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Evolving Wi-Fi: An Analysis of 802.11ax and 802.11be Standards in Modern Wireless Networks

Abstract:

The evolution of Wi-Fi protocols addresses growing consumer demands for widespread Internet of Things (IoT) integration, high-speed data transfer, and reduced network congestion. This paper explores the technological advancements and capabilities of Wi-Fi 6 (802.11ax) and Wi-Fi 7 (802.11be). These standards are crucial for delivering higher throughput and reliable connections in dense network environments. Wi-Fi 6 improves performance through Orthogonal Frequency-Division Multiple Access (OFDMA) and Multi-User Multiple Input Multiple Output (MU-MIMO). Wi-Fi 7 further enhances performance with increased channel band bandwidth[1] width and multi-link operation support. The new standards enable emerging applications such as virtual reality and ultra-high-definition video streaming.

Introduction:

The growing number of connected devices is straining current wireless networking technologies, necessitating bandwidth and connection density increases. The evolution of IEEE 802.11 standards has been crucial in addressing these challenges. Wi-Fi 6 enhances network capacity, reduces latency, and improves overall efficiency in environments densely populated with connected devices with technologies like OFDMA and an improved implementation of MU-MIMO (Lopez-Perez et al. 113).

Wi-Fi 7 builds upon Wi-Fi 6 to support even higher data rates and more reliable services across an expanded array of frequency bands. Innovations in this standard include the adoption of 320 MHz channel bandwidths and the capability to produce up to 16 spatial streams. Furthermore, Wi-Fi 7 introduces Multi-Link Operation, allowing devices to utilize multiple frequency bands simultaneously for data transmission, significantly boosting throughput and reducing latency in high-demand scenarios. Additionally, the Multi-Resource Unit feature enhances channel flexibility to meet high throughput needs, improving efficiency and network adaptability in diverse operational environments. These advancements reflect a shift towards accommodating an increasing number of devices and supporting the complex digital ecosystems that require robust, high-speed connections, such as IoT implementations (Lopez-Perez et al. 113).

Technical Description:

Past Milestones:

802.11b (1999): As the first widely successful Wi-Fi standard, 802.11b introduced speeds up to 11 Mbps and achieved commercial success (Wilhelmsson et al., 2022).

802.11a/g (1999/2003): These standards introduced higher frequencies and speeds (up to 54 Mbps), with 802.11g combining the benefits of 802.11b's range and 802.11a's speed, enhancing wireless access across consumer and enterprise markets (Wilhelmsson et al., 2022).

802.11n (2009): Brought enhancements such as MIMO (Multiple Input, Multiple Output) technology, which uses multiple antennas to improve the signal and increase the data rate up to 600 Mbps (Wilhelmsson et al., 2022).

802.11ac (2013): Also known as Wi-Fi 5, it increased the maximum data rates up to several gigabits per second, optimizing Wi-Fi for multiple devices and high-bandwidth applications (Wilhelmsson et al., 2022).

[1] The range of frequencies used to transmit data between devices, affecting the network's data rate and capacity.

Other Current/Future Versions:

802.11ay: Enhances 60 GHz Wi-Fi with increased range and throughput of at least 20 Gb/s, adding features like single-user (SU-)MIMO and MU-MIMO like 802.11ax (Wilhelmsson et al., 2022).

802.11az: Focuses on enhancing positioning capabilities with accuracy better than 1 meter (Wilhelmsson et al., 2022).

802.11ba: Introduces Wake-up Radio for low-power IoT devices, significantly reducing power consumption (Wilhelmsson et al., 2022).

802.11bb: Develops standards for operation in the light spectrum for Li-Fi applications (Wilhelmsson et al., 2022).

Wi-Fi 6 versus Wi-Fi 7:

Wi-Fi 6:

Wi-Fi 6 introduces several technologies to improve efficiency and capacity in dense environments. According to Dugand, the technology improves on Wi-Fi 5 with “double the maximum MIMO configuration, double the maximum channel bandwidth and a higher modulation scheme,” which results in “more than 5 times the maximum data rate at PHY level[2]” (Dugand). However, the key to Wi-Fi 6’s success lies in its higher network efficiency, especially in device-dense areas offering higher throughput and lower latency. This efficiency is largely due to two innovative features:

(1) OFDMA: Increases network efficiency and latency through more efficient data packing (Lopez-Perez et al. 113). This technology enables simultaneous data transmission by multiple users within the same channel, significantly surpassing previous generations (OFDM[3]) in terms of efficiency. The figure below (Figure 1) shows how OFDMA transfers data for multiple users simultaneously instead of sequentially, as in OFDM. OFDMA can, therefore transmit data to three users at the same time it would take OFDM to transmit to one.

