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Wi-Fi Training Program Module – 3

Q1. What are the different 802.11 PHY layer standards? Compare their characteristics.

Here's a comparison of different IEEE 802.11 PHY layer standards:

Standard	Year	Frequency Band	Max. Data Rate	Modulation	Channel Width	Range
802.11	1997	2.4 GHz	2 Mbps	DSSS, FHSS	20MHz	Short
802.11b	1999	2.4 GHz	11 Mbps	DSSS, complementary Coding Keying (CCK)	20MHz	~100 m
802.11a	1999	5 GHz	54 Mbps	Orthogonal Frequency Division Multiplexing (OFDM)	20MHz	~35 m
802.11g	2003	2.4 GHz	54 Mbps	OFDM	20MHz	~100 m
802.11n	2009	2.4 & 5 GHz	600 Mbps	OFDM, Multiple Input Multiple Output (MIMO)	20/40 MHz	~100 m
802.11ac	2013	5 GHz	6.93 Gbps	OFDM, MU-MIMO	20/40/80/160 MHz	~35 m
802.11ax (Wi-Fi 6)	2019	2.4 & 5 GHz	9.6 Gbps	OFDMA, MU-MIMO	20/40/80/160 MHz	~ 100 m

Q2. What are DSSS and FHSS? How do they work?

Frequency Hoping Spread Spectrum (FHSS):

- **The ISM Band range between 2.400 GHz and 2.483 GHz is divided into 79 - 1MHz frequencies (from 2.402 to 2.480 GHz) is the ISM band.**
- **This technique is used in Bluetooth devices to minimize eavesdropping and interface from other networks that use the ISM band.**
- **The data is divided into small pieces called packets and is hopped across the available frequencies.**
- **The hop between frequencies up to 1600 times per second, i.e., so the minimum interference with other devices working in same frequency is about 625µsec.**

Direct Sequence Spread Spectrum (DSSS):

- **Is a method used in wireless communication to spread the signal over a wider bandwidth than the original signal.**
- **The original data signal is multiplied by a high-rate spreading code, often called a pseudo-noise (PN) code.**
- **This spreading code has a much higher frequency than the data signal, which results in the spreading of the signal across a broader bandwidth.**

FHSS	DSSS
Multiple frequencies are used	Multiple frequency is used
Hard to find the user's frequency at any instant of time	User frequency, once allotted is always the same
Frequency reuse is allowed	Frequency reuse is not allowed
Sender need not wait	Sender has to wait if the spectrum is busy
Power strength of the signal is high	Power strength of the signal is low
It is never affected by interference	It can be affected by interference
It is cheaper	It is expensive
This is the commonly used technique.	This technique is not frequently used.

Q3. How do modulation schemes work in the PHY layer? Compare different modulation schemes and their performance across various Wi-Fi standards.

Modulation is the process of encoding information onto a carrier wave by altering its properties such as:

CCK:

- **Complementary Code Keying is a form of phase-shift keying (PSK) that uses a set of complementary codes—sequences of bits with special properties to represent data using 8-chip sequence.**
- **8 chips allow enough unique combinations (up to 256) to encode 8 bits efficiently.**
- **This is the CCK code word formula:**
  C = {e^j(ϕ1+ϕ2+ϕ3+ϕ4), e^j(ϕ1+ϕ3+ϕ4), e^j(ϕ1+ϕ2+ϕ4), e^j(ϕ1+ϕ4), e^j(ϕ1+ϕ2+ϕ3), e^j(ϕ1+ϕ3), e^j(ϕ1+ϕ2), e^j(ϕ1)}

BPSK:

- **BPSK represents data using two distinct phase shifts (typically 0° and 180°) of a carrier signal — one bit per symbol (either 0 or 1).**
- **It is the most robust but slowest modulation scheme, highly resistant to noise and used in poor signal conditions (e.g., in the lowest data rate modes of Wi-Fi).**

QPSK:

- **QPSK uses four different phase shifts (0°, 90°, 180°, 270°) to represent 2 bits per symbol, doubling the data rate compared to BPSK.**

