IEEE 802.11ax: Highly Efficient WLANs for Intelligent Information Infrastructure

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The authors overview the key technology features of IEEE 802.11ax such as OFDMA PHY, UL MU-MIMO, spatial reuse, OFDMA random access, power saving with TWT, and STA-2-STA operation, and explain translating these features to enhance user experience, highlighting the design principles to facilitate smart environments and identifying new technological opportunities.

ABSTRACT

Recently, IEEE 802.11ax, introducing the fundamental improvement of WLANs, was approved as the next generation WLAN technology. Satisfying tremendous user demands for user experience, IEEE 802.11ax will fuel the future intelligent information infrastructure to serve big data transportation and diverse smart application scenarios. In this article, we overview the key technology features of IEEE 802.11ax such as OFDMA PHY, UL MU-MIMO, spatial reuse, OFDMA random access, power saving with TWT, and STA-2-STA operation, and explain translating these features to enhance user experience, highlighting the design principles to facilitate smart environments and identifying new technological opportunities.

INTRODUCTION

With the global population expected to double by 2050, the world is experiencing extreme urbanization. While modern cities rely more and more on Wi-Fi Internet connections and hotspots to operate, significant growth with proliferation of Wi-Fi devices requires further technological breakthroughs to meet the needs of high-density urban application scenarios in modern cities, particularly for future smart cities with big data and mobile computing. The emerging big data analytics enabling intelligent services of smart cities [1, 2], particularly for real-time services, requires efficient information infrastructure to transport sensor data and processing data, and even intelligence, in wireless network design [3]. Wi-Fi (i.e., IEEE 802.11) therefore plays a critical role in the information infrastructure of smart cities, in addition to hotspots. However, it has been 20 years since the first technical approval of the IEEE 802.11 draft in 1997. Highly efficient wireless LANs are therefore very much wanted to serve the intelligent information infrastructure for future human society.

In the dense Wi-Fi/WLAN operating environments, sufficient bandwidth does not necessarily translate to high network throughput and thus satisfactory delay or latency for good user experience, due to severe system performance degradation caused by collisions from channel contention and inference from coexisting WLANs and neighboring devices [4-6]. Therefore, a new technology paradigm arises to revolutionize WLAN technology for user experience and consequently focus on the performance metrics of multi-user on delay, latency, and average per-user throughput, instead of increasing the physical layer transmission rate and peak throughput under a single-user scenario.

To meet such requirements, the IEEE Standards Association (IEEE-SA) approved IEEE 802.11ax in March 2014. The scope of the IEEE 802.11ax amendment is to define standardized modifications to both the IEEE 802.11 physical (PHY) layer and medium access control (MAC) sublayer for high-efficiency operation in frequency bands between 1 and 6 GHz, and the goal of IEEE 802.11ax is to provide a better user experience by improving by least four times the average throughput per user in densely deployed environments. It includes the following key features:
- Orthogonal frequency-division multiple access (OFDMA) PHY
- Downlink/uplink multi-user multiple-input multiple-output (DL/UL MU MIMO)
- Spatial reuse
- Trigger frame
- OFDMA random access
- Power saving with target wake time (TWT)
- Station-to-station (STA2STA, S2S) operation

Since the early acquaintance with IEEE 802.11ax of both industrial and academic players, a few papers exploring IEEE 802.11ax have initially confirmed the network design [7–9]. However, at the beginning of the standard development process, only a brief overview of some solutions was discussed in TGax, leaving many interesting issues requiring further understanding. In this article we present an overview of the key features of the upcoming IEEE 802.11ax amendment. Although the work is expected to be finished by 2019, draft standard IEEE 802.11ax-D1.1 adopted in February 2017 supplies the entire view of the novel solutions developed in the Task Group.

The rest of the article is organized as follows. The next section provides a brief overview of the important PHY advancements in IEEE 802.11ax. Next, we expose key technologies proposed for IEEE 802.11ax MAC to improve the efficiency of high density WLAN. Finally, we conclude the article.

IEEE 802.11AX PHY

IEEE 802.11ax revolutionarily employs MU technology as PHY layer transmission in both UL and DL to serve more users at the same time. MU technology includes both OFDMA and MU-MIMO. OFDMA is the multi-user variant of orthog-

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onal frequency-division multiplex (OFDM) [10] where different subsets of subcarriers are allocated to multiple users, allowing simultaneous access to radio resource.

OFDMA PHY

Similar to OFDM, OFDMA employs multiple subcarriers, but the subcarriers are divided into multiple groups, and each group is referred to as a resource unit (RU). RUs are allocated to multiple mobile stations according to their channel conditions and service requirements. The use of OFDMA reduces preamble and channel access overhead by amortizing those overheads across several users, and provides additional efficiency gains by assigning each user an RU where narrowband interference and deep fading can be avoided.

In DL transmissions, an access point (AP) may increase the power on some RUs while serving weak users to maximize DL throughputs in the basic service set (BSS) by shifting power away from strong users; on the other hand, UL OFDMA gains are mainly due to the aggregation of multiple users whereby each user transmits on its assigned RU, contributing to a higher signal-to-noise ratio (SNR) at the AP. Typically, STAs have lower output transmit power than APs, and this power asymmetry reduces the UL throughput and can also limit the BSS range. UL OFDMA can be used to compensate for such power asymmetry. The AP allocates smaller RUs to STAs with weak UL, improving SNR for those STAs.

