MAC Methodologies

The MAC layer's primary goal is to prevent collisions and ensure efficient medium access in a shared wireless environment, where multiple devices compete for the same frequency channel. MAC methodologies achieve this by defining rules for when and how devices can transmit, using contention-based or contention-free approaches. These methodologies operate within the **Distributed Coordination Function (DCF)**, **Point Coordination Function (PCF)**, or **Hybrid Coordination Function (HCF)** frameworks, with enhancements for Quality of Service (QoS) and high-efficiency networks.

Key Objectives:

1. **Collision Avoidance**: Minimize simultaneous transmissions that cause data loss.
2. **Fair Access**: Ensure all devices have equitable opportunities to transmit.
3. **Efficiency**: Maximize channel utilization and throughput.
4. **QoS Support**: Prioritize traffic for time-sensitive applications (e.g., voice, video).
5. **Scalability**: Support dense networks with many devices.

Core Components:

- **Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)**: The foundation of most 802.11 MAC methodologies, using physical and virtual carrier sensing to avoid collisions.
- **Interframe Spacing (IFS)**: Time gaps between frames (e.g., SIFS, DIFS) to prioritize certain transmissions.
- **Backoff Mechanism**: Random delays to reduce contention after a busy channel.
- **Network Allocation Vector (NAV)**: A virtual carrier-sensing mechanism to reserve the medium.
- **Management/Control Frames**: Used to coordinate access (e.g., RTS/CTS, ACK).

Primary MAC Methodologies in IEEE 802.11

1. **Distributed Coordination Function (DCF)**
2. **Point Coordination Function (PCF)**
3. **Enhanced Distributed Channel Access (EDCA)**
4. **Hybrid Coordination Function Controlled Channel Access (HCCA)**
5. **Orthogonal Frequency Division Multiple Access (OFDMA)**

1. Distributed Coordination Function (DCF)

DCF is the fundamental contention-based MAC methodology in 802.11, using **CSMA/CA** to manage medium access. It is mandatory in all 802.11 networks and operates without centralized control, making it distributed and robust.

1. **Carrier Sensing**:
    - **Physical Carrier Sensing**: The station listens to the channel to detect ongoing transmissions (using the radio's clear channel assessment, or CCA).
    - **Virtual Carrier Sensing**: The station checks the **NAV** (set by the Duration/ID field in received frames) to determine if the medium is reserved.
2. **Interframe Spacing**:
    - If the channel is idle, the station waits for a **Distributed Interframe Space (DIFS)** before attempting to transmit.
    - DIFS is longer than other IFS (e.g., SIFS), ensuring higher-priority frames (e.g., ACKs) get precedence.
3. **Backoff Mechanism**:
    - If the channel is busy or a collision occurs, the station selects a random **backoff time** (in slot times, typically 9–20 μs) from a **Contention Window (CW)**.
    - The CW starts at CWmin (e.g., 15 slots) and doubles after each collision (up to CWmax, e.g., 1023 slots).
    - The station decrements the backoff counter when the channel is idle and transmits when it reaches zero.
4. **Transmission**:
    - The station sends its frame (e.g., data, management) if the channel remains idle after DIFS and backoff.
    - The receiver responds with an **ACK frame** after a **Short Interframe Space (SIFS)** to confirm successful receipt.
5. **RTS/CTS (Optional)**:
    - To mitigate the **hidden node problem**, the station may send a **Request to Send (RTS)** frame and wait for a **Clear to Send (CTS)** response before transmitting data.
    - RTS/CTS frames set the NAV for nearby stations, reserving the medium.

---

2. Point Coordination Function (PCF)

PCF is a contention-free MAC methodology that uses centralized control by the AP to manage medium access. It operates in a **Contention-Free Period (CFP)**, where the AP polls stations to grant transmission opportunities. PCF is optional and rarely implemented in practice.

1. **Contention-Free Period (CFP)**:
    - The AP initiates a CFP by sending a **Beacon frame** with a **CF Parameter Set**, announcing the start and duration of the CFP.

- The CFP alternates with a **Contention Period (CP)**, where DCF operates.

2. **Polling**:
    - The AP sends **CF-Poll frames** to specific stations, granting them exclusive access to the medium for a defined period.
    - Polled stations transmit data or respond with a **CF-ACK** or **Null frame** if no data is available.
    - The AP may combine polling with data delivery (e.g., **CF-Poll + Data**).
3. **Interframe Spacing**:
    - PCF uses a **Point Interframe Space (PIFS)**, shorter than DIFS but longer than SIFS, allowing the AP to seize the medium before DCF stations.
4. **CFP Termination**:
    - The AP ends the CFP with a **CF-End frame**, resuming DCF operation in the Contention Period.
5. **NAV**:
    - The NAV is set during the CFP to prevent DCF stations from transmitting, ensuring contention-free access.

---

3. Enhanced Distributed Channel Access (EDCA)

EDCA, introduced in IEEE 802.11e (QoS enhancements), is an advanced contention-based MAC methodology that extends DCF to provide **Quality of Service (QoS)** by prioritizing traffic. It uses differentiated access parameters for different traffic categories.

