An Overview of the 802.11ax Standard

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***Abstract*—By introducing the WLAN standard 802.11ax, IEEE adjusted Wi-Fi for an era with more users and more connected devices than ever. New developments regarding the Internet of Things, as well as an increasing number of high-density networks, required major improvements compared to the previous standard 802.11ac. Also called High Efficiency Wi-Fi 6, 802.11ax enables more users than ever to be connected to one single access point using new key technologies like OFDMA and MU-MIMO. Wi-Fi 6 also enhances large distance transmissions and improves transmission quality. This paper gives an introduction to the most prominent technologies introduced by Wi-Fi 6 and examines these changes in comparison to its predecessor Wi-Fi 5. Nonetheless, there are several shortcomings of Wi-Fi 6 that will likely be addressed by its successor Wi-Fi 7, which is to be released in 2024.**

***Index Terms*—802.11ax, Wi-Fi 6, High Efficiency Wi-Fi, ODFMA, BSS-Coloring, MU-MIMO**

1. Introduction

Wireless local area networks (WLANs) and cellular networks are becoming increasingly popular. Cisco [1] recently estimated that in 2023, three times more devices were connected to IP networks than there are humans on earth. Compared to 2018, 15 percent more humans will have access to the Internet by the end of 2023, as a study [1] has shown.
With the increasing number of Internet users, the strain on Wi-Fis also amplifies. Especially high-density wireless networks face challenges. Users continue to ask for higher performance and improved user experience. As a response to these challenges, the Institute of Electrical and Electronics Engineers (IEEE) has developed 802.11ax, also known as High Efficiency Wi-Fi or Wi-Fi 6. [2]
Introduced in October 2018, Wi-Fi 6 includes several key technologies crucial to serving a larger number of devices and users in high-density networks. [3] Therefore, two new key technologies are introduced: Orthogonal Frequency Division Multiple Access (OFDMA) and uplink Multi-User Multiple Input Multiple Output (MU-MIMO). Both technologies enable many stations to transmit to the same access point (AP) and vice versa. [4] OFDMA splits a channel into multiple resource units, which can then be employed by numerous stations simultaneously. [4] MU-MIMO uses spatial streams to allow simultaneous transmissions. [4]
Furthermore, Wi-Fi 6 aims to enhance transmissions over larger distances and improve transmission quality by introducing new technologies like midambles, which are symbols added to a transmission for noise reduction. [5]
Compared to its predecessor 802.11ac, also known as Wi-Fi 5, Wi-Fi 6 comes with many new features regarding Physical and MAC[1] Layers. [2]
Therefore, we will present the changes regarding the Physical Layer in Section 2 and MAC Layer changes in Section 3. The new features will be explained one by one. Section 4 summarizes these features and Section 5 briefly introduces Wi-Fi 6's successor Wi-Fi 7, which is supposed to be released in 2024. [7] While this paper provides only a short explanation of the new changes, a more in-depth description can be found in the work by Sankaran et al. [5]. A very recent overview is presented in the work by Natkaniec et al. [8]. For more in-depth information on the two most prominent features, MIMO and OFDMA, readers are referred to the publications by Yang et al. [9] and Lanante et al. [10].

2. Physical Layer

This section presents the changes introduced by 802.11ax regarding the Physical Layer. First, changes made to enable the implementation of OFDMA and MU-MIMO will be explained, namely Resource Units, spacing and symbol duration, and newly introduced frame formats. Following, the two modulation schemes, Quadratic Amplitude and Dual Carrier modulation, will be introduced. Then, two new features targeting Internet of Things use cases, namely Target Wake Time and Midambles, are presented. In the last subsection, we elucidate changes regarding the frequency range, data rate, and guard band.