NUMEROLOGY AND TONE PLAN

In order to better serve OFDMA features and outdoor scenarios, the subcarrier spacing should be as small as possible to minimize the relative guard interval overhead and provide better frequency selective gain. However, insufficient subcarrier spacing increases the sensitivity of the OFDM transmission due to Doppler spread and different kinds of frequency inaccuracies. The choice of a 4× longer symbol with 78.125 kHz subcarrier (i.e., tone) spacing in IEEE 802.11ax was found to offer a good balance between these two constraints. IEEE 802.11ax supports 0.8 μs, 1.6 μs, and 3.2 μs guard interval durations to cover a range of delay spread for indoor and outdoor channels and accommodate the timing difference between users in UL OFDMA and MIMO transmission.

In IEEE 802.11ax, the following RUs are defined for DL/UL transmission: 26-tone RU, 52-tone RU, 106-tone RU, 242-tone RU, 484-tone RU, 996-tone RU, and 2x996-tone RU. The location of these RUs in 20, 40, and 80 MHz and the maximum number of RUs in the 20 MHz, 40 MHz, 80 MHz, 160 MHZ, and 80+80 MHz bandwidth are shown in Fig. 1. It implies that up to 9 users in 20 MHz, 18 users in 40 MHz, 37 users in 80 MHz, and 74 users in 160 MHz are supported in an OFDMA transmission.

IEEE 802.11AX PPDU FORMATS

Four IEEE 802.11ax physical layer convergence protocol data unit (PPDU) formats are defined to support single-user (HE SU PPDU), multi-user (HE MU PPDU and HE trigger-based PPDU), and extended range transmissions (HE ER SU PPDU), as shown in Figs 2a–2d. The preamble in all these
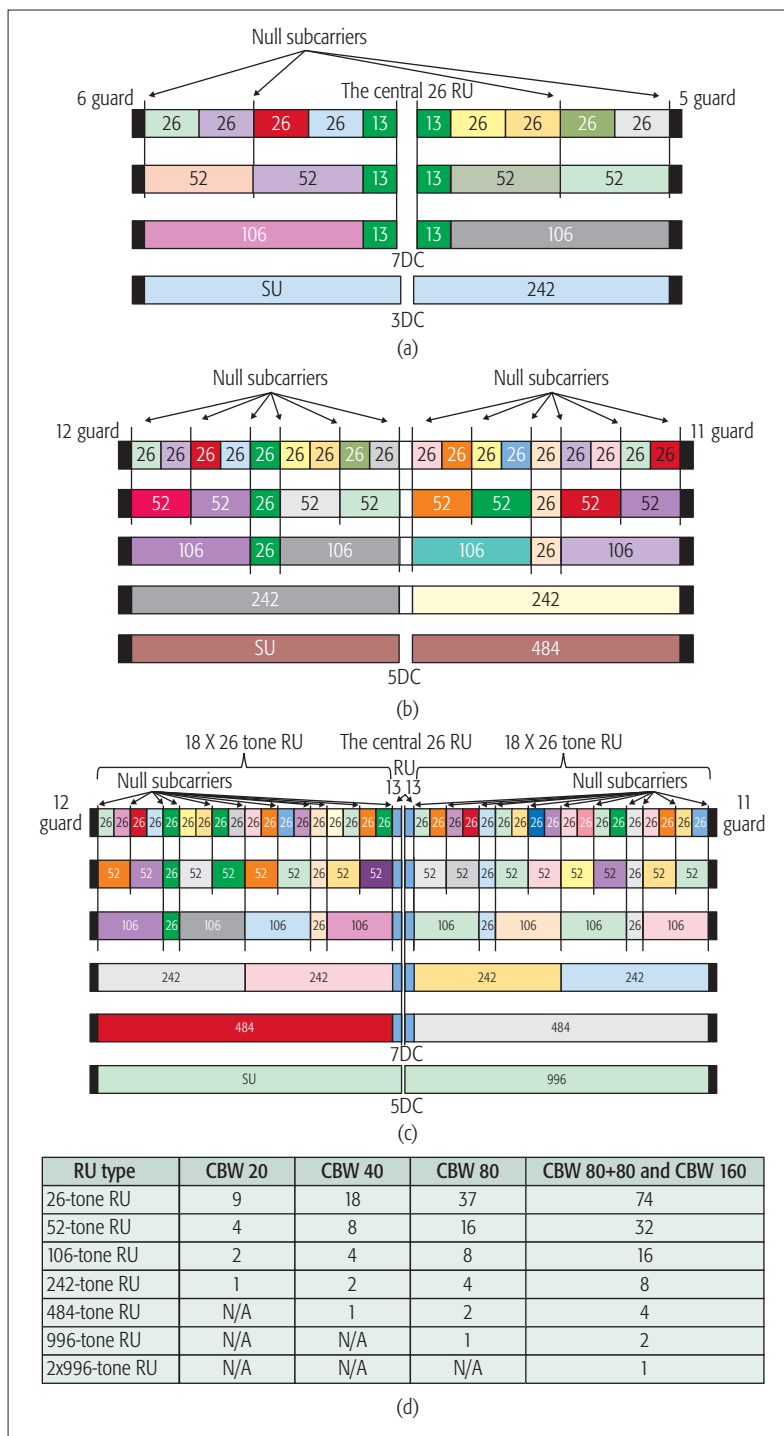
Figure 1. RU locations and maximum number of RUs for each channel width: a) RU locations in a 20 MHz HE PPDU; b) RU locations in a 40 MHz HE PPDU; c) RU locations in an 80 MHz HE PPDU; d) maximum number of RUs for each channel width.

