High-efficiency WLANs for dense deployment scenarios

B T VIJAY* and B MALARKODI

Department of Electronics and Communication Engineering, National Institute of Technology,
Tiruchirappalli 620 015, India
e-mail: bt.vvts@gmail.com; malark@nitt.edu

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Abstract. In this article, we review the latest technical attributes such as orthogonal frequency division multiple access (OFDMA), multi-user MIMO (MU-MIMO) and enhanced clear channel assessment (CCA) for better spatial reuse used in the 802.11ax amendment to the 802.11 standard that leads to PHY and MAC enhancements for high-density scenarios of access points (APs). IEEE 802.11ax, also referred to as high-efficiency wireless local area network (WLAN) (HEW), provides mechanisms to thoroughly utilize the unlicensed spectrum bands (2.4 and 5 GHz) and strengthen the user experience. The functional requirements of HEW are stressed on interactive video transmission latency and access efficiency to meet quality of service (QoS) requirements. Finally, we investigate three configurations—MU-MIMO, OFDMA and combination of both or mixed mode—for 4-user AP transmission schemes in 802.11ax. The performance of the MU schemes varies with packet size and operating SNR. OFDMA is more efficient than MU-MIMO at low SNRs for all packet sizes, which means 5th percentile stations (STAs) can get desired throughput.

Keywords. CCA; high-efficiency WLAN (HEW); spatial reuse; MAC; multi-user (MU); OFDMA; throughput; 802.11ax; efficiency.

1. Introduction

The use of IEEE 802.11-based wireless local area networks (WLANs) has more than doubled in recent times due to its ability to provide increased mobility and simplicity, with reduced cost of installation and maintenance. It has triggered massive WLAN deployment in geographically restricted environments that involve multiple overlapping basic service sets (OBSSs). Since its first release in 1997, the standard defines the MAC procedures to support local area network (LAN) applications with quality of service (QoS) requirements, including the transport of voice, audio and video (AV). The standard describes MAC mechanisms to support the prioritization of management frames, and specifies mechanisms to improve AV streaming QoS while maintaining data and voice performance [1]. The recently approved standard IEEE 802.11ac-2013 enables very high throughput (VHT) greater than 1 Gbps. The most significant PHY layer upgrades are the 80-MHz channel access and 160 MHz (80 + 80) combination approach, 8×8 MIMO antenna service and downlink multi-user MIMO (DL MU-MIMO), which can be useful to permit aggregated frames to be sent from the access point (AP) to many receivers through multiple spatial streams [2–4]. A critical MAC layer enhancement is TXOP sharing, which can be

useful to handle quite a few downlink traffic streams to many receiver stations (STAs) concurrently. WLAN interfaces are being implemented in more and more products such as personal computers and smart phones connections, resulting in rapid growth of the market for Wi-Fi-enabled terminals with over 12 billion cumulative shipments from 2015 onwards [2, 5, 6]. However, new problems have emerged with the proliferation of WLAN connections. One problem is degradation of transmission efficiency, which occurs when many Wi-Fi terminals interfere with each other. The cause of this is that WLAN devices acquire channel access opportunities under the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocol, which avoids simultaneous transmission on the same frequency resource; this means that the transmission opportunities of each terminal decrease in dense deployment scenarios. Also, users utilize WLAN for many different applications such as video streaming and offloading.

A new study group called high-efficiency WLAN (HEW): IEEE 802.11ax to enhance 802.11 PHY and MAC in 2.4 and 5 GHz unlicensed bands was formed recently. HEW focused on improving spectrum efficiency, area throughput and real-world performance in both indoor and outdoor deployments in the presence of interfering sources, dense heterogeneous networks and in moderate-heavy user-loaded APs. Task Group 802.11ax (TGax) is an advanced version of WLAN in the set of WLAN Standards,

*For correspondence

and it is a successor to IEEE 802.11ac. IEEE 802.11ax is predicted to have a maximum capacity of around 10 Gbps by utilizing orthogonal frequency division multiple access (OFDMA) PHY, AP-initiated trigger frame, spatial reuse (SR) and multi-user MIMO (MU-MIMO) supporting both uplinks as well as downlinks, which delivers 4 times the throughput of IEEE 802.11ac; aggregation mechanism for ACK/BA is still in the mid-stages of development, expected to be accomplished in 2019 [7].