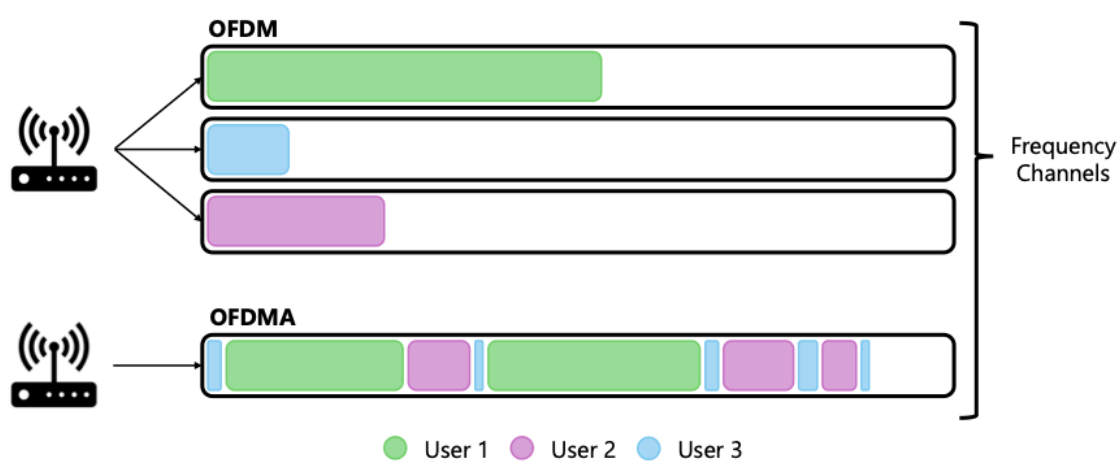

Figure 1

(2) MU-MIMO: Enhances throughput and efficiency by allowing data transmission to and from several devices simultaneously (Lopez-Perez et al. 113). This feature is crucial in crowded settings, supporting numerous devices that require concurrent access. See Figure 2 for the difference between MU-MIMO and SU-MIMO.

[2] Physical Level of OSI model.

[3] Orthogonal Frequency-Division Multiplexing (OFDM) is a data encoding method on multiple carrier frequencies to optimize spectral efficiency and reduce interference in wireless signals. OFDM is utilized in 802.11a, 802.11g, 802.11n, and 802.11ac.

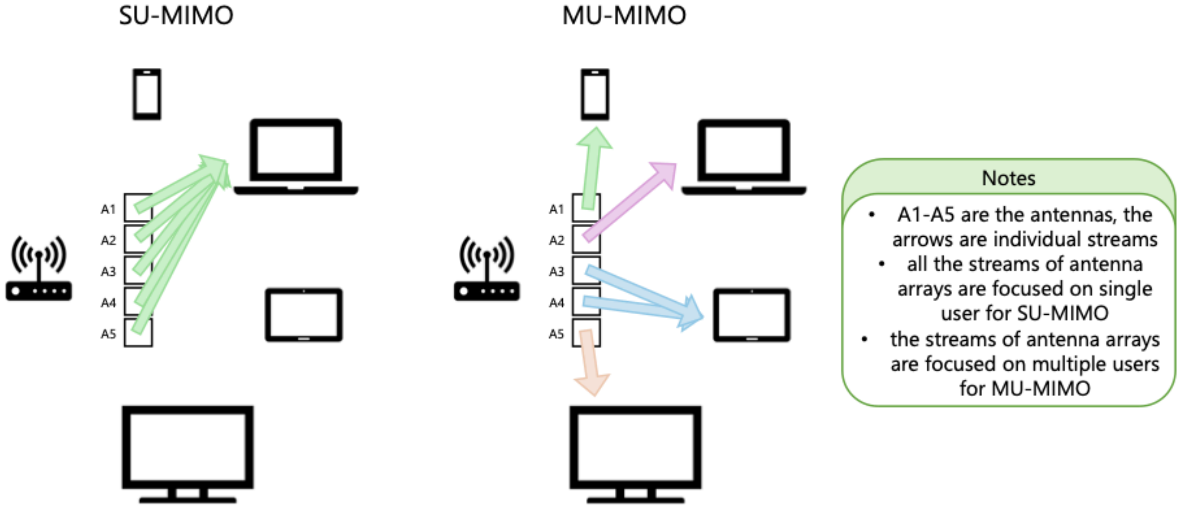

Figure 2

As mentioned before, this standard also features a new modulation scheme, 1024-QAM[4], which Lopez-Perez et al. note “provides a 25% increase in data rate under the same conditions as 256-QAM” (113), pushing the boundaries of data transmission speeds in optimal conditions.