RU type	CBW 20	CBW 40	CBW 80	CBW 80+80 and CBW 160
26-tone RU	9	18	37	74
52-tone RU	4	8	16	32
106-tone RU	2	4	8	16
242-tone RU	1	2	4	8
484-tone RU	N/A	1	2	4
996-tone RU	N/A	N/A	1	2
2x996-tone RU	N/A	N/A	N/A	1

PPDU formats contains a legacy preamble portion to support coexistence with legacy STAs (i.e., to ensure backward compatibility), which is followed by an HE-preamble portion to support IEEE 802.11ax enhanced features.

The HE SU PPDU is used for single-user transmission only (to a single STA or the AP), while the HE MU PPDU is used for multi-user transmission (to one or more STAs). The HE MU PPDU is designed for OFDMA and/or MU-MIMO transmission, which requires the HE-SIG-B field to
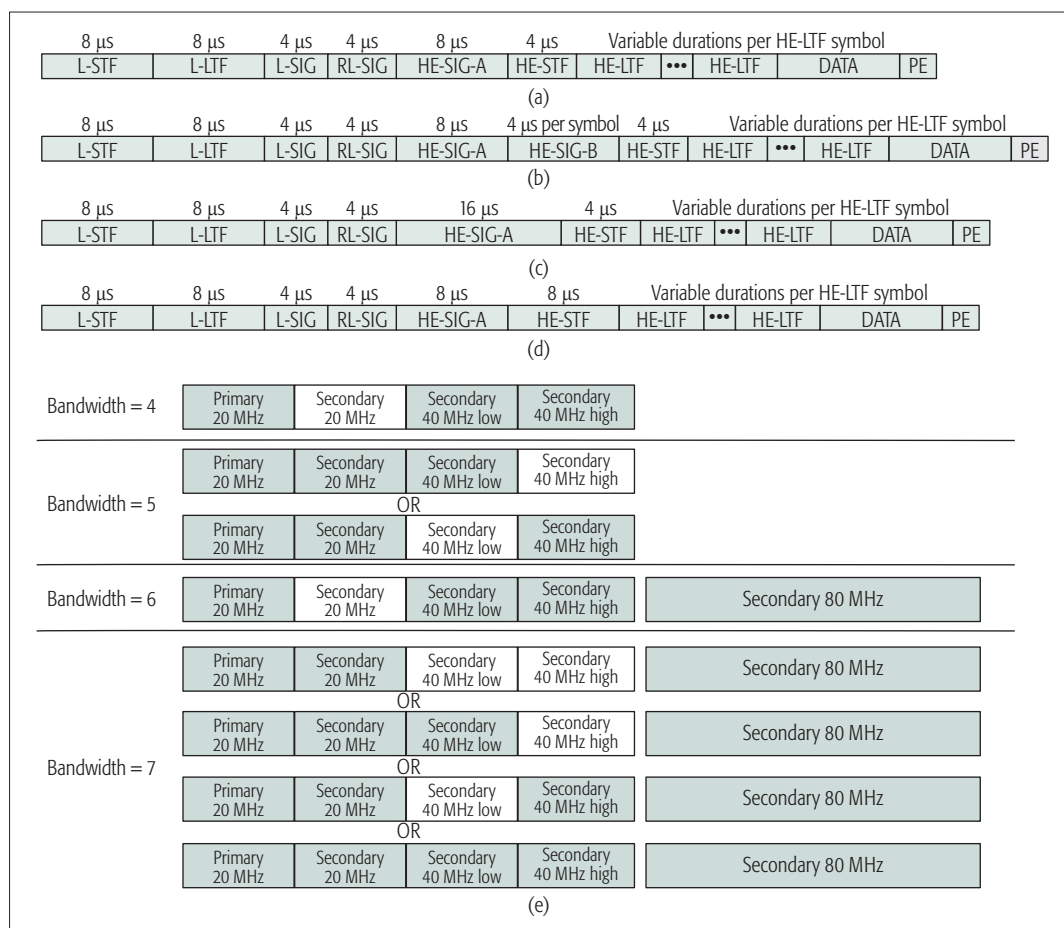
Figure 2. HE PPDU formats and bandwidth modes of preamble puncturing: a) HE SU PPDU format; b) HE MU PPDU format; c) HE extended range SU PPDU format; d) HE trigger-based PPDU format; e) bandwidth modes of preamble puncturing.

assign one or more STAs in a PPDU. A STA may also transmit an HE MU PPDU to the AP that supports its reception.