2.1. Resource Unit Allocation

As one major focus of 802.11ax lies on enabling high-density networks, resource unit allocation helps deal with large numbers of devices connected to the same access point: In Wi-Fi 6, the channel bandwidth is divided by frequency and time. This results in time-frequency blocks called Resource Units (RU). An access point can assign RUs to a particular user. Thus, several stations can transmit simultaneously without collisions. This RU allocation provides the basis for OFDMA. [5]

1. Please note that the extended ISO/OSI model separates the Data Link Layer into two sublayers, the Media Access Control (MAC) Layer and the Logical Link Control (LLC) Layer. [6]

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2.2. Spacing and Symbol Duration

In order to support the use of these Resource Units, Wi-Fi 6 has a four-times decrease in the interval length between subcarriers combined with a four-fold increase in the duration of transmitted symbols. [11] The shortened subcarrier interval increases noise sensitivity. To counter this, symbol duration and guard intervals were increased. [12], [13]
Guard intervals are defined intervals that are used to preserve orthogonality between subcarriers. If chosen too short, intersymbol and intercarrier interference is possible. [14] To avoid these negative consequences, guard intervals and symbol duration have been adjusted in Wi-Fi 6, making the channel more tolerant to jitter, increasing its robustness and transmission efficiency as well as enhancing throughput. Additionally, less bandwidth is wasted. [12], [13]

2.3. Frame Formats

To enable OFDMA and MIMO, the Wi-Fi 6 standard also includes four different physical layer conformance procedure protocol data unit frame formats (PPDU frame formats) [5], [8], [13]:

- Single User PPDU: used for transmissions between only two stations. Wi-Fi 5 already included this PPDU.
- Extended Range Single User PPDU: for transmissions over large distances between two stations. This PPDU can only be used without MIMO, as its main focus is to ensure reliability over a long distance.
- Multi User PPDU: for downstream transmissions with many users involved. This PPDU is needed when using downlink MU-MIMO and MU-OFDMA.
- Trigger based PPDU: used for upstream transmissions involving many users, particularly for uplink MU-MIMO and MU-OFDMA.

2.4. QAM Modulation

To increase the maximum data rate, 1024 Quadratic Amplitude Modulation (QAM) has been introduced. It focuses on use cases with very high channel qualities where data is transmitted over short distances. Using this modulation, ten bits can be transmitted simultaneously. This leads to a potential increase of the available data rate by 25 percent compared to the maximum data rate offered by Wi-Fi 5. However, such a high modulation is susceptible to noise and cannot be applied in low-quality channels or over larger distances. [5], [12], [13]

2.5. Dual Carrier Modulation

1024 QAM cannot be used across large distances. Therefore, dual carrier modulation has been included in Wi-Fi 6. Two subcarriers are modulated using the same information to create redundancy. The receiver can use this to deal with decoding errors. This increases the overall connection robustness and performance across larger distances. Using dual carrier modulation comes at a cost: Only half of the data rate is available, and the modulation can only be utilized for the transmission of Single User PPDUs. [5], [12]

2.6. Target Wake Time

As stated by Sankaran et al. [5], one of the main goals of Wi-Fi 6 was not only to increase throughput but also have a steady power demand compared to its predecessor Wi-Fi 5. The target wake time (TWT) can be used for power saving. Stations can conduct a wake schedule agreement with their access point. They are only awake when necessary and otherwise in power safe mode. Using this feature, a station and an access point agree on a TWT session period, defining the time period when the station has to be awake. Within this time frame, the station can send and receive data. If a station is not needed, it can go to sleep. This reduces congestion of the used medium and saves the station's battery power. [5]
Therefore, this feature is handy when paired with Internet of Things devices. Multiple devices can be connected to a network without increasing congestion and decreasing their battery lifetime. [15]

2.7. Midamble

This feature has been specifically designed for use cases where a connected object, e.g., a drone, moves with up to 60 km/h. A midamble is a high-efficiency long training field (HE-LTF) symbol that can be added to the PPDU payload. Using this information, a receiver can improve its channel estimate. A channel estimate describes the properties of the used channel, like the produced noise or distortion. These properties can then be used to remove unwanted noise and make the connection more reliable. [5], [16]

