

The PPDU (PLCP Protocol Data Unit) frame format in the IEEE 802.11 PHY layer varies across Wi-Fi generations (e.g., 802.11a/b/g/n/ac/ax) to accommodate evolving technologies like OFDM, MIMO, MU-MIMO, and OFDMA. The PPDU structure consists of a preamble, header, and payload (PSDU), with adaptations reflecting improvements in efficiency, multi-user support, and higher data rates.

#### Types of PPDU

1. **Legacy PPDU**: Used in 802.11a/b/g, designed for single-user, non-MIMO environments with basic modulation schemes.
2. **HT (High Throughput) PPDU**: Introduced in 802.11n, supports MIMO and wider channels (20/40 MHz).
3. **VHT (Very High Throughput) PPDU**: Introduced in 802.11ac, enhances MIMO with up to 8 spatial streams and 160 MHz channels.
4. **HE (High Efficiency) PPDU**: Introduced in 802.11ax (Wi-Fi 6), supports OFDMA, MU-MIMO, and 1024-QAM for multi-user efficiency.
5. **HE ER (High Efficiency Extended Range) PPDU**: A variant of HE PPDU in 802.11ax, optimized for extended range in outdoor or low-density scenarios.

#### PPDU Frame Format Across Wi-Fi Generations

##### 1. Legacy PPDU (802.11a/b/g)

Structure:

Preamble:

Short Training Field (STF): 8  $\mu$ s, for coarse synchronization.

Long Training Field (LTF): 8  $\mu$ s, for fine synchronization and channel estimation.

Header (PLCP Header):

- Signal Field (SIG): 24 bits (RATE, LENGTH, Parity, 6 Tail bits), indicates modulation and data length.
- Service Field: 7 bits, initializes scrambler.
- Tail Bits: 6 bits, resets encoder.
- CRC: 16 bits, for header error detection.

Payload (PSDU): Variable length (up to 4095 bytes), modulated with BPSK/QPSK/16-QAM/64-QAM, encoded with convolutional coding.

Duration: Approximately 20  $\mu$ s preamble + 4  $\mu$ s header + payload time (depends on rate, e.g., 6-54 Mbps in 802.11a).

Features: Single-user, 20 MHz channels, no MIMO, designed for basic indoor use.

##### 2. HT PPDU (802.11n)

Structure:

Preamble:

- Legacy Preamble (L-STF, L-LTF)\*\*: 16  $\mu$ s, for backward compatibility with 802.11a/g.

- HT-STF: 4  $\mu$ s, for MIMO synchronization.
- HT-LTF(s): Variable (e.g., 4  $\mu$ s per stream, up to 4 streams), for channel estimation in MIMO.

Header:

- L-SIG: 4  $\mu$ s, legacy signal field for compatibility.
- HT-SIG: 8  $\mu$ s, 40 bits (MCS, channel width 20/40 MHz, MIMO details, CRC, Tail).

Payload (PSDU): Up to 65,535 bytes, modulated with BPSK to 64-QAM, supports 20/40 MHz channels.

Duration: Varies with MIMO configuration (e.g., 24  $\mu$ s preamble/header + payload time, up to 600 Mbps).

Features: Introduces MIMO (up to 4x4), optional 40 MHz channels, greenfield mode (no legacy preamble) for pure 802.11n networks.

### **3. VHT PPDU (802.11ac)**

Structure:

Preamble:

- L-STF, L-LTF, L-SIG: 20  $\mu$ s, for legacy compatibility.
- VHT-SIG-A: 8  $\mu$ s, 52 bits (group ID, partial AID, bandwidth 20/40/80/160 MHz, MCS, STBC).
- VHT-STF: 4  $\mu$ s, for MIMO training.
- VHT-LTF(s): Variable (e.g., 4  $\mu$ s per stream, up to 8 streams).
- VHT-SIG-B: 4  $\mu$ s, 26 bits, per-user MCS and coding.

Header: Embedded in VHT-SIG fields, includes beamforming and multi-user data.

Payload (PSDU): Up to 65,535 bytes, supports 256-QAM, 80/160 MHz channels.

Duration: Approximately 28-32  $\mu$ s preamble/header + payload time (up to 1.3 Gbps or more).

Features: MU-MIMO (up to 4 users), 256-QAM, wider channels, beamforming for enhanced range and throughput.

### **4. HE PPDU (802.11ax)**

Structure:

Preamble:

- L-STF, L-LTF, L-SIG: 20  $\mu$ s, for legacy compatibility.
- RL-SIG 4  $\mu$ s, repeated L-SIG for protection.
- HE-SIG-A: 8  $\mu$ s, 52 bits (bandwidth, BSS color, RU allocation for OFDMA).
- HE-STF: 4  $\mu$ s, for MIMO training.
- HE-LTF(s): Variable (e.g., 3.2-13.6  $\mu$ s depending on streams, up to 8).

- HE-SIG-B Optional, 4  $\mu$ s, per-user RU allocation (present in MU mode).

Header: Distributed across HE-SIG-A/B, includes OFDMA and MU-MIMO scheduling.

Payload (PSDU): Up to 65,535 bytes, supports 1024-QAM, 20/40/80/160 MHz, divided into RUs for multiple users.

Duration: Varies (e.g., 32-40  $\mu$ s preamble/header + payload time, up to 9.6 Gbps).

Features: OFDMA (up to 74 RUs), MU-MIMO (up to 8 users), 1024-QAM, improved efficiency in dense environments.

## **5. HE ER PPDU (802.11ax Extended Range)**

Structure:

Similar to HE PPDU but optimized for range.

Preamble: Includes extended LTFs (e.g., 6.4  $\mu$ s per symbol) and reduced modulation in SIG fields for robustness.

Header: Simplified HE-SIG for lower data rates (e.g., BPSK).

Payload: Supports lower MCS (e.g., BPSK 1/2) for longer reach, smaller RUs.

Duration: Longer preamble (up to 40+  $\mu$ s) + extended payload time for range.

Features: Targets outdoor or low-density use, sacrificing speed for coverage.

**Evolution:** Legacy PPDU supports basic single-user transmission, HT/VHT PPDUs add MIMO and wider channels, and HE PPDUs introduce OFDMA and multi-user efficiency.

**Adaptability:** Each generation retains legacy compatibility while adding fields (e.g., HT-SIG, VHT-SIG, HE-SIG) for new features like MU-MIMO and 1024-QAM.

**Performance:** Frame duration and complexity increase with advanced standards, balancing throughput, range, and multi-user support.