The HE extended range SU PPDU is used for SU transmission, which is intended for extended range transmission to a single STA or the AP. Unlike other PPDU formats, this PPDU format contains an HE-SIG-A field that has a repetition of each symbol and a power-boosted preamble for reliable performance with longer coverage. The PPDU payload is limited to a single spatial stream and uses either a 242-tone RU or a 106-tone RU fixed on the right side of the primary 20 MHz channel.

The HE trigger-based PPDU is used for UL MU transmission that is a response to a trigger frame. This PPDU format is identical to the HE SU PPDU format except using a longer length of HE STF field in the HE preamble portion. Instead of using the HE-SIG-B field, the information required for the UL MU transmission from one or more STAs is carried by the trigger frame that initiates this transmission.

In IEEE 802.11ax, an HE PPDU may have a Packet Extension (PE) field appended at the end of the PPDU. The PE field is used to provide the recipient of the PPDU the needed processing time at the end of an HE PPDU. The possible durations are 0 µs, 4 µs, 8 µs, 12 µs, and 16 µs. The PE field, when present, is transmitted with the same average power as the data field, and its content is arbitrary.

Modulation and Coding Scheme

For an HE SU PPDU and an HE ER SU PPDU, the modulation and coding scheme (MCS) index is carried in the HE-SIG-A field. For an HE MU PPDU, the per-user MCS index is carried in the HE-SIG-B field.

IEEE 802.11 is well known to adopt adaptive modulation and coding to trade between data rates and range. IEEE 802.11ax introduces MCS 10 and MCS 11 to enhance the spectral efficiency in high SNR regions, up to uniform 1024-quadrature amplitude modulation (QAM) constellation with gray bit mapping. MCS 10 and MCS 11 are optional for SU and MU but are only permitted in RUs of 242 or more subcarriers.

IEEE 802.11ax introduces dual subcarrier modulation (DCM) to enhance the robustness of transmissions in low SNR regions and in the presence of narrowband interference. DCM is only applied to MCS 0, MCS 1, MCS 3, and MCS 4 with only a single spatial stream or two spatial streams. DCM modulates the same information on a pair of subcarriers, which is a repetition scheme in frequency domain to enhance the performance.

In IEEE 802.11ax, support of low-density parity check (LDPC) is mandatory for STAs declaring support for at least one of the HE 40/80/160/80+80 SU PPDU bandwidths, for STAs declaring support for more than 4 spatial streams, and for STAs declaring support for 1024-QAM.

20 MHz Only Operation and RU Restriction Rules

IEEE 802.11ax allows devices that only support 20 MHz channel bandwidth. In IEEE 802.11ax, the AP in 5 GHz shall be 80 MHz capable and operate for both 80 MHz capable STAs and 20 MHz only STAs. A 20 MHz only STA operates with 20 MHz channel width only, in frequency bands between 1 and 6 GHz. A 20 MHz-only STA supports all HE mandatory features except some features related to channel width and coding.

When a 20 MHz operating STA is a recipient of either 40, 80, 80+80, or 160 MHz DL-OFDMA, or one of the transmitters of 40, 80, 80+80, or 160 MHz UL-OFDMA, RU tone mapping in 20 MHz is not aligned with 40, 80, 80+80, or 160 MHz RU tone mapping. Due to misalignment of these RU locations, some of these RUs are impacted by transmit/receive filtering or DC tones, and may result in significant performance penalty. To improve the throughput and interoperability, some RUs in 20 MHz operating STAs are restricted to be used in 40, 80, 80+80, or 160 MHz OFDMA operation.

Preamble Puncturing

IEEE 802.11ac introduces 80 MHz and 160 (80+80) MHz channel for higher bandwidth and throughput. In IEEE 802.11ax, 20 MHz, 40 MHz, 80 MHz, and 160 (80+80) MHz are supported in 5 GHz band. However, in real deployment 80 MHz and 160 MHz bandwidth channels may not be realistic to use due to the following:

- The unlicensed spectrum in 5 GHz is not contiguous. In practice, 80 and 160 MHz bandwidth channels are not easy to get since there are only five non-overlapping 80 MHz bandwidth channels and one non-overlapping 160 MHz bandwidth channel in the United States when dynamic frequency selection (DFS) is used.
- Since the transmit power regulations are different in each band, for a BSS that needs high transmit power (e.g., outdoor/big house deployment), the number of channels is further reduced.
- Radar spectrum overlaps with part of 5 GHz unlicensed spectrum, so the channel cannot be used when radar signal is detected.
- The deployment of legacy APs operating at narrowband (e.g., 11a/n) makes it hard for the AP to find a clear 80 MHz or 160 (80+80) MHz bandwidth channel.

IEEE 802.11ax tackles this issue of bandwidth unavailability through preamble puncturing, allowing an AP to transmit an HE MU PPDU in punctured 80 or 160 (80+80) MHz format when part of the 20 MHz sub-channel(s) in secondary channels of the channel bandwidth is (are) busy.

