Power Saving in the MAC Layer

The primary goal of power saving in the MAC layer is to minimize the time a station's radio is active, as the radio consumes significant power when transmitting, receiving, or idle. The MAC layer achieves this by:

1. Allowing stations to enter a **sleep mode** (low-power state) when not communicating.
2. Coordinating with the AP to buffer data for sleeping stations and signal when data is available.
3. Using efficient wake-up schedules to balance power savings with communication reliability.

The power saving schemes rely on **Beacon frames**, **Traffic Indication Map (TIM)**, and **Delivery Traffic Indication Map (DTIM)** to manage station-AP communication, along with specific protocols for data retrieval and scheduling.

Types of Power Saving Mechanisms in the MAC Layer

The IEEE 802.11 standard defines several power saving mechanisms, each tailored to different network scenarios and device requirements. These mechanisms have evolved with newer Wi-Fi standards (e.g., 802.11n, 802.11ax) to improve efficiency and support high-density environments. The main types are:

1. **Legacy Power Save Mode (PSM)**
2. **PS-Poll (Power Save Poll)**
3. **Automatic Power Save Delivery (APSD)**
4. **Target Wake Time (TWT)**
5. **Spatial Multiplexing Power Save (SMPS)**
6. **Operating Mode Indication (OMI)**

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1. Legacy Power Save Mode (PSM)

Legacy PSM, introduced in the original 802.11 standard, allows stations to enter a low-power sleep state and wake up periodically to check for buffered data at the AP. It is the foundational power saving mechanism in Wi-Fi.

1. **Entering PSM**:
    - During association, the station specifies its **Listen Interval** (in Beacon intervals) in the Association Request frame, indicating how often it will wake up to check Beacons.

    - The station sets the **Power Management bit** to 1 in the Frame Control field of its frames to inform the AP it is entering PSM.
2. **Buffering Data**:
    - The AP buffers unicast data for stations in PSM and indicates buffered data in the **TIM** field of Beacon frames. Each station has an **Association ID (AID)**, and the TIM bitmap marks which AIDs have pending data.
    - Multicast/broadcast data is buffered and indicated in the **DTIM** field, sent every few Beacon intervals (e.g., every 3 Beacons).
3. **Waking Up**:
    - The station wakes up at its Listen Interval to receive Beacon frames and check the TIM/DTIM.
    - If the TIM indicates buffered unicast data (for the station's AID), the station sends a **PS-Poll frame** (see below) or a data frame to retrieve the data.
    - If the DTIM indicates multicast/broadcast data, all stations wake up to receive it.
4. **Data Retrieval**:
    - The AP sends buffered unicast data in response to a PS-Poll or data frame, with the **More Data bit** set to 1 if additional frames are buffered.
    - Multicast/broadcast data is sent immediately after the DTIM Beacon.
5. **Returning to Sleep**:
    - After receiving data (or if no data is buffered), the station returns to sleep until the next Listen Interval.

Use Cases:

- Early Wi-Fi devices (e.g., 802.11b/g).
- Low-power IoT devices with infrequent data exchanges (e.g., temperature sensors).

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2. PS-Poll (Power Save Poll)

PS-Poll is a mechanism within PSM where a station explicitly requests buffered data from the AP using a **PS-Poll frame**, typically after seeing its AID in the TIM.

1. The station wakes up to receive a Beacon and checks the TIM.
2. If the TIM indicates buffered data (AID bit set), the station sends a **PS-Poll frame** to the AP, including its AID.
3. The AP responds with one buffered data frame (or a null frame if no data remains) and sets the **More Data bit** to indicate additional buffered frames.
4. The station sends additional PS-Poll frames for each remaining buffered frame or returns to sleep.
5. The AP sends an **ACK** to confirm receipt of the PS-Poll, ensuring reliable communication.

Use Cases:

- Devices with low-to-moderate traffic requiring explicit data retrieval.
- Legacy networks where advanced power saving mechanisms are unavailable.

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3. Automatic Power Save Delivery (APSD)

APSD, introduced in IEEE 802.11e (QoS enhancements), improves upon legacy PSM by allowing more flexible and efficient data delivery for stations in power save mode. It is designed for QoS-sensitive applications (e.g., voice, video) and supports two variants: **Unscheduled APSD (U-APSD)** and **Scheduled APSD (S-APSD)**.