Wi-Fi 6E:

Wi-Fi 6E extends the capabilities of Wi-Fi 6 by incorporating the 6 GHz band ((5.925 GHz to 7.125 GHz), adding up to seven 160 MHz channels or up to fourteen 80 MHz channels), significantly expanding the available spectrum for wireless communications. According to Dugand, while Wi-Fi 6 operates on the 2.4 GHz and 5 GHz bands, these frequencies have become increasingly crowded due to the proliferation of various wireless technologies such as Bluetooth, Zigbee, and Thread. The 5 GHz band, often referred to as the “express highway” to avoid congestion, is also becoming stretched, especially with the growing demand for higher data bandwidth driven by more video streaming services and the rise in remote work during the COVID-19 pandemic (Dugand). Intel highlights that this additional spectrum provides Wi-Fi 6E devices with a dedicated space free from legacy Wi-Fi interference, enhancing performance for applications such as gaming and augmented/virtual reality (Intel). The trade-off for this new band is a more limited range and reduced ability to penetrate walls and ceilings.

Wi-Fi 7:

Wi-Fi 7 improves on Wi-Fi 6 and 6e, introducing several enhancements. One of the major improvements is the increase in channel bandwidth to 320 MHz, effectively doubling the capacity from 160 MHz, which markedly elevates data throughput capabilities. Lopez-Perez et al. note that Wi-Fi 7 is designed to “support a maximum throughput of at least 30 Gb/s... using carrier frequencies between 1 and 7.125 GHz” (113).

Additionally, Wi-Fi 7 integrates Multi-Link Operation (MLO), a feature that Dugand describes as allowing “the ability to aggregate two channels from the same or different bands to increase the throughput,” an essential feature for managing the demands of high-bandwidth applications such as virtual reality and ultra-high-definition streaming (Dugand). Chauhan et al. further detail that this allows

[4] Quadrature Amplitude Modulation: A digital modulation method used in Wi-Fi that modulates both amplitude and phase of a carrier wave to encode data. The higher the QAM level (e.g., 16-QAM, 256-QAM, 1024-QAM) indicates higher data rates but requires better signal quality.

devices to “operate across multiple frequency bands or channels simultaneously” (1). MLO also enhances load balancing by seamlessly switching between channels to minimize contentions and retries, reducing latency.

Figure 3

Another critical feature of Wi-Fi 7 is the Multi Resource Unit (MRU), which, similar to MLO, allows the aggregation of two contiguous or disjointed Resource Units on the same channel to meet a single user's high throughput needs. This flexibility in channel management underlines Wi-Fi 7's capability to handle diverse and dynamic network demands effectively.

The standard supports up to 16 spatial streams[5] (up from 8 streams), potentially doubling the throughput capabilities compared to Wi-Fi 6. Chauhan et al. describe this as “a monumental enhancement in handling multiple devices and operations simultaneously” (1). Additionally, introducing enhanced MU-MIMO and a better modulation method (4096-QAM) significantly improves communication efficiency and throughput in optimal conditions. Lopez-Perez et al. remark that the integration of “320 MHz Channel Bandwidth and Multi-Link Operation ensures it can handle future high-throughput applications that Wi-Fi 6 starts to strain under” (113).

These advancements make Wi-Fi 7 nearly five times faster than Wi-Fi 6/6E, positioning it as a critical technology for the next generation of wireless communication (Dugand).

Conclusion:

The relentless evolution of Wi-Fi technology, driven by the insatiable global thirst for connectivity and bandwidth, manifests through the development of standards like 802.11ax (Wi-Fi 6) and 802.11be (Wi-Fi 7). Each generation of Wi-Fi not only addresses the limitations of its predecessors but also anticipates and shapes the networking landscapes of the future. Wi-Fi 6 has laid a robust foundation, enhancing network efficiency and capacity with advanced features like OFDMA and MU-MIMO, optimized for dense and complex environments. Wi-Fi 7 builds upon these improvements, offering higher data rates and improved reliability across a broader spectrum range. This advancement enables a new realm of applications, from immersive virtual reality to comprehensive smart city infrastructures.

[5] Spatial stream: unique data stream that is transmitted over a separate spatial path or dimension. In the context of MIMO, a spatial stream represents an independent path over which data can be transmitted simultaneously to increase throughput.

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