Preamble puncturing is optional for both the AP and STA sides. The support of preamble puncturing is indicated in the HE capabilities element. In the preamble puncturing modes, the preamble part will be punctured, which means it will not be transmitted, in the busy 20 MHz sub-channel(s). Preamble puncturing is designed to enhance the channel utilization for the dense AP deployment scenarios where 80 or 160 (80+80) MHz bandwidth may not be fully available all the time.

The bandwidth modes of preamble puncturing are showed in Fig. 2e, in which the blank 20 MHz sub-channels are punctured. [1] For 80 MHz transmissions, only one of the 20 MHz sub-channels other than the primary 20 MHz channel will be punctured. For 160/80+80 MHz transmissions, either the secondary 20 MHz sub-channel will be punctured in the primary 80 MHz channel, or the two 20 MHz sub-channels corresponding to the primary 40 MHz channel will not be punctured (at least one of the other 20 MHz sub-channels corresponding to the 160/80+80 MHz channel will be punctured).

DL/UL MU-MIMO

Both DL and UL MU-MIMO transmissions are supported on portions of the PPDU bandwidth, which contains at least 106 tones. In an MU-MIMO resource unit, there is support for up to eight users with up to four space-time streams per user with the total number of space-time streams not exceeding eight. Combining OFDMA and MU-MIMO enables two-dimensional scheduling: frequency and spatial.

IEEE 802.11ax introduces UL MU-MIMO, which improves the aggregate throughput of an IEEE 802.11ax network by parallelization of multiple transmissions on the UL. It is expected to be very useful for long packet transmissions from multiple STAs and reducing the collision probability in the case of a large number of STAs. Compared to UL OFDMA, UL MU-MIMO is more suitable for STAs that are close to an AP with good receiving SNR value and channel condition, and an AP is more sensitive to the difference of received power when using UL MU-MIMO. However, like UL OFDMA, UL MU-MIMO adds system complexity in terms of the time, frequency, and power synchronization needed for these transmissions.
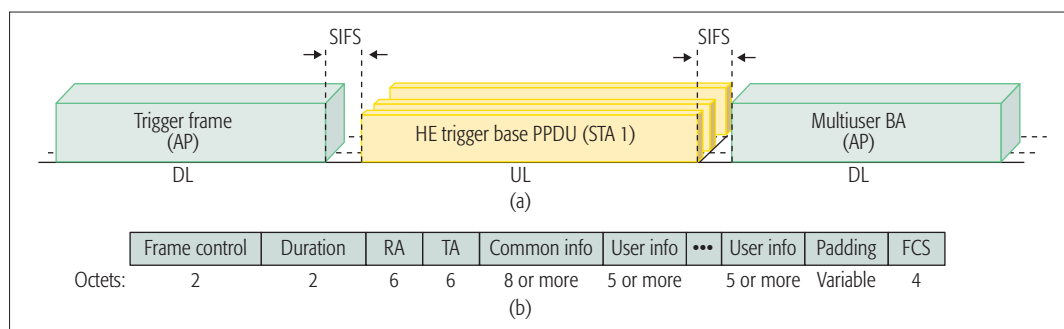
IEEE 802.11ax MAC

The introduction of OFDMA PHY into IEEE 802.11ax enjoys advantages of mature, highly efficient PHY and smooth hybrid integration with cellular systems as heterogeneous wireless communication networks. On the other hand, OFDMA PHY creates a new and fundamental challenge in IEEE 802.11ax MAC design due to the multiple users sharing a frequency carrier/band, resulting in a new technology challenge in carrier sense [4, 7]. Hence, different thinking on MAC design for IEEE 802.11ax is required to innovate a new MAC protocol for multi-user OFDMA PHY in both DL and UL, while being backward compatible with the original MAC based on carrier sense multiple access with collision avoidance (CSMA/CA). The basic idea is to leverage the concept of four-way handshaking [11] by establishing a trigger frame to allow efficient operation of multiuser PHY.

UL MU Procedure

UL MU transmissions leverage a new control frame called a trigger frame. As illustrated in Fig. 3a, AP sends a trigger frame to multiple STAs to trigger them to transmit frames in UL MU-MIMO when an AP obtains the channel. The frame format of a basic trigger frame is shown in Fig. 3b. A common Info subfield carries the common information for all the triggered STAs, while a user info subfield carries the information for each of the triggered STAs independently.

> In an MU-MIMO resource unit, there is support for up to eight users with up to four space-time streams per user with the total number of space-time streams not exceeding eight. Combining OFDMA and MU-MIMO enables two-dimensional scheduling: frequency and spatial.

Figure 3. UL MU-MIMO procedure and trigger frame: a) the basic UL MU-MIMO procedure: a) the basic UL MU-MIMO procedure; b) trigger frame format.

After receiving the trigger frame and ensuring that it is one of the target STAs, each of the triggered STAs needs to complete the following in a fixed time slot:

• Synchronize with the trigger frame, including pre-compensation for carrier frequency offset (CFO) error and symbol clock error.

• Check the CCA value (energy detection only) and NAV at the channels indicated by the trigger frame if channel sensing is required in the trigger frame.

• Pre-correct its transmitted power based on the parameters in the trigger frame.