1. **Access Categories (ACs)**:
    - EDCA defines four ACs, each with a separate queue and access parameters:
        - **AC_VO (Voice)**: Highest priority, for low-latency applications (e.g., VoIP).
        - **AC_VI (Video)**: High priority, for streaming.
        - **AC_BE (Best Effort)**: Medium priority, for general traffic (e.g., web browsing).
        - **AC_BK (Background)**: Lowest priority, for non-critical traffic (e.g., file transfers).
2. **Differentiated Parameters**:
    - Each AC has its own:
        - **Arbitration Interframe Space (AIFS)**: Shorter for higher-priority ACs (e.g., AIFS[AC_VO] < AIFS[AC_BE]).
        - **Contention Window (CWmin, CWmax)**: Smaller for higher-priority ACs, reducing backoff time.
        - **Transmission Opportunity (TXOP)**: Higher-priority ACs get longer TXOPs to send multiple frames in a burst.
    - Example parameters:
        - AC_VO: AIFS = 2 slots, CWmin = 3, CWmax = 7, TXOP = 1.5 ms.
        - AC_BE: AIFS = 3 slots, CWmin = 15, CWmax = 63, TXOP = 0 ms.
3. **CSMA/CA with EDCA**:

- Each AC queue operates as a virtual station, performing CSMA/CA independently.
    - If multiple AC queues within a station contend simultaneously, the highest-priority queue wins (internal collision resolution).
    - The station transmits the frame from the winning AC, using the corresponding AIFS, CW, and TXOP.
4. **RTS/CTS and NAV**:
    - Similar to DCF, EDCA supports RTS/CTS to mitigate hidden nodes and sets the NAV for medium reservation.
5. **QoS Signaling**:
    - Stations and APs negotiate QoS parameters during association using **TSPEC (Traffic Specification)** or QoS Capability IEs.
    - **Block ACKs** improve efficiency by acknowledging multiple frames in a single response.

---

4. Hybrid Coordination Function Controlled Channel Access (HCCA)

HCCA, also introduced in IEEE 802.11e, is a contention-free MAC methodology that extends PCF to provide QoS through centralized, scheduled access. It operates within the **Hybrid Coordination Function (HCF)**, combining contention-free and contention-based access.

1. **Controlled Access Phase (CAP)**:
    - The AP initiates CAPs during the Contention Period (CP) or Contention-Free Period (CFP), seizing the medium after a **PIFS** (shorter than DIFS).
    - CAPs are announced via Beacon frames or QoS-specific management frames.
2. **Polling and Scheduling**:
    - The AP uses a **QoS-aware scheduler** to allocate **TXOPs** to stations based on their **TSPEC** (Traffic Specification), which defines traffic requirements (e.g., data rate, delay bounds).
    - The AP sends **QoS CF-Poll frames** to grant TXOPs to specific stations for specific ACs.
    - Polled stations transmit data within their TXOP, adhering to QoS parameters.
3. **Data Delivery**:
    - The AP may combine polling with data delivery (e.g., **QoS Data + CF-Poll**).
    - Stations respond with QoS Data, ACK, or Null frames.
4. **CAP Termination**:
    - The AP ends the CAP with a **CF-End frame**, resuming EDCA or DCF operation.
5. **NAV**:
    - The NAV is set during CAPs to prevent contention-based transmissions, ensuring controlled access.

---

5. Orthogonal Frequency Division Multiple Access (OFDMA)

OFDMA, introduced in IEEE 802.11ax (Wi-Fi 6), is an advanced MAC methodology that divides the channel into smaller subchannels (Resource Units, or RUs) to serve multiple stations simultaneously. It is a hybrid approach, combining contention-based and contention-free access, and is designed for high-efficiency networks.

1. **Channel Division**:
    - The channel (e.g., 20/40/80/160 MHz) is divided into **Resource Units (RUs)**, each as small as 2 MHz, supporting multiple users in parallel.
    - RUs are allocated for uplink (UL) or downlink (DL) transmissions.
2. **Trigger-Based Access**:
    - The AP sends a **Trigger Frame** to schedule OFDMA transmissions, specifying which stations can use which RUs and when.
    - Stations respond with uplink data in their assigned RUs during a **Multi-User (MU) TXOP**.
    - The AP acknowledges with a **Multi-User Block ACK (MU-BA)**.
3. **Random Access**:
    - The AP may allocate RUs for **Uplink OFDMA Random Access (UORA)**, allowing stations to contend for access using a random backoff within the RU.
    - Used for low-latency or unscheduled traffic (e.g., IoT sensor updates).
4. **Contention-Based Access**:
    - OFDMA integrates with EDCA for non-scheduled transmissions, allowing stations to contend for the channel using CSMA/CA.
5. **NAV and Synchronization**:
    - Trigger Frames set the NAV to reserve the medium for MU TXOPs.
    - Precise timing ensures synchronized UL/DL transmissions across RUs.