FSK:

- **Transmits data by shifting between different frequencies to represent binary values (e.g., one frequency for 0 and another for 1), making it simple and robust but limited in speed.**
- **We can also code multiple bits; for example, we can code 2 bits at the same time and assign 4 different frequencies.**

QAM:

- **Combines both amplitude and phase variations to encode multiple bits per symbol, enabling high data rates but requiring a strong, clean signal.**

Modulation	Data Rate
CCK	8 bits per symbol
BPSK	1 bit per symbol
QPSK	2 bits per symbol
FSK	1 bit per symbol
4-FSK	2 bits per symbol
16-QAM	4 bits per symbol
64-QAM	6 bits per symbol
256-QAM	8 bits per symbol

Standard	Modulation
802.11	DSSS, FHSS
802.11b	DSSS, complementary Coding Keying (CCK)
802.11a	Orthogonal Frequency Division Multiplexing (OFDM)
802.11g	OFDM
802.11n	OFDM, 64-QAM, MIMO
802.11ac	OFDM, 256-QAM, MU-MIMO
802.11ax (Wi-Fi 6)	OFDMA, 1024-QAM

Q4. What is the significance of OFDM in WLAN? How does it improve performance?

- **Orthogonal Frequency Division Multiplexing is a digital multi-carrier modulation scheme that extends the concept of single subcarrier modulation by using multiple subcarriers within the same single channel.**
- **Rather than transmit a high-rate stream of data with a single subcarrier, OFDM makes use of a large number of closely spaced orthogonal subcarriers that are transmitted in parallel.**
- **The spacing between the subcarriers is such that they are orthogonal to each other to avoid interference.**

OFDM (Orthogonal Frequency Division Multiplexing) is a modulation technique used in modern WLAN standards like IEEE 802.11a/g/n/ac/ax. It splits a high-speed data stream into multiple slower streams and transmits them in parallel over several orthogonal subcarriers.

OFDM improves performance in WLAN:
1. Efficient Use of Bandwidth: Subcarriers in OFDM overlap in frequency but remain mathematically orthogonal, allowing more data to be transmitted in the same bandwidth.
2. Resilience to Multipath Fading: OFDM is ideal for indoor WLAN environments where signals reflect off walls and it uses longer symbol durations and a cyclic prefix to eliminate inter-symbol interference (ISI) caused by multipath propagation.
3. High Data Rates: By transmitting data in parallel over many subcarriers, OFDM supports higher throughput, enabling fast Wi-Fi.
4. Robustness to Narrowband Interference: Since the data is spread across many subcarriers, interference on one subcarrier affects only a small portion of the overall data.

Q5. How are frequency bands divided for Wi-Fi? Explain different bands and their channels.

Wi-Fi operates in three primary frequency bands:

1. **2.4 GHz Band**
2. **5 GHz Band**
3. **6 GHz Band (introduced with Wi-Fi 6E and extended in Wi-Fi 7)**

Each band is divided into channels, which are specific frequency ranges used for wireless communication. Proper channel separation helps reduce interference and enables multiple devices to connect efficiently.

1. **2.4 GHz Band**
    - **Frequency Range: 2.400 – 2.4835 GHz**
    - **Number of Channels: 14 channels (availability depends on the country)**
    - **Channel Width: 20 MHz**
    - **Overlapping: Channels are spaced only 5 MHz apart, so most channels overlap, causing interference.**
    - **Non-overlapping Channels: Only 3 – Channels 1, 6, and 11 are non-overlapping in most regions.**
    - **Usage: Common for legacy devices and has good range, but prone to interference from other electronics (e.g., Bluetooth, microwaves).**