2.8. Other Changes

Wi-Fi 6 also includes several other noticeable changes on the Physical Layer [13], [17]:

- Frequency range: While Wi-Fi 5 only offers 5 GHz, Wi-Fi 6 includes 2.4 and 5 GHz. In combination with 1024 QAM, this increases the throughput.
- Maximum data rate: 802.11ax features a maximum data rate of 9.6 Gbps when used with the maximum number of possible MIMO streams. Compared to the 6.9 Gbps offered by 802.11ac, this leads to an approximately 40 percent higher maximum data rate compared to Wi-Fi 5.
- Guard band: Wi-Fi 6 supports guard bands of 0.8, 1.6, and 3.2 µs, whereas its predecessor only supports 0.4 and 0.8 µs.

3. MAC Layer

This chapter presents the technologies introduced by 802.11ax that affect the MAC Layer. First, we explain three crucial technologies that are implemented in Wi-Fi 6 to allow spatial reuse. Then, the concept of Multi-BSSIDs is presented. Last, the two key features of Wi-Fi 6, Uplink/Downlink MU-MIMO and OFDMA, are elaborated.

3.1. Spatial Reuse

Every station belongs to a basic service set (BSS). If two BSSs are very close, stations might be able to detect signals belonging to the respective other BSS as well. Both access points in both BSS might use the same channel. Especially in high-density networks, this can lead to collisions, reduced data rates, and high congestion. To counter this effect, Wi-Fi 6 implements three distinct changes working together to enable a distinction between transmissions belonging to a station's own BSS (intra-BSS) and a foreign BSS (inter-BSS). This can be used to allow parallel transmissions originating from different BSS. [5], [12]

3.1.1. BSS Network Coloring. According to Sankaran and Gulasekaran [5], especially high-density networks can benefit from this new feature. With network coloring, a PPDU can be classified as either intra-BSS or inter-BSS. If a PPDU is intra-BSS, the PPDU has been sent by a station within the same BSS. Inter-BSS PPDUs originate from stations belonging to a different BSS. By being able to distinguish between intra- and inter-BSS PPDUs, stations and APs can recognize PPDUs they do not have to decode and process. To enable BSS coloring, every BSS gets assigned a so-called BSS color. A BSS color is a number between 1 and 63. This number can either be assigned distributed or centralized. With the centralized distribution, a third party assigns BSS colors to the access points. When distributed assignment is chosen, an AP will select its own color different to those of its neighbors. APs advertise their BSS color in the designated field that is part of a beacon frame. Beacon frames are sent periodically to advertise the presence of a network. If a station notices a collision of BSS colors, it sends its own AP a BSS collision event report frame to inform it about the collision. If the AP then decides to change its BSS color, it can include a color change announcement in its next beacon frame. This ensures that all associated stations are always up to date regarding their BSS color. [5]

3.1.2. NAV Mechanism. As spatial reuse allows to treat inter- and intra-BSS PPDUs differently, the network allocation vector (NAV) also has to be split into an intra-BSS NAV and an inter-BSS NAV. The two NAVs act as timers that prohibit stations from sending while another transmission is still ongoing. [5], [18]
With Wi-Fi 5, only one NAV timer was present. If only one NAV timer would be used in Wi-Fi 6, Contention Free End Control (CF-End) frames could cancel a NAV, leading to a malfunction, as this would affect both inter- and intra-BSS frames. [18] With two NAV timers, stations can distinguish between inter-BSS and intra-BSS transmissions and prevent inter-BSS interference. If the two timers are both zero, a station can lower its back-off counter. [5] CF-End frames only cancel either the inter-BSS NAV or intra-BSS NAV. [18] If at least one timer is unequal to zero, the station has to stay in the idle state to avoid collisions. [5], [18]

