

What Does Ultra High Reliability Mean from a Physical-Layer Perspective?

Wi-Fi 8 (IEEE 802.11bn) Draft 1.0 brings greater clarity to the physical-layer features designed to achieve Ultra High Reliability.

The release of Wi-Fi 8 (802.11bn) Draft 1.0 has provided significant clarity on the physical-layer features meant to achieve Ultra High Reliability (UHR). While some might have anticipated groundbreaking new modulations, wider channels beyond 320 MHz, or entirely new MIMO schemes, this initial draft reveals a more nuanced approach. Wi-Fi 8 introduces refined mechanisms to optimize and fine-tune existing features, enhancing their capabilities.

It's a reality that, even with Wi-Fi 7's extensive feature set — including UL-OFDMA, MLO, and 320-MHz channels — the widespread real-world deployment remains a challenge. Despite compelling marketing, practical network implementation, and making such advanced features consistently perform, these are complex tasks.

Consequently, with Wi-Fi 8, the IEEE appears to have deliberately introduced features aimed at fundamentally improving link resilience across varied channel conditions and enhancing overall reliability.

This article delves into these details, categorizing the new physical-layer features primarily under three umbrella

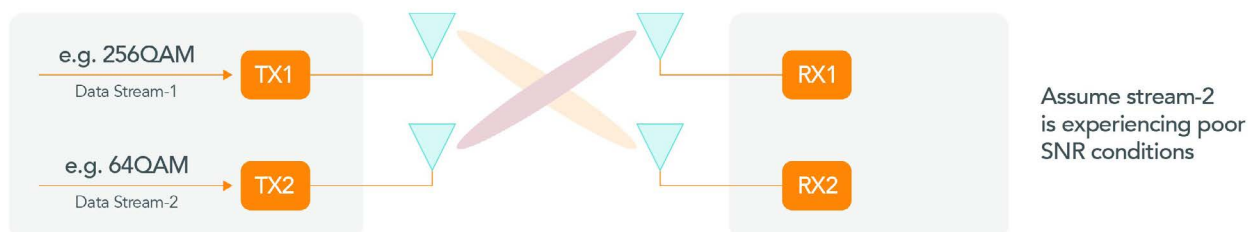
segments: robustness, reliability, and range. To ensure clarity, it's crucial to understand the distinction between robustness and reliability, as these terms are often used interchangeably.

Robustness refers to signal integrity and resilience — how well the signal maintains its quality and resists degradation from noise or interference under challenging channel conditions. Reliability, on the other hand, signifies the probability of successful transmission. It's the assurance that data will be delivered to the receiver with minimal retransmissions.

Both metrics are complementary and crucial for high-quality communication. Understanding their differences is vital to comprehending the impact of Wi-Fi 8's new features and precisely what they're designed to deliver. With these distinctions established, we will now examine each feature within its respective category.

Robustness: New Modulation and Coding Scheme (MCS) Combinations

The primary goal with these new MCS combinations is to enhance rate adaptation. While Wi-Fi 8 doesn't introduce



1. Tailoring modulation to the specific characteristics of each spatial stream.

entirely new modulation schemes, it significantly improves the resilience of existing ones. This is achieved by introducing lower code rates, which increase the redundancy of the transmission.

Wi-Fi 7's MCS 0-15 are carried over to Wi-Fi 8, with the addition of new indexes (17, 19, 20, and 23) for QPSK, 16QAM, and 256QAM modulations (Fig. 1), as defined in the D0.3 draft specification.

Unequal Modulation (UEQM)

This feature enables the use of asymmetric modulation schemes across multiple spatial streams, primarily to enhance transmission efficiency in multiple-input multiple-output (MIMO) systems.

Traditionally, MIMO transmissions apply the same modulation scheme across all spatial streams, irrespective of their individual channel conditions. This often results in the overall data rate being limited by the weakest stream, as different streams may experience varying SNR conditions. UEQM addresses this by allowing different modulation orders to be applied to individual streams, adapting based on their respective channel conditions to optimize the overall transmission.

It's important to note that the current specification for UEQM permits its use only for configurations with two to four spatial streams, excludes BPSK modulation, and is limited to single-user MIMO (SU-MIMO) cases.

Enhanced Long-Range PPDU (ELR-PPDU)

IEEE has introduced enhanced long-range physical-layer protocol data units (ELR-PPDUs) specifically for client devices within the UHR framework. The primary intent of ELR-PPDUs is to mitigate the significant link-budget imbalance between the uplink (UL) and downlink (DL).

A common challenge in Wi-Fi is that access points (APs)

operate at much higher transmit power, making them easily heard by client devices. Conversely, client devices, due to their typically lower transmit power, are often “unheard” by the AP, especially at greater distances. This power disparity creates a link-budget imbalance that severely impacts devices farther from the AP.

To address this, UHR introduces ELR-PPDUs, which are fixed-bandwidth (20 MHz) PPDU designed for single spatial streams. They can be utilized for both downlink and uplink operations in the 2.4-GHz band but are restricted to uplink-only transmissions in the 5- and 6-GHz bands.