2. **5 GHz Band**
    - **Frequency Range: 5.150 – 5.825 GHz (varies slightly by region)**
    - **Number of Channels: Up to 25 channels (varies by country and regulations)**
    - **Channel Widths: 20 MHz, 40 MHz, 80 MHz, and 160 MHz**
    - **Non-overlapping Channels: Many – due to wider spacing and support for larger bandwidths.**
    - **Indoor use: Channels (36–48) are used for indoor wireless communication.**
    - **DFS Channels: Channels (52–144) require Dynamic Frequency Selection (DFS) to avoid radar systems.**
    - **Outdoor use: Channels (149–165) are used for outdoor wireless communication.**
    - **Usage: Faster speeds and less interference compared to 2.4 GHz, but shorter range and weaker wall penetration.**

3. 6 GHz Band (Wi-Fi 6E and Wi-Fi 7)

- **Frequency Range: 5.925 – 7.125 GHz (available in select regions)**
- **Number of Channels: Up to 59 new 20 MHz channels**
- **Channel Widths: 20 MHz, 40 MHz, 80 MHz, 160 MHz (Wi-Fi 6E); up to 320 MHz in Wi-Fi 7**
- **Interference: Minimal – it's a newly opened band with no legacy devices, ideal for high-speed, low-latency applications.**
- **Usage: Future-proof band designed for next-gen devices, AR/VR, 8K streaming, etc.**

Channel Widths and Wi-Fi Channel Bonding:

- **20 MHz: Standard channel width with no bonding; used in both 2.4 GHz and 5 GHz bands.**
- **40 MHz: Bonds two 20 MHz channels for double the speed; used in 2.4 GHz and 5 GHz bands.**
- **80 MHz: Bonds four 20 MHz channels; offers higher speeds, commonly used in 5 GHz and 6 GHz bands.**
- **160 MHz: Bonds eight 20 MHz channels; provides maximum throughput in 5 GHz and 6 GHz bands, but more prone to interference.**

Q6. What is the role of Guard Intervals in WLAN transmission? How does a short Guard Interval improve efficiency?

Guard Intervals in WLAN Transmission:

- **A Guard Interval (GI) is a small-time gap inserted between data symbols in wireless communication, especially in systems using OFDM (Orthogonal Frequency Division Multiplexing) like Wi-Fi (WLAN).**
- **Guard Intervals (GIs) are short time gaps inserted between OFDM symbols to prevent Inter-Symbol Interference (ISI). ISI occurs when the delayed signals from a previous symbol interfere with the current one due to multipath propagation—a phenomenon where signals reflect off walls, furniture, or other objects and arrive at the receiver at different times.**
- **The Guard Interval allows these delayed signals (multipath components) to settle before the next symbol begins, ensuring signal integrity and reducing bit errors during reception.**

Short Guard Interval (SGI)

A Short Guard Interval reduces the standard interval from 400 ns to 200 ns, offering several performance benefits:

- **Higher Data Throughput: By minimizing the idle time between symbols, more symbols can be transmitted in a given period, increasing overall network throughput by around 10%.**
- **Reduced Latency: Shorter GIs decrease the time spent on overhead, improving response time for real-time applications like video conferencing, VoIP, and gaming.**
- **Improved Spectral Efficiency: SGI enables better utilization of the channel, allowing more data to be transmitted over the same bandwidth.**

Q7. Describe the structure of an 802.11 PHY layer frame. What are its key components?

The 802.11 PHY (Physical) layer frame, also known as the PLCP (Physical Layer Convergence Protocol) frame, is responsible for the physical transmission of data over wireless media in Wi-Fi networks. It sits at the bottom of the OSI model and interacts with the MAC layer above it.

There are multiple versions of the PHY layer depending on the 802.11 standard (e.g., 802.11a/b/g/n/ac/ax), but they all follow a general structure. Here's a breakdown of the general structure of a PHY layer frame:

1. **Preamble**
2. **Header (PLCP Header)**
3. **Payload (PSDU – PLCP Service Data Unit)**

1. Preamble:

The preamble helps the receiver synchronize with the signal. It allows the receiver to lock onto the signal timing and prepare for data reception.

- **Short Training Field (STF) – For signal detection and AGC (Automatic Gain Control).**
- **Long Training Field (LTF) – For channel estimation.**
- **Signal Field (SIG) – Contains information about the rate, length, etc.**

2. PLCP Header (PHY Header)

This follows the preamble and contains important control information required for decoding the payload.

