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

   The IEEE 802.11 PHY layer standards define how data is physically transmitted over the air in wireless networks (Wi-Fi). Each standard improves upon previous ones in terms of speed, efficiency, range, and frequency usage.

Wi Fi Generation	Standard	Frequency Band	Year of Introduction	Modulation Techniques	Maximum Bandwidth	Theoretical Speed	Remarks
Wi Fi 1	802.11	2.4 GHz	1997	DSSS, FHSS	20 MHz	2 Mbps	Very low speed: up to 2 Mbps.
Wi Fi 2	802.11 b	2.4 GHz	1999	DSSS, CCK	20 MHz	11 Mbps	Longer range, but slower
Wi-Fi 3	802.11 a	5 GHz	1999	OFDM (BPSK, QPSK, 16-QAM, 64-QAM)	20 MHz	54 Mbps	Shorter range due to 5 GHz
Wi Fi 3	802.11 g	2.4 GHz	2003	OFDM (BPSK, QPSK, 16-QAM, 64-QAM)	20 MHz	54 Mbps	Backward compatible with 802.11b. Range till 40m
Wi Fi 4	802.11 n	2.4 / 5 GHz	2002	OFDM (BPSK, QPSK, 16-QAM, 64-QAM), MIMO	40 MHz	600 Mbps	MIMO introduced.
Wi Fi 5	802.11 ac	5 GHz	2013	OFDM (BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM), MU-MIMO	160 MHz	6.93 Gbps	High throughput
Wi-Fi 6	802.11 ax	2.4 / 5 GHz	2019	OFDM (BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM, 1024-QAM),	160 MHz	9.6 Gbps	Better for dense environments

				MU-MIMO			
Wi Fi 6E	802.11 ax	6 GHz	2020	OFDM (BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM, 1024-QAM), MU-MIMO	160 MHz	9.6 Gbps	Next Gen, High throughput
Wi Fi 7	802.11 be	2.4 /5/6 GHz	2024	OFDMA (BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM, 1024-QAM, 4096-QAM), MU-MIMO, CMU-MIMO	320 MHz	46 Gbps	Next Gen, Ultra High throughput

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

Aspect	DSSS (Direct Sequence Spread Spectrum)	FHSS (Frequency Hopping Spread Spectrum)
Definition	A spread spectrum technique where data is spread by multiplying with a pseudo-random noise (PN) code.	A spread spectrum technique where data is transmitted by rapidly switching (hopping) frequencies according to a pseudo-random sequence.
Working	- Each bit is multiplied by a high-speed chipping code. - Spreads signal across a wide band. - Receiver uses the same code to decode.	- Data is divided into time slots. - In each slot, transmission occurs at a different frequency. - Transmitter and receiver hop in sync.
Bandwidth Usage	Uses Wider Bandwidth	Narrower channel
Frequency Usage	Uses one wide frequency band during transmission.	Uses multiple narrow bands, hops between them during transmission.

Data Rate, Speed	Higher (up to 11 Mbps in 802.11b)	Lower (up to 2 Mbps in early 802.11)
Resistance to Interference	High	Moderate
Security	Good	Better
Implementation Complexity	Complex Hardware with easier implementation	Easier Hardware with complexity due to synchronization
Use Cases	802.11b	802.11 pre b , Bluetooth
Similarity	Both spread the original signal over a wider frequency range to improve resistance and security. Both provide better robustness against interference than narrowband systems. Both are more secure than basic RF modulation techniques due to spreading/hopping.	

3. 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 data (0s and 1s) onto a carrier signal by altering its amplitude, frequency, or phase. In Wi-Fi, modulation is used to maximize data rate, increase robustness, and optimize signal quality depending on the environment. The higher the modulation order, the more bits per symbol, but also more susceptible to noise.
   Wi-Fi standards usually use phase shift keying modulation techniques for transmission namely binary phase shift keying (BPSK), quadrature phase shift keying (QPSK) and quadrature amplitude modulation (QAM).