3.1.3. Parameterized Spatial Reuse. As explained by Mozaffariahrar et al. [12], parameterized spatial reuse helps to enable parallel transmissions. With Wi-Fi 5, stations were not able to send during inter-BSS transmissions even if its sender was so far away that it would not cause interference. BSS network coloring enables stations to distinguish between inter-BSS and intra-BSS transmissions. Parameterized spatial reuse allows stations to cancel the reception of inter-BSS PPDUs or transmit simultaneously. If an inter-BSS PPDU has a power level below a previously determined threshold, a station can treat the medium as if idle and transmit nonetheless. Furthermore, an AP can include its acceptable interference level in the trigger frame. Neighboring APs from different BSSs can then adopt their BSS such that the valid signals they want to receive do not interfere. [5], [12]

3.2. Multi-BSSID

According to Sankaran et al. [5], enhanced multi-BSSID advertisement (EMA) has been developed to reduce the overhead created by management frames. Before Wi-Fi 6, every AP was required to answer probe request frames with beacon frames and also send such a frame on a regular basis. This led to problems when multiple APs were within a very close range which is often the case in high-density environments like stadiums. Every time a new device sends a probe request frame, every AP in range has to answer, leading to a large overhead. With the newly introduced EMA mode, an AP can distinguish between transmitted and non-transmitted basic service set identifiers (BSSIDs) and only answer probe responses for transmitted BSSIDs. Information about non-transmitted BSSIDs is attached to the transmitted BSSID probe response and beacon frames. This aggregation reduces management frame overhead in Wi-Fi 6.

3.3. UL/DL MU-MIMO

Uplink/Downlink multi-user multiple-input multiple-output (UL/DL MU-MIMO) is one of the new key technologies of Wi-Fi 6. [5], [12]
Using downlink MIMO, APs can transmit to numerous stations simultaneously. This works by transmitting a PPDU that combines physical layer conformance procedure service data units (PSDUs) for multiple stations. Each PSDU is transmitted on a different spatial stream. A field in the header of the PPDU indicates the association identifier of the respective station and its dedicated spatial stream. APs can choose new recipients and their streams for every PPDU, fostering flexibility. This feature was already included in Wi-Fi 5, although Wi-Fi 6 now supports up to eight spatial streams. [5], [12]
The newly introduced feature uplink MU-MIMO follows a similar principle. In high-density networks, collisions occur frequently. Although there are mechanisms like request-to-send-clear-to-send (RTS-CTS) protection that aim to prevent collisions, they still occur regularly. Uplink MU-MIMO aims to counter this by ensuring that numerous stations can transmit at the same time. To arrange

a suitable point in time where all stations can transmit simultaneously, an AP sends a trigger frame. Without this synchronization, an AP could not decode the transmitted data easily. Once received, the AP can collectively decode all spatial streams. [5], [12]

3.4. OFDMA

The second key feature, in addition to UL/DL MU-MIMO, is orthogonal frequency division multiple access, short OFDMA. Wi-Fi 5 only offered the usage of orthogonal frequency division multiplexing (OFDM). It is a modulation scheme where a channel is divided into various subcarriers. Transmissions can be done using the subcarriers. This spread takes the whole spectrum and only single users can use OFDM. This increases the collision likelihood in situations with many connected stations, like conference halls or universities. [4], [12]

Orthogonal frequency division multiple access (OFDMA), as presented by Wi-Fi 6, provides a new approach to enable simultaneous transmissions. It also enables higher throughput in high-density networks. OFDMA depends on the allocation of RUs to different stations as described in section 2.1. By using RUs, OFDMA only affords part of the spectrum and multiple simultaneous transmissions are possible, making OFDMA one of the major improvements for high-density networks. Furthermore, RUs within the same transmission can have different sizes depending on the transmitted data. [12], [5]

As was the case for MU-MIMO, OFDMA can be distinguished between uplink and downlink multi-user OFDMA. Uplink OFDMA also requires trigger frames. An AP can send this frame to align the transmission of multiple stations. The trigger frame also contains information about which RUs are assigned to which station. Differing from uplink MU-MIMO, the different data do not thwart each other as they are part of different RUs. Once the AP has received the data, it can send a Multi-STA BACK frame to acknowledge all RUs of all stations. [4]