- **Rate – Modulation and coding scheme used.**
- **Length – Size of the payload in bytes.**
- **Service – Reserved for future use.**
- **Parity – For error checking.**
- **Tail – To terminate convolutional encoding.**

3. Payload (PSDU)
This is the actual MAC frame that has been passed down from the MAC layer for transmission. It contains:
- **MAC header**
- **Frame body (data)**
- **FCS (Frame Check Sequence)**

Q8. What is the difference between OFDM and OFDMA?

OFDM (Orthogonal Frequency Division Multiplexing):
OFDM is a digital modulation technique that splits a high-speed data stream into multiple lower-speed streams and transmits them simultaneously over several orthogonal subcarriers. This approach improves spectral efficiency and reduces the effects of multipath fading and inter-symbol interference. In OFDM, all the subcarriers are used by a single user at a given time, making it ideal for single-user transmission with high throughput and robustness in wireless environments. It is widely used in earlier Wi-Fi standards like 802.11a, 802.11g, and 802.11n.
OFDMA (Orthogonal Frequency Division Multiple Access):
OFDMA builds on OFDM by enabling multiple users to access the channel simultaneously. It achieves this by dividing the subcarriers into smaller groups called Resource Units (RUs), which are dynamically allocated to different users based on their data needs. This allows for more efficient use of bandwidth, lower latency, and better support for many users, making it highly suitable for dense environments like offices or stadiums. OFDMA is a core feature of newer standards like 802.11ax (Wi-Fi 6) and LTE.

Feature	OFDM (Orthogonal Frequency Division Multiplexing)	OFDMA (Orthogonal Frequency Division Multiple Access)
Purpose	Transmits data from a single user over multiple subcarriers	Transmits data from multiple users simultaneously over subsets of subcarriers
Access Type	Single-user	Multi-user (better resource sharing)
Subcarrier	All subcarriers are used by one user at a time	Subcarriers are divided among users
Efficiency	Less efficient in uplink/downlink scheduling	More efficient, especially in dense networks
Latency	Higher latency in multi-user scenarios	Lower latency, supports parallel transmissions
Used in	802.11a/g/n (Wi-Fi 4)	802.11ax (Wi-Fi 6)

Q9. What is the difference between MIMO and MU-MIMO?

MIMO (Multiple Input Multiple Output)
MIMO uses multiple antennas at both the transmitter and receiver to send and receive more than one data stream simultaneously. This improves data throughput, signal reliability, and range for a single user. It increases performance by using spatial multiplexing, where separate data streams travel through different antenna paths.
MU-MIMO (Multi-User MIMO)
MU-MIMO is an advanced form of MIMO that allows a wireless access point to communicate with multiple devices at the same time, instead of serving one device per transmission. It significantly boosts efficiency in environments with many users, as the access point can split its spatial streams across multiple clients, reducing wait times and improving overall network performance. MU-MIMO is supported in standards like 802.11ac (downlink) and 802.11ax (uplink & downlink).

Feature	MIMO	MU-MIMO
Users served	Single user at a time	Multiple users at the same time
Use case	High throughput for one device	Efficient sharing among many devices
Standard	802.11n	802.11ac, 802.11ax

Q10. What are PPDU, PLCP, and PMD in the PHY layer?

PPDU (Physical Protocol Data Unit):

- **The PPDU is the complete unit that includes both control and data information necessary for successful communication.**
- **It is what is actually transmitted by the physical hardware, and it consists of multiple components, including the PLCP header and the actual user data from the MAC layer.**
- **It encapsulates the PLCP header, PLCP preamble, and the PSDU (Physical Service Data Unit, which comes from the MAC layer).**
- **It is the final package sent out by the PHY layer.**

PLCP (Physical Layer Convergence Protocol):