Modulation	Bits/Symbol	Robustness	Speed	Use
BPSK	1 bit	Very High	Low	802.11 a/b/g/n
QPSK	2 bits	High	Moderate	802.11 a/g/n/ac
16- QAM	4 bits	Medium	Higher	802.11 a/g/n/ac/ax
64-QAM	6 bits	Lower	High	802.11 n/ac
256-QAM	8 bits	Lower	Very High	802.11 ac/ax
1024-QAM	10 bits	Low	Ultra-High	802.11 ax
4096-QAM	12 bits	Very Low	Extreme High	802.11 e

4. What is the significance of OFDM in WLAN? How does it improve performance?
   OFDM (Orthogonal Frequency Division Multiplexing) is a digital modulation technique where a high-speed data stream is split into multiple lower-speed streams, and each is transmitted simultaneously on different orthogonal subcarriers (frequencies). It is a key technology that revolutionized WLAN performance starting from 802.11a/g onward, and it continues to be the backbone of modern Wi-Fi standards. It allows high-speed data transmission over wireless channels and helps handle multipath fading and interference in indoor environments. Bandwidth splitting ensures an efficient transmission while orthogonality reduces interference. This technology allows high spectral efficiency thus more data is transmitted in less bandwidth. The flexibility in sub carrier modulation also adds on the efficiency of the system.

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

a. 2.4 GHz
  - This is the oldest and most widely used Wi-Fi band.
  - It ranges from 2.400 GHz to 2.4835 GHz.
  - There are 14 channels, each 20 MHz wide, but due to overlap, only channels 1, 6, and 11 are typically used to avoid interference.
  - It has better range and wall penetration, but suffers from congestion due to interference from many devices like microwaves, Bluetooth, and cordless phones.
  - It supports Wi-Fi standards like 802.11b/g/n/ax.

b. 5 GHz
  - This band offers more non-overlapping channels, less interference, and higher data rates than 2.4 GHz.
  - It spans from 5.150 GHz to 5.825 GHz (depending on the region).
  - The channels are divided into groups called UNII bands (UNII-1, UNII-2, UNII-2e, UNII-3).
  - Some of these channels require DFS (Dynamic Frequency Selection) to avoid interference with radar systems.
  - It supports Wi-Fi standards like 802.11a/n/ac/ax.
  - It allows use of wider channels (up to 160 MHz), enabling faster speeds.

c. 6 GHz
  - This is a new band introduced with Wi-Fi 6E and Wi-Fi 7.
  - It ranges from 5.925 GHz to 7.125 GHz, offering a huge chunk of clean spectrum.
  - It supports 59 new channels (each 20 MHz), and allows ultra-wide channels up to 320 MHz, which is ideal for high-bandwidth applications.
  - It has very low interference, but also shorter range and lower wall penetration than 5 GHz.
  - Only available in Wi-Fi 6E and Wi-Fi 7 devices, and often restricted to indoor use in many regions.

d. 60 GHz
  - This is a high-frequency band used by technologies like Wi Gig (802.11ad and 802.11ay).
  - It ranges from 57 GHz to 71 GHz, depending on country regulations.
  - The main advantage of this band is its ability to support extremely high data rates, up to 40 Gbps, thanks to very wide channel bandwidths (2.16 GHz per channel).
  - It is ideal for short-range, line-of-sight communications such as VR headsets, wireless displays, or ultra-fast file transfers.
  - However, it cannot penetrate walls and has very limited range, typically 1–10 meters.

6. What is the role of Guard intervals in WLAN transmission? How does a short Guard interval improve efficiency?
   A Guard Interval is a short time delay inserted between symbols (data units) during transmission in OFDM-based systems like Wi-Fi. Its main purpose is to prevent inter-

symbol interference (ISI) caused by multipath propagation—when signals reflect off walls or objects and arrive at slightly different times. In wireless environments (especially indoors), a transmitted signal can bounce and create echoes. These echoes may arrive slightly delayed compared to the main signal. If the receiver starts reading the next symbol before the echo from the previous one dies out, it causes interference. The Guard Interval ensures there's a gap between each symbol so that echoes from the previous symbol fade away before the next one arrives. This helps the receiver correctly interpret each symbol.
Short guard improves efficiency by:

- Higher Data Throughput
  A shorter guard interval means more symbols can be transmitted in the same amount of time, directly increasing data rates.
- Better Spectral Efficiency
  Reducing the idle time between symbols leads to more efficient use of available bandwidth.
- Up to 10–11% Throughput Gain
  Using a short GI can boost the actual throughput by up to 10–11%, depending on signal conditions.

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

The PHY frame consists of two main sublayers:

- PMD (Physical Medium Dependent) Sublayer
- PLCP (Physical Layer Convergence Protocol)
  xplanation of each component in PHY layer frame
- PMD: Handles actual transmission & reception over the physical medium (modulation, RF signals).
- PLCP: Prepares MAC data for transmission. Adds timing & synchronization info.
- PLCP Preamble: Helps receiver detect and synchronize with incoming signal.
- PLCP Header: Contains rate, length, modulation info.
- PSDU: MAC Protocol Data Unit (MPDU) – actual data payload from MAC layer.
- PPDU: Entire PHY frame (PLCP + PSDU). This is what is transmitted over the air.

