, and PMD.

1. PPDU (PLCP Protocol Data Unit):

- The PPDU is the complete frame that the PHY layer transmits over the air.
- It includes the preamble, header, and data payload.
- The MAC layer data is encapsulated within the PPDU, making it the actual unit transmitted to the receiver.

2. PLCP (Physical Layer Convergence Protocol):

- The PLCP is a sublayer of the PHY responsible for adapting MAC layer frames for physical transmission.
- It adds the preamble and PHY header to the data to assist the receiver in synchronization and decoding.
- It also ensures proper formatting and signaling, enabling compatibility between different PHY types.

3. PMD (Physical Medium Dependent):

- The PMD sublayer deals with the actual transmission and reception of bits through the wireless medium.
- It converts digital data into analog signals (modulation) and vice versa (demodulation).
- It directly interacts with the antennas and handles tasks like frequency conversion, power control, and RF signal processing.

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11. What are the Types of PPDU? Explain the PPDU Frame Format Across Different Wi-Fi Generations.

In IEEE 802.11 WLAN systems, the **PPDU (PLCP Protocol Data Unit)** is the fundamental unit transmitted by the physical layer. It encapsulates the MAC frame along with necessary physical layer signalling and synchronization components.

1. Legacy PPDU (802.11a/g):

- **Used In:** Wi-Fi 4 and earlier
- **Structure:**
    - Preamble: Legacy Short Training Field (L-STF) and Long Training Field (L-LTF)
    - Signal Field: Legacy SIGNAL (L-SIG)
    - Data: Encapsulated MAC frame
- **Features:** Basic single-user transmission; no support for MIMO or high throughput enhancements.

2. HT PPDU (High Throughput – 802.11n):

- **Used In:** Wi-Fi 4
- **Types:**
    - HT-Mixed: Backward compatible with legacy devices
    - HT-Greenfield: Optimized for pure 802.11n networks (not widely used)
- **Structure:**
    - Legacy Preamble (L-STF, L-LTF, L-SIG)
    - HT-SIG, HT-STF, HT-LTF
    - Data Field
- **Features:** Supports MIMO, wider channels (20/40 MHz), short guard intervals.

3. VHT PPDU (Very High Throughput – 802.11ac):

- **Used In:** Wi-Fi 5
- **Structure:**
    - Legacy Fields (L-STF, L-LTF, L-SIG)
    - VHT-SIG A & B, VHT-STF, VHT-LTF
    - Data Field
- **Features:** Enhanced MIMO (up to 8 streams), beamforming, higher QAM (256-QAM), 80/160 MHz channels.

4. HE PPDU (High Efficiency – 802.11ax):

- **Used In:** Wi-Fi 6
- **Types:**
    - HE-SU PPDU: For single user
    - HE-MU PPDU: For multi-user (OFDMA, MU-MIMO)
    - HE-Trigger-Based PPDU: For uplink multi-user

  - HE-Extended Range (ER) PPDU: For long-range low-power transmission
- **Structure:**
  - L-STF, L-LTF, L-SIG
  - HE-SIG-A, HE-SIG-B, HE-STF, HE-LTF
  - Data Field
- **Features:** OFDMA, uplink MU-MIMO, 1024-QAM, Target Wake Time (TWT), better efficiency in dense environments.

12. How is the data rate calculated?

The **data rate** in Wi-Fi refers to the speed at which data is transmitted over the wireless medium. It depends on several physical layer parameters including modulation, coding, channel width, guard interval, and the number of spatial streams.

Data Rate Calculation Formula:

Data Rate = (Number of Subcarriers) × (Bits per Subcarrier) × (Coding Rate) × (Symbol Rate) × (Number of Spatial Streams)

- **Modulation Scheme (Bits per Subcarrier):**
  Determines how many bits each subcarrier can carry (e.g., BPSK = 1, QPSK = 2, 16-QAM = 4, 64-QAM = 6, 256-QAM = 8, 1024-QAM = 10 bits).
- **Coding Rate:**
  Indicates how much of the data is useful (e.g., 1/2, 2/3, 3/4, 5/6). A 3/4 coding rate means 75% of the transmitted bits are data.
- **Symbol Rate (Symbols/sec):**
  Inversely related to the symbol duration, which is affected by the **guard interval (GI)**. A shorter GI increases symbol rate.
- **Number of Subcarriers:**
  Depends on the channel bandwidth (e.g., 52 subcarriers for 20 MHz in OFDM, more in wider bands).
- **Number of Spatial Streams:**
  With MIMO, multiple streams can be transmitted simultaneously to increase throughput.