• Prepare PPDU as the PHY parameters indicated in the trigger frame.

To make sure an AP can decode the simultaneous transmission in UL MU correctly, the design of HE trigger-based PPDU (Fig. 2d) has two parts:

•The pre-HE parts of the preambles of all the HE trigger-based PPDUs are completely the same. The specific approach is that when the triggered STA starts its transmission in UL MU, it needs to copy HE-SIG-A related information from the previous trigger frame into the HE-SIG-A field of its HE trigger-based PPDU. The benefits of this design are that it can let an AP treat the received signal as being from one transmitter, while it can also protect the transmission by using the legacy preamble to report necessary information about the current PPDU to non-HE STAs.

•The HE LTF would be mutually orthogonal between any two of the triggered STAs. Each of the triggered STAs selects one column of the P matrix (defined in IEEE 802.11n and IEEE 802.11ac) to multiply the basic HE LTF element to form its own HE LTF sequence based on the STA order in the trigger frame. An AP can distinguish each user by utilizing this orthogonality when receiving HE trigger-based PPDUs. In this way, the AP can estimate the UL channel state information between the AP and each STA, and then decode each HE trigger-based PPDU correctly.

All the HE trigger-based PPDUs shall have the same length as indicated in their previous trigger frame. After receiving the HE trigger-based PPDUs, the AP has to send an acknowledgment in response to the triggered STAs. The AP has two choices here: send an individual acknowledgment to each STA by using DL OFDMA BA or one frame incorporating the response to all the STAs (M-BA). Based on our simulation results shown in Fig. 4, we can see that OFDMA BA can provide better packet error rate (PER) performance com-pared to M-BA, while M-BA has less overhead in 20 and 40 MHz transmissions. Hence, an AP can decide which format of acknowledgement to use based on the scenarios.

Before triggering UL MU-MIMO transmissions, the AP collects the requirements of each STA by receiving the following information from STAs: buffer status report (BSR) and/or bandwidth query report (BQR). Furthermore, STAs can simply send its request to AP by using null data packet (NDP) feedback to ask for UL MU transmission. The NDP feedback scheme is also based on the orthogonality at the HE-LTF subfield.

SPATIAL REUSE

In a traditional Wi-Fi system (e.g. IEEE 802.11n/ac), when detecting PPDU with received power higher than –82dBm, a STA will defer its data transmission attempt to avoid interference to the overlapping basic service set (OBSS), which may restrict the system throughput. Spatial reuse (SR) operation is introduced in an 802.11ax system; the objective of SR operation is to improve the system-level performance, the utilization of medium resources, and power saving in dense deployment scenarios by early identification of signals from OBSSs and interference management. The improved system-level performance by HE spatial reuse is achieved by the enhanced channel access. Some information carried in the HE PHY header such as BSS color (a partial BSS identifier), UL flag, and/or STA ID can be used for identification of the BSS.

A STA may transmit an SR PPDU on top of the ongoing PPDUs to either a STA or a non-HE STA to increase the system throughput and not update its NAV timers based on frames carried in the PPDU when the following SR conditions are met that allow the transmission of an SR PPDU:

• The received PPDU is an Inter-BSS PPDU.

• The received power level of the PPDU is below the OBSS_PD level.

• The PPDU is not:
 –A non-HT PPDU that carries an individually addressed public action frame where the RA field is equal to the STA MAC address
 –A non-HT PPDU that carries a group addressed public action frame

OBSS_PD-based spatial reuse provides a STA the flexibility to operate at a higher CCA level, called the OBSS_PD level, to achieve better performance in dense deployment scenarios. A STA is allowed to use a higher OBSS_PD level than the minimum receiver sensitivity level if the
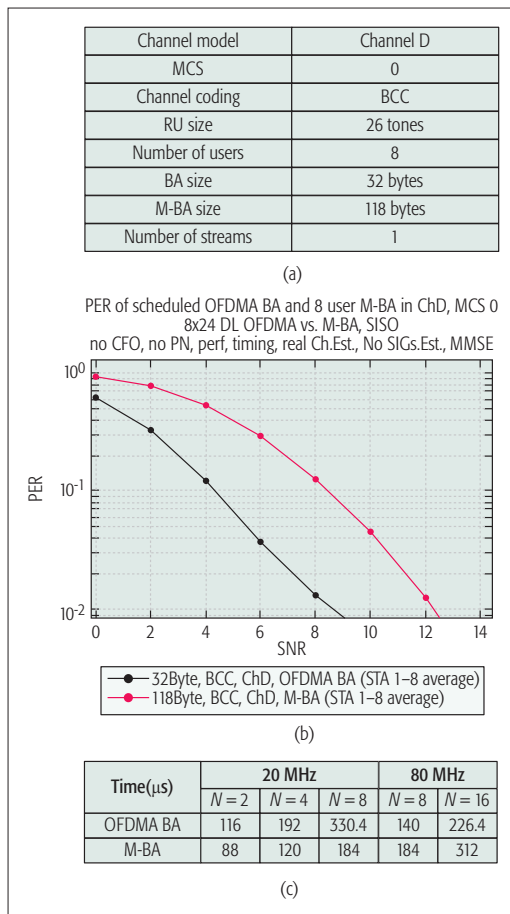
Figure 4. Comparison between OFDMA BA and M-BA: a) simulation parameters; b) PER performance; c) overhead comparison.