8. What is the difference between OFDM and OFDMA?

Feature	OFDM	OFDMA
Definition	Orthogonal Frequency Division Multiplexing divides a high-speed data stream into multiple lower-speed streams, each transmitted over separate subcarriers.	Orthogonal Frequency Division Multiple Access divides the subcarriers into **Resource Units (RUs)**, with each user assigned one or more RUs

User Access	Single user per transmission	Multiple users can transmit simultaneously
Subcarrier Allocation	All subcarriers used by one user	Subcarriers divided into Resource Units (RUs) per user
Efficiency	Less efficient in dense networks	Highly efficient in dense/multi-user environments
Latency	Higher (due to serial access)	Lower (parallel access reduces waiting time
Uplink Support	No multi-user uplink	Supports multiuser uplink and downlink.
Channel Utilization	Can be underutilized with small data packets	Better Channel usage
Use Case	High-speed single-user communication	High efficiency multi user scenarios
Used in	Wi-Fi 4 (802.11n), Wi-Fi 5 (802.11ac)	Wi-Fi 6 (802.11ax), Wi-Fi 7 (802.11be)

9. What is the difference MIMO and MU-MIMO?

Feature	MIMO (Multiple input Multiple output)	MU- MIMO (Multi User MIMO)
Purpose	Improves data rate and reliability for a single user	Serves multiple users simultaneously
User Support	One user at a time	Multiple users at once
Spatial Streams	All streams go to one device	Streams are split among different devices
Uplink Support	No	Yes
Performance Benefit	Higher speed and coverage for one device	Increased total network throughput for multiple users
Introduced In	Wi-Fi 4 (802.11n)	Wi Fi 5, Wi Fi 6
Ideal For	Streaming, downloads on a single device	Dense environments (offices, smart homes, etc.)

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

PPDU (PLCP Protocol Data Unit)

- The complete PHY layer frame that is transmitted over the air.
- It includes PLCP preamble, PLCP header, payload (PSDU), which is the MAC layer data.
- It's the actual **transmission unit** from the PHY layer, carrying all the info needed for the receiver to decode the signal correctly.

PLCP (Physical Layer Convergence Protocol)

- A sub-layer of the PHY layer that sits just above the physical medium.
- Prepares MAC layer data for transmission.
- Adds the preamble and header.

- Converts the MAC frame into a PPDU.
- It contains Preamble: (Used for synchronization and channel estimation), PLCP Header:(Contains metadata like data rate and frame length).

PMD (Physical Medium Dependent) Sublayer

- The **lowest sublayer** of the PHY layer.
- Deals with the **actual modulation**, **encoding**, and **transmission** of bits over the medium (air).
- It converts the bits into **electromagnetic signals** and transmits them via antenna.

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

The PPDU (PLCP Protocol Data Unit) is the format in which data is transmitted over the air at the physical (PHY) layer. Each generation of Wi-Fi (802.11 standards) has its own PPDU format, optimized for its features and performance goals.

Wi Fi Standard	PPDU Type	Structure
802.11a/g	Legacy OFDM PPDU	| Preamble | SIGNAL | Data |
802.11b	DSSS/CCK PPDU	| SYNC | SFD | Signal | Service | Length | CRC | PSDU |
802.11n	HT PPDU (High Throughput)	| Legacy Preamble | HT-SIG | HT-STF | HT-LTF | Data |
802.11ac	VHT PPDU (Very High Throughput)	| Legacy Preamble | VHT-SIG-A | VHT-STF | VHT-LTF(s) | VHT-SIG-B | Data |
802.11ax	HE PPDU (High Efficiency)	| L-STF | L-LTF | L-SIG | HE-SIG-A | HE-STF | HE-LTF(s) | HE-SIG-B | Data |
802.11be	EHT PPDU (Extremely High Throughput)	| L-STF | L-LTF | L-SIG | EHT-SIG-A | EHT-STF | EHT-LTF(s) | EHT-SIG-B | Data |

12. How is the data rate calculated?

Data Rate = (NSD × NBPSCS × R × NSS)/(TDFT + TGI)

- NSD: Number of data subcarriers (e.g., 980 for 80 MHz in 802.11ax)
- NBPSCS: Number of coded bits per subcarrier (depends on modulation)
- R: Coding rate (e.g., 5/6, 3/4) – fraction of data bits to total bits
- NSS : Number of spatial streams
- TDFT: OFDM symbol duration
- TGI: Guard Interval duration