- **The PLCP (Physical Layer Convergence Protocol) is a sublayer within the PHY layer that acts as an interface between the MAC layer and the lower PMD sublayer.**
- **It takes the MAC Protocol Data Unit (MPDU), adds necessary PHY-specific information like preambles, headers, and training sequences, and formats it into the PPDU.**
- **The PLCP header helps the receiver understand how to decode the rest of the transmission, specifying things like data rate, packet length, and modulation scheme.**
- **It is like the interface that prepares the data to be sent physically.**

PMD (Physical Medium Dependent)

- **The PMD (Physical Medium Dependent) sublayer is responsible for the actual transmission and reception of the data bits over the physical medium, such as radio waves in wireless systems.**
- **It converts the digital signals from the PLCP into analog waveforms suitable for the wireless channel and performs tasks like modulation, spreading, and up/down conversion.**
- **Actually transmits and receives the modulated signal over the medium (air, fiber, etc.).**
- **Deals with modulation, encoding, signal generation, and RF transmission/reception.**
- **This part that talks directly to the physical world, handling the hardware-specific stuff.**

Q11. What are the types of PPDU? Explain the PPDU frame format across different Wi-Fi generations.

In Wi-Fi (IEEE 802.11), PPDU stands for Physical Protocol Data Unit, which is the data packet that is actually transmitted over the air at the physical layer. Different Wi-Fi generations define various types of PPDUs to support new features and improve performance. There are four main types of PPDUs:

- **Legacy PPDU**
- **HT PPDU**
- **VHT PPDU**
- **HE PPDU**

1. Legacy PPDU:

- **Legacy PPDUs are used in Wi-Fi standards before 802.11n.**
- **The Legacy PPDU has a preamble (consisting of a short training field and a long training field), a signal field indicating the rate and length of the packet, and the data field containing the MAC frame.**
- **It's designed for backward compatibility and does not support advanced features like MIMO.**
- **It provides basic modulation and coding for legacy devices.**

HT PPDU:

- **High Throughput – Used in 802.11n**
- **HT PPDUs introduce MIMO and OFDM to increase throughput.**
- **HT PPDUs have a preamble, HT-SIG (Signal field), HT-STF (Short Training Field), HT-LTF (Long Training Field), and Data.**
- **There are three types of HT PPDUs: HT-Mixed, HT-Greenfield, and HT-NonHT. HT-Mixed ensures backward compatibility with legacy devices, while HT-Greenfield offers higher efficiency but is only compatible with HT-capable devices.**

VHT PPDU:

- **Very High Throughput – Used in 802.11ac / Wi-Fi 5**
- **VHT PPDUs improve upon HT by increasing the channel bandwidth to 80/160 MHz and supporting more spatial streams (up to 8).**
- **The VHT PPDU includes a legacy preamble for backward compatibility, followed by VHT-specific fields like VHT-SIG-A, VHT-STF, VHT-LTF, and VHT-SIG-B.**
- **These provide more information about the MIMO configuration, modulation, and coding scheme (MCS), allowing for enhanced throughput and efficiency.**

HE PPDU:

- **High Efficiency – Used in 802.11ax / Wi-Fi 6**
- **HE PPDUs are designed for dense environments, supporting OFDMA, MU-MIMO, and BSS coloring.**
- **There are four types: HE SU, HE MU, HE TB (Trigger-Based), and HE ER SU (Extended Range).**
- **The HE PPDU starts with a legacy preamble for compatibility, then has HE-SIG-A, HE-STF, HE-LTF, and HE-SIG-B fields.**
- **These allow scheduling of multiple users simultaneously, reducing latency and improving overall network efficiency.**

Q12. How is the data rate calculated?

The data rate in Wi-Fi is the rate at which data is transmitted over the wireless medium, and it's influenced by several parameters depending on the Wi-Fi generation. Here's a general formula and explanation of how the data rate is calculated:

Data Rate=$\dfrac{(\textbf{Number of Subcarriers}\times\textbf{Bits per Subcarrier})+(\textbf{Coding Rate}\times\textbf{Number of Spatial Streams})}{(\textbf{Symbol duration})}$