In the following sections, first we discuss the functional requirements for IEEE 802.11ax. Second, we introduce the high-efficiency PHY enhancements and briefly explain MU aggregation and HE channel sounding protocol; third, we talk about new features of high-efficiency MAC, mainly covering SR operation using enhanced clear channel assessment (CCA) by dynamic sensitivity control (DSC) with colour codes and opportunistic adaptive CCA (OA-CCA); in the same section, we discuss the target wake time (TWT) operation and access efficiency requirements for HEW. Lastly, we present the AP throughput analysis with the help of three configurations—MU-MIMO, OFDMA and combination of both or mixed mode—for DL MU transmission in IEEE 802.11ax, followed by the conclusion.

2. Functional requirements

There have been research works in the HEW study group for functional requirements that highlight essential scope concepts of 802.11ax (HEW). (a) System performance: the 802.11ax amendment shall provide at least one mode of operation capable of achieving at least four times improvement in the average throughput per STA (measured at the MAC data service AP) in a dense deployment scenario while maintaining or improving the power efficiency per STA. The HEW shall bring latency to a desirable level to meet QoS requirements in a high-density deployment scenario, which is discussed briefly in the next subsection. (b) Spectrum efficiency: the 802.11ax amendment shall provide a mechanism to facilitate efficient use of spectrum resources and to manage interference between neighbouring OBSS in a dense deployment scenario. The 802.11ax amendment shall provide a mechanism to increase the spectral efficiency of 20-MHz and larger channels in scenarios with a high density of HEW STAs and scenarios with the presence of legacy devices. The 802.11ax amendment may provide a mechanism to increase frequency reuse efficiency and manage interference in the deployment scenarios with a high density of HEW STAs and with the presence of transmission between non-AP STAs. (c) Bands of operation: define bands of operations in frequency bands between 1 and 6 GHz. (d) Backward compatibility and coexistence: legacy performance shall not be significantly degraded by operation in or in

proximity to a HEW network. Finally, the 802.11ax amendment shall define mechanisms to improve the 5th percentile of per STA throughput without degradation of afore-listed performance requirements.

Interactive video transmission latency requirement: The mechanisms defined in the 802.11ax amendment shall significantly improve the average transmission latency of latency-sensitive applications to satisfy QoS requirements when compared with the active IEEE 802.11 standard and its amendments operating in the same band (IEEE 802.11n in 2.4 GHz and IEEE 802.11ac in 5 GHz) and the same deployment scenario. The transmission latency is measured from the time that the MPDU is set for transmission (i.e., beginning of CSMA/CA access); MAC receives a packet till the time that PHY begins transmitting. It is clear that the video traffic will continue to rise and will become the dominating traffic type for WLAN in the current situation. HD TVs and the popularity of video casting from/to mobile devices are defining the user experience by the quality of a wireless video [7]. PER is a primary QoS metric. Along with PER, video traffic uses WLAN packet latency and jitter as added metrics for QoS. Since HEW needs to provide QoS for high-density video traffic, HEW functional requirements should also address video packet delay across the WLAN.

HEW needs packet latency requirement: For most streaming video services (e-education, Netflix, etc.), sizeable video buffering at the display is used to combat jitter and adds 1–10 s end-to-end delay. Packet delay is only a small portion of total delay, and even high delays (10–50 ms) are regarded as tolerable. However, for interactive video, wireless virtual desktop and other video applications, end-to-end delay is not acceptable. HEW must define a packet latency requirement that will address the needs of next generation users using delay-sensitive applications. The WLAN packet delay must result from an end-to-end delay plan for interactive video applications. The WLAN portion of the end-to-end delay should be an added functional requirement for HEW just for delay-sensitive applications [7–9].