Figure 5. Illustration of the adjustment rules for OBSS_PD and TX_PWR.

received PPDU is identified to be from an OBSS. The OBSS_PD level is set in conjunction with transmit power control following a certain rule to improve the system-level performance and the utilization of the spectrum resources.
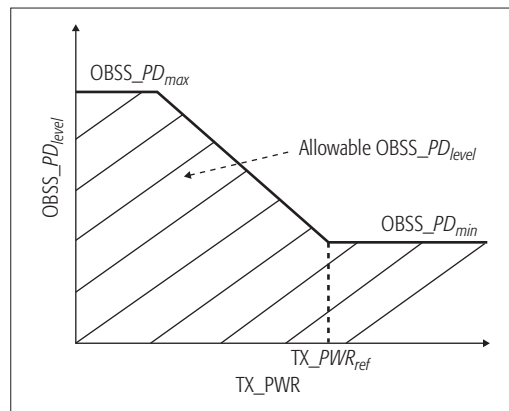
When using OBSS_PD-based spatial reuse, a STA is allowed to adjust the OBSS_PD level in conjunction with its transmit power based on the following adjustment rule:

Allowable OBSS_PD$_{leve}$, $\leq$ max(OBSSPD$_{min}$, min(OBSSPD$_{max}$, OBSSPD$_{min}$ + (TXPWR$_{ref}$ − TXPWR)))

where TX_PWR_{ref} is a reference power level defined as 21 dBm. $OBSS\_PD_{level}$ is allowed to be adjusted within the range between $OBSS\_PD_{max}$ and $OBSS\_PD_{min}$, in which a lower transmit power corresponds to a higher allowable $OBSS\_PD$ level. It should be noted that the STA can operate at the legacy CCA level without employing a higher $OBSS\_PD$ level. The adjustment rule is illustrated in Fig. 5.

OFDMA RANDOM ACCESS

In UL OFDMA, an AP assigns each RU to a STA to transmit UL PPDU in OFDMA format. When the AP expects that there are some STAs to do UL transmission, but does not know the specific STAs, it could assign one or more RUs for multiple STAs to transmit through OFDMA-based random access.

An AP assigns the RUs for random access by indicating value AID 0 in the AID subfield of the user info field within the trigger frame. A STA maintains an OFDMA backoff (OBO) counter, which is different from an EDCA backoff counter, for OFDMA-based random access. When the STA receives a trigger with random access, it should reduce the OBO counter by the number of random access RUs. The STA could randomly select one of the random-access RUs to do UL OFDMA transmission when its OBO counter reaches 0 or below. Readers may refer to [4] for detailed OFDMA RA procedure.

There are many use cases for OFDMA-based random access. Before an AP does UL MU scheduling, it needs to know the buffer status of STAs. It is easy to get for periodically traffic, and also can piggyback the buffer status report (BSR) by a STA when doing contiguous transmission. But for burst traffic, it is not efficient to report the BSR. A STA could report the BSR through UL SU transmission, but it is very inefficient because the BSR is very short. It is also very inefficient for an AP to poll STAs one by one when there are large number of associate STAs. For this scenario, an AP only needs to estimate how many STAs may have BSRs to send, and then assign some RUs for random access accordingly.

The second use case is to fully use the unallocated RUs in UL OFDMA. The scheduling of RUs in OFDMA PHY could be very complicated in the implementation. There are RUs that hard to assign to any STAs in some cases. For example, when an AP gets a 20 MHz channel and there are 3 STAs with the same amount of data to transmit, the AP can only assign a 52-tone RU for each STA. That will leave three 26-tone RUs unallocated. These three 26-tone RUs could be used for OFDMA-based random access. Otherwise, they will be wasted.

OFDMA-based random access is also useful for unassociated STAs. In a real deployment, an AP usually has higher transmit power than a STA, so some STAs at the edge can hear the beacon from an AP, but its packet cannot be transmitted to the AP. In this situation, the AP cannot schedule this unassociated STA because tje AP does not know of the existence of this STA. Thus, the OFDMA-based random access is the only way for this STA's signal to get to the AP.

Figure 6. Power management in IEEE 802.11ax: a) an example of broadcast TWT operation; b) operation mode indication.

POWER MANAGEMENT

IEEE 802.11ax includes a lot of power saving (PS) schemes to further save power besides the existing power saving mechanisms, including target wake time (TWT), cascade indication, opportunistic power save, intra-PPDU power save, and operation mode indication (OMI).