Using downlink OFDMA, an AP can send to multiple stations at the same time. Information about these transmissions does not have to be transmitted via control frames but is included in the PPDU preamble. Again, RUs are assigned to different stations. The reception of the data is then simultaneously acknowledged by the participating stations using uplink OFDMA. The necessary trigger frame has been delivered to the stations as part of the MAC protocol data unit (MPDU) included in the original PPDU. [4]

4. Conclusion

High Efficiency Wi-Fi 6 includes many new features that mostly focus on enhancing user experience in high-density networks. The most prominent features include OFDMA, MU-MIMO, and Spatial Reuse, including BSS Network Coloring.

To enable these key features, many other changes were necessary. For the introduction of OFDMA and MU-MIMO, RUs had to be included, trigger frames and multi-user PPDUs to be developed. [5], [8], [13] To allow a four-times shorter spacing, the symbol duration was decreased by a factor of four. [12], [13] Spatial reuse relies on the introduction of two NAV timers, parameterized spatial reuse and BSS network coloring. With these mechanisms, stations and APs can easily distinguish between inter- and intra-BSS transmissions. [12], [5], [18]

Apart from these changes, 802.11ax focuses on providing higher throughput: 1024 QAM modulation can theoretically increase the data rate offered by Wi-Fi 5 by 25 percent. In case 1024 QAM is not possible, dual carrier modulation can be used to foster connection robustness and performance. [12], [5], [13] Not only with regard to dual carrier modulation, Wi-Fi 6 aims to enhance user experience over larger distances. The Extended Range single-user PPDU is provided to transmit between two stations across larger distances where MIMO cannot be applied. [8], [5], [13] Furthermore, Wi-Fi 6 also introduces Multi-BSSID to reduce management frame overhead in high-density networks where APs can distinguish between transmitted and non-transmitted BSSIDs. [5]

Another focus of Wi-Fi 6 is the Internet of Things: The introduction of a target wake time is crucial, as many smart devices require batteries. [15]

Midamble symbols are added to the PPDU payload to reduce noise and distortion that occur in channels where objects move. [5]

Overall, Wi-Fi 6 has shown many popular improvements compared to its predecessor Wi-Fi 5 and upgraded user experience, especially in high-density networks, while setting the basis for many IoT applications.

5. Outlook

While Wi-Fi 6 has been highly anticipated, real-world deployment has shown some shortcomings. It has been shown, for example, that for single users, Wi-Fi 5 enables a higher throughput over some distances [11] and it has been noted that Wi-Fi 6 only allows one RU to be allocated to one station [19]. To address these issues, IEEE already launched a working group to design its successor shortly after publishing Wi-Fi 6. 802.11be, also known to become Wi-Fi 7, is said to be released in 2024. [7], [19], [20] Several innovations that overcome shortcomings of Wi-Fi 6 have been identified for Wi-Fi 7, with the most important being:

- OFDMA: Access points should act as schedulers that allocate spectral resources. This is supposed to reduce delay. [7], [19]
- QAM: 4096-QAM modulation would allow for 12 bit symbols to be sent at the same time. Compared to the current 1024 QAM, this increases the data rate by 20 percent. [7]
- Resource Units: RUs are supposed to be enhanced by allocation schemes to be able to assign multiple RUs to one station. This is said to enhance network throughput when combined with OFDMA. [7], [19]
- Extended MU-MIMO: Wi-Fi 7 aims to increase the number of possible spatial streams to 16, doubling the currently available maximum number of streams. As this might influence the accuracy of the channel state information negatively, Wi-Fi 7 will likely also include a channel-sounding method. [19]

Up until now, the final draft of Wi-Fi 7 has not been released and the improvements contained are therefore still subject to change. If Wi-Fi 7 manages to live up to its name, Extremely High Throughput, and further facilitates the use of Internet of Things devices [7], [20], 802.11be will lead the way forward to a more digitalized world.

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