1. **Entering APSD**:
   - During association, the station indicates APSD support and specifies **Access Categories (ACs)** (e.g., Voice, Video, Best Effort) for power saving in the QoS Capability IE.
   - The station sets the **Power Management bit** to 1 to enter power save mode.
2. **Buffering Data**:
   - The AP buffers data for APSD-enabled stations, prioritizing frames based on ACs (per IEEE 802.11e EDCA).
   - The TIM/DTIM in Beacon frames indicates buffered data, as in legacy PSM.
3. **Unscheduled APSD (U-APSD)**:
   - The station wakes up and sends a **trigger frame** (a QoS Data or Null frame) to the AP, indicating it is awake and ready to receive data for a specific AC.
   - The AP responds with buffered frames for that AC, sending multiple frames in a single **service period** (a burst of data).
   - The AP sets the **End of Service Period (EOSP)** bit to 1 in the last frame to signal the end of the burst.
   - The station returns to sleep after the service period.
4. **Scheduled APSD (S-APSD)**:
   - The AP and station negotiate a fixed schedule for data delivery during association, using **TSPEC (Traffic Specification)** to define intervals and ACs.
   - The station wakes up at predetermined times to receive buffered frames without sending trigger frames.
   - The AP delivers frames during these scheduled periods.
5. **Returning to Sleep**:
   - After receiving data (or if no data is buffered), the station returns to sleep until the next trigger or scheduled wake-up.

Use Cases:

- Smartphones, tablets, and laptops running real-time applications (e.g., VoIP, video conferencing).
- QoS-enabled networks requiring low-latency data delivery.

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4. Target Wake Time (TWT)

TWT, introduced in IEEE 802.11ah (Wi-Fi HaLow) and enhanced in 802.11ax (Wi-Fi 6), allows stations and APs to negotiate specific times for data exchange, enabling precise scheduling of wake-up periods. It is highly efficient for IoT and dense networks.

1. **TWT Negotiation**:
    - During association or via management frames, the station and AP exchange **TWT Request/Response frames** to agree on:
        - **Wake Time**: When the station wakes up.
        - **Wake Interval**: Time between wake periods.
        - **Service Period Duration**: Duration of data exchange.
        - **TWT Flow ID**: Identifies the TWT session (for multiple concurrent sessions).
    - Two modes:
        - **Individual TWT**: Negotiated between a single station and AP.
        - **Broadcast TWT**: AP assigns wake times to multiple stations via Beacon frames.
2. **Entering Power Save**:
    - The station enters a deep sleep mode, waking only at the agreed TWT Service Periods.
3. **Data Exchange**:
    - During the TWT Service Period, the AP sends buffered data (unicast or multicast) to the station, and the station may transmit uplink data.
    - The AP uses **OFDMA** (in 802.11ax) to serve multiple stations simultaneously, reducing contention.
4. **Returning to Sleep**:
    - After the Service Period, the station returns to sleep until the next TWT wake time.

Use Cases:

- IoT devices (e.g., smart meters, environmental sensors) with predictable, infrequent traffic.
- Wi-Fi 6 networks in dense environments (e.g., stadiums, offices).
- Applications requiring deterministic data delivery (e.g., industrial automation).

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5. Spatial Multiplexing Power Save (SMPS)

SMPS, introduced in IEEE 802.11n and enhanced in later standards, reduces power consumption by limiting the number of spatial streams (MIMO antennas) used for transmission and reception.

1. **SMPS Modes**:
   - **Static SMPS**: The station uses a single spatial stream for all communication, reducing power consumption.
   - **Dynamic SMPS**: The station switches to a single spatial stream when idle or receiving short frames, enabling multiple streams only for high-throughput data.
2. **Negotiation**:
   - During association, the station indicates SMPS support in the **HT Capabilities IE** (High Throughput, 802.11n).
   - The station or AP can dynamically switch modes using **SMPS Action frames** or frame headers.
3. **Operation**:
   - In Static SMPS, the station's radio operates with one antenna, minimizing power usage.
   - In Dynamic SMPS, the station monitors traffic and enables additional antennas only for MIMO transmissions, returning to single-stream mode afterward.
4. **Data Exchange**:
   - The AP adjusts its transmission to match the station's SMPS mode, ensuring compatibility.

Use Cases:

- Laptops, smartphones, and tablets using 802.11n/ac/ax in power-constrained scenarios.
- Environments with mixed traffic (e.g., low-bandwidth control messages and high-bandwidth streaming).

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6. Operating Mode Indication (OMI)

OMI, introduced in IEEE 802.11ax (Wi-Fi 6), allows stations to dynamically adjust their operating mode (e.g., channel width, number of spatial streams) to save power and optimize performance.

1. **OMI Negotiation**:
   - The station signals its operating mode preferences in the **HE Capabilities IE** (High Efficiency, 802.11ax) during association.
   - The station or AP uses **OMI Control fields** in data or management frames to request mode changes.
2. **Mode Adjustment**:
   - **Channel Width**: The station reduces channel width (e.g., from 80 MHz to 20 MHz) to lower power consumption at the cost of throughput.
   - **Spatial Streams**: The station reduces the number of spatial streams, similar to SMPS.
   - **Receive Parameters**: The station adjusts modulation or coding schemes for power efficiency.
3. **Data Exchange**:

    - The AP respects the station's OMI settings, transmitting frames compatible with the reduced mode.
4. **Dynamic Updates**:
    - The station can switch modes dynamically based on traffic needs, using OMI Action frames or frame headers.

Use Cases:

- Wi-Fi 6 devices in high-density environments (e.g., airports, campuses).
- Applications with variable bandwidth needs (e.g., mixed IoT and streaming traffic).