To ensure extended range and reliability, these PPDU employ lower MCS rates (specifically MCS 0 and 1) to minimize misinterpretation and errors. Furthermore, they incorporate four-times frequency-domain duplication over a 52-tone regular resource unit (RRU) for added redundancy, significantly enhancing reliability.

A typical UHR ELR-PPDU must include an ELR-MARK field and an ELR-SIG field. The ELR-MARK field provides additional signaling, enabling the receiver to distinguish a UHR ELR-PPDU from other PPDU. It enhances detection by using predefined tone patterns for cross-correlation at the receiver. The ELR-SIG field, on the other hand, carries essential information required to interpret the UHR ELR-PPDU correctly.

Reliability: Longer Low-Density Parity Codes (LDPC)

With UHR, IEEE has introduced a significant enhancement to forward error correction: a codeword length of 3,888 bits for station (client) devices. This effectively doubles the longest codeword length available in Wi-Fi 7, substantially improving the system's ability to correct errors.

What are LDPC codes? In plain language, LDPC codes

Device Class	Operating Bands	Max EIRP	Max EIRP Power Spectral Density
Standard Power Access Point (AFC Controlled)	U-NII-5 (5.925-6.425 GHz)	36 dBm	23 dBm/MHz
Client Connected to Standard Power Access Point	U-NII-7 (6.525-6.875 GHz)	30 dBm	17 dBm/MHz
Low-Power Access Point (indoor only)	U-NII-5 (5.925-6.425 GHz)	30 dBm	5 dBm/MHz
Client Connected to Low-Power Access Point	U-NII-6 (6.425-6.525 GHz) U-NII-7 (6.525-6.875 GHz) U-NII-5 (6.875-7.125 GHz)	24 dBm	-1 dBm/MHz

2. Summary of power requirements in the 6-GHz frequency band.

are a mechanism that adds redundant or “parity” bits to the original data. These extra bits enable the receiver to successfully correct errors that may occur during transmission, making the data more resilient to challenging channel conditions and significantly increasing the probability of successful decoding. This, in turn, helps avoid retransmissions.

While longer codes are highly effective at maintaining higher effective throughput, they introduce latency because both the encoder (at the transmitter) and the decoder (at the receiver) must process larger codewords. However, the added robustness proves highly effective in noisy environments (poor SNR conditions), particularly benefiting clients at the edge of an AP’s coverage.

Per the specification, the TB PPDU code type is indicated through the UL FEC Coding Type subfield within the User Info field. A setting of “0” signifies the use of binary convolutional code (BCC) codes, while “1” indicates the choice for LDPC codes. Furthermore, if the 2xLDPC subfield of the User Info field is set to “1,” it denotes the use of the nominal 3,888-bit LDPC codeword length. If set to “0,” it indicates the use of shorter codeword lengths (648, 1,296, or 1,944 bits).

Range: Distributed RU (dRU)

As the name implies, it involves the distribution of resource unit (RU) tones over a larger bandwidth (Fig. 2). To understand its significance, consider the background: In 2020, when the FCC opened the 6-GHz band for unlicensed use, it established strict transmit power guidelines for Wi-Fi APs and client devices to protect incumbent services.

Among these, low-power indoor (LPI) client devices face the tightest limit of -1 dBm/MHz power spectral density (PSD). This stringent PSD requirement often limits uplink (UL) transmit range — it creates an inherent UL/DL power imbalance where APs can easily be heard by clients, but clients struggle to reach distant APs reliably.

The dRU feature is specifically designed to benefit these LPI client devices operating in the 6-GHz band. It allows RU tones to be distributed over non-consecutive physical subcarriers, effectively reducing the number of tones per 1 MHz assigned to each station. With this innovative approach devices can transmit higher UL OFDMA power, thereby effectively extending transmission range without exceeding regulatory PSD requirements.

Key Specifications and Limitations

- **Usage:** dRU is permitted exclusively in uplink UHR trigger-based (TB) PPDU for single-user scenarios only, with a maximum of two spatial streams. It’s not supported in multi-user MIMO (MU-MIMO) configurations.
- **MCS support:** All modulation and coding schemes are

allowed for dRU transmissions, with the sole exception of MCS-15.

- **Minimum RU size:** The smallest supported RU size for dRU is 26-tone.
- **Supported distribution bandwidths (DBWs):** dRU supports distribution bandwidths of 20, 40, and 80 MHz, with a maximum DBW of 80 MHz.
 - For a 20-MHz TB PPDU, the DBW is limited to 20 MHz.
 - For a 40-MHz TB PPDU, the DBW is limited to 40 MHz.
- **Hybrid mode support:** dRU also supports a hybrid mode, allowing for the coexistence of both dRUs and regular RUs (rRUs) within a single OFDMA transmission.
 - This hybrid mode is applicable to 160- and 320-MHz bandwidths.
 - The minimum RU size in hybrid mode is 242 tones.

Fortifying Wireless Connectivity

The physical-layer features, though subtle, are meticulously designed to strengthen the three core pillars of wireless connectivity: coverage, speed, and reliability. These attributes profoundly impact the end-consumer experience. With a clear focus on determinism and reliability, such features are optimized for both access points and resource-limited client stations, enhancing uplink range and connectivity. This strategic design also aims to maximize spectrum and resource utilization.

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