The TWT mechanism was designed in IEEE 802.11ah for STAs to stay in PS mode without listening for a beacon for a long time. It is a kind of scheduled transmission when a STA wakes up in PS mode. The STAs can be scheduled at different times to minimize contention between them. There are two types of TWT in IEEE 802.11ax: individual TWT and broadcast TWT. Individual TWT needs individual TWT agreements between two STAs, while broadcast TWT does not need to establish an individual TWT agreement between a TWT scheduling STA and TWT scheduled STAs. An example of broadcast TWT operation is shown in Fig. 6a, where an AP is the TWT scheduling STA, and STA 1 and STA 2 are the TWT scheduled STAs. In broadcast TWT, the STA in PS mode only needs to listen to the beacon containing a TWT information element (IE), which can be negotiated at the beginning through TBTT negotiation. When the STA finds itself in the TWT IE, it needs to wake up at the indicated time to listen to the trigger frame of other downlink frames. Except for the above situations, the STA does not wake up until the next beacon with TWT IE.

An AP can also indicate the start time of a trigger frame with random access allocations in the TWT IE of a beacon frame. STAs in PS mode will wake up before the indicated start time after receiving a TWT IE. If there are more than one trigger frames in a sequence for random access, these trigger frames shall set their cascade indication field to 1 except for the last trigger frame in this sequence.

An opportunistic power save mechanism is based on broadcast TWT and splits a beacon interval into several periodic broadcast service periods (SPs). At the beginning of each SP, the scheduling information to all STAs is provided by transmitting a traffic indication map (TIM) frame or a fast initial link setup (FILS) discovery frame that includes a TIM element. That is, the TIM here provides the scheduling information.

Intra-PPDU PS is a mechanism for STAs to save power in a short time (shorter than PPDU length) but very frequently. When a STA finds that the received PPDU has a BSS color different from itself, or the received PPDU is not itself, the STA enters the doze state until the end of this PPDU. The busier the channel is, the more power is saved in this mechanism.
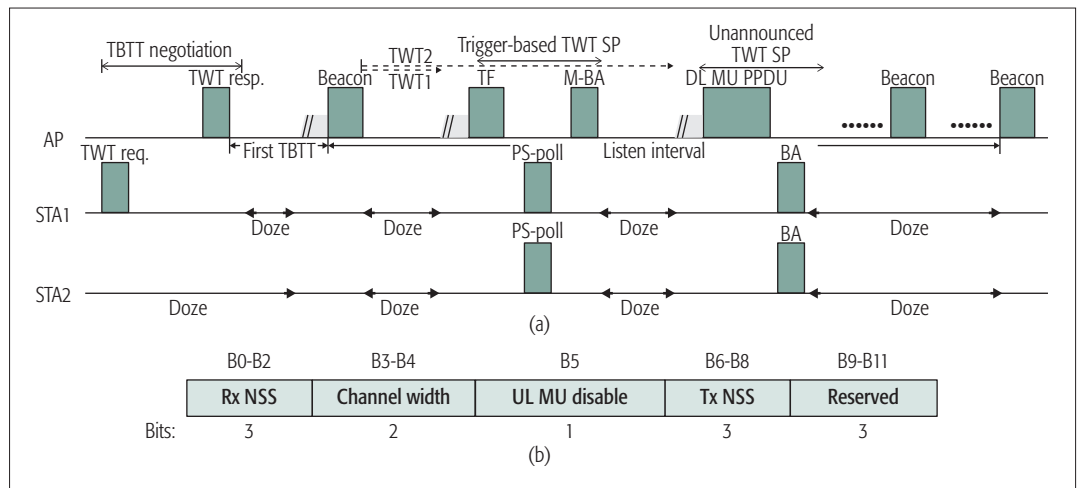
Operation mode indication (OMI) is able to reduce the power consumption when the STA is transmitting or receiving signals by changing some PHY parameters like bandwidth and number of spatial streams. OMI can be done at either the receiver side (ROMI), the transmitter side (TOMI), or both sides. The format of OMI is defined in Fig. 6b.

QUIET TIME PERIOD

The S2S operations in the proximity of HE BSS will likely increase contention and introduce inefficiency due to lack of coordination between S2S operations and HE operations. The quiet time period feature mitigates the coexistence issue between HE BSS and S2S operations, such as Wi-Fi Aware, Wi-Fi Direct, and Tunneled Direct Link Setup (TDLS).

The quiet time period (QTP) element defines a period for an S2S operation during which only the STA that supports the S2S operation transmits frames. During the period, a STA should not transmit frames unless it participates in the S2S operation.

CONCLUSIONS

This article highlights the key features and advancements in both the PHY and MAC layers of IEEE 802.11ax, their anticipated uses and benefits, and their mandatory and optional classification information based on the up-to-date standard draft and specification. Researchers and engineers shall be able to easily understand the current perspectives and key features of IEEE 802.11ax after reading this article.

Devising a well-performing PHY and MAC protocol for new generation WLANs can be a challenging task, but it is also an interesting area of research. We have focused on the open issues

and provide a description of the mechanisms that is enough to model and investigate them. Hence, we believe that this article will attract researchers to IEEE 802.11ax, and thus contribute to the paradigm shift of IEEE 802.11ax and facilitate information infrastructure for data analytics in smart cities.

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We have focused on the open issues and provide a description of the mechanisms enough to model and investigate them. Hence, we believe that this article will attract researchers to IEEE 802.11ax and so will contribute to the paradigm shift of IEEE 802.11ax and to facilitate information infrastructure for data analytics in smart cities.