3. High-efficiency PHY

A high-efficiency device will be asked to keep essential requirements of the legacy WLAN PHY layers. This could be a HE device operating at 2.4 GHz having to meet the legacy PHY requirements; a HE device operating in the 5 GHz band will have to work with the legacy and VHT PHY specifications. Despite this submission requirement, there are vital improvements in 802.11ax from past 802.11 generations. Several variations are the inclusion of service designed for MU-MIMO in the uplink and downlink along with OFDMA. Further, Modify in dot11ax has the symbol time of 12.8 μ s, which is four times the legacy symbol time

Table 1. Overview comparison of dot11n, dot11ac and dot11ax.

	IEEE 802.11n	IEEE 802.11ac	IEEE 802.11ax
Frequency bands (GHz)	2.4, 5	5	2.4, 5
Channel bandwidth (MHz)	20, 40	20, 40, 80, 80 + 80, 160	20, 40, 80, 80 + 80, 160
Subcarrier spacing (kHz)	312.5	312.5	78.125
Symbol time (μ s)	3.2	3.2	12.8
Cyclic prefix (μ s)	0.8	0.8, 0.4	0.8, 1.6, 3.2
Multi-user (MU)	No	Only downlink	AP-initiated uplink Tx plus downlink Tx
Modulation	OFDM	OFDM	OFDM, OFDMA
Data subscriber modulation	BPSK, QPSK, 16-QAM, 64-QAM	BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM	BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM, 1024-QAM
Coding	BCC (mandatory) LDPC (optional)	BCC (mandatory) LDPC (optional)	BCC (mandatory) LDPC (mandatory)
Data rates	72.2 Mbps (20 MHz, 1 SS) 600 Mbps (40 MHz, 4 SS)	433 Mbps (80 MHz, 1 SS) 6.93 Gbps (160 MHz, 8 SS)	600.4 Mbps (80 MHz, 1 SS) 9.6078 Gbps (160 MHz, 8 SS)

of 3.2 μ s. Three major reasons concerning increase of the symbol time are as follows [8, 10]: (i) robustness in outdoor channels, (ii) better tolerance to timing jitter across users in UL MU-MIMO/OFDMA and (iii) better indoor efficiency by cutting down cyclic prefix (CP) overhead. Along with the increased symbol time, dot11ax requires support for three CPs time [8–11] (table 1): (a) 0.8 μ s—legacy CP time with the longer symbol time improves efficiency due to reduced overhead from the CP, (b) 1.6 μ s—focusing on high efficiency in outdoor channels and indoor UL MU-MIMO/OFDMA and (c) 3.2 μ s—concentrate on robustness in the more appropriate case of outdoor UL MU-MIMO/OFDMA.

As an effect of the longer symbol time, the subcarrier spacing reduces from 312.5 to 78.125 kHz, and the FFT size for a channel bandwidth of 20 MHz grows from 64 to 256. Narrow subcarrier spacing helps improved equalization, and thereby a better channel robustness. However, the implementation complexities increase as FFT grows. Also, there are two new MCSs, 1024 QAM 3/4 and 1024 QAM 5/6, denoted as MCS10 and MCS11, respectively, applicable for channels with a bandwidth larger than 20 MHz; also, as the subcarrier spacing becomes smaller, the CFO (carrier frequency offset) correction is required to be more appropriate. Figure 1a shows the new HE PPDU formats and table 2 provides the acronym decoder ring for the fields used in the PPDU [12].

SU and MU formats: Currently two types of preambles (SU format and MU format) are defined with differentiation on whether SIGB is transmitted or not. While the MU format carries the most general OFDMA + MU-MIMO packets, the SU format provides efficiency for single-user transmissions. Both preambles can be used by any device

for transmission in the UL, DL or peer to peer. Both preambles are essential for 11ax and we therefore propose that both shall be mandatory

Legacy preamble: To keep backward compatibility with legacy devices (11a/n/ac), it is straightforward to prepend a legacy preamble before each 11ax PPDU; dot11ax receiver can initially acquire synchronization through L