### Q3)Modulation Schemes in Wi-Fi PHY Layer

Modulation is the process of encoding digital data onto a carrier signal for wireless transmission. Different Wi-Fi standards use various modulation schemes to optimize data rate, range, and reliability.

**1. Key Modulation Techniques in Wi-Fi**

**(A) Basic Digital Modulation Types**

1. **ASK (Amplitude Shift Keying)**
   * Rarely used in Wi-Fi.
   * Data encoded by varying signal amplitude.
2. **FSK (Frequency Shift Keying)**
   * Used in early wireless (e.g., FHSS in 802.11).
   * Data encoded by shifting frequency.
3. **PSK (Phase Shift Keying)**
   * **BPSK (Binary PSK)**
     + 1 bit per symbol (robust, low data rate).
     + Used in 802.11 (1 Mbps mode).
   * **QPSK (Quadrature PSK)**
     + 2 bits per symbol (better efficiency).
     + Used in 802.11 (2 Mbps mode).
4. **QAM (Quadrature Amplitude Modulation)**
   * Combines amplitude and phase modulation.
   * Higher-order QAM = more bits per symbol = higher speed.
   * **16-QAM** (4 bits/symbol), **64-QAM** (6 bits/symbol), **256-QAM** (8 bits/symbol), **1024-QAM** (10 bits/symbol).
5. **OFDM (Orthogonal Frequency Division Multiplexing)**
   * Splits data into multiple subcarriers to reduce interference.
   * Used in **802.11a/g/n/ac/ax/be**.

**2. Modulation Schemes Across Wi-Fi Standards**

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| --- | --- | --- | --- |
| Standard | Modulation Scheme | Max Data Rate | Key Features |
| 802.11 (1997) | DSSS (BPSK/QPSK), FHSS | 2 Mbps | Basic spread spectrum. |
| 802.11b (1999) | DSSS (CCK, QPSK) | 11 Mbps | Improved 2.4 GHz range. |
| 802.11a (1999) | OFDM (BPSK to 64-QAM) | 54 Mbps | 5 GHz, less interference. |
| 802.11g (2003) | OFDM (same as 802.11a) | 54 Mbps | 2.4 GHz, backward-compatible. |
| 802.11n (2009) | OFDM + MIMO (up to 64-QAM) | 600 Mbps | 40 MHz channels, spatial streams. |
| 802.11ac (2013) | OFDM + MU-MIMO (up to 256-QAM) | 6.9 Gbps | 160 MHz channels, beamforming. |
| 802.11ax (2019, Wi-Fi 6) | OFDMA (up to 1024-QAM) | 9.6 Gbps | Better efficiency, BSS coloring. |
| 802.11be (2024, Wi-Fi 7) | OFDMA + Multi-Link (up to 4096-QAM) | 46 Gbps | 320 MHz channels, lower latency. |

**3. Performance Comparison**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Modulation | Bits/Symbol |  | Data Rate | Usage |
| BPSK | 1 |  | Low | 802.11 (1 Mbps) |
| QPSK | 2 |  | Medium | 802.11 (2 Mbps) |
| 16-QAM | 4 |  | High | 802.11a/g/n |
| 64-QAM | 6 |  | Very High | 802.11n/ac |
| 256-QAM | 8 |  | Ultra High | 802.11ac/ax |
| 1024-QAM | 10 |  | Extreme | 802.11ax |
| 4096-QAM | 12 |  | Future | 802.11be (Wi-Fi 7) |

**Trade-offs:**

* **Higher-order QAM (e.g., 1024-QAM)** → More data but **less reliable** (needs strong signal).
* **Lower-order PSK (e.g., BPSK)** → Slower but **works in weak signals**.
* **OFDM/OFDMA** → Better spectral efficiency, handles multipath interference.

**4. Evolution of Wi-Fi Modulation**

* **Early Wi-Fi (802.11/b)** → DSSS/FHSS (BPSK, QPSK).
* **Mid-era (802.11a/g)** → OFDM (up to 64-QAM).
* **Modern Wi-Fi (802.11n/ac/ax/be)** → MIMO, MU-MIMO, higher QAM.
* **Future (Wi-Fi 7+)** → 4096-QAM, Multi-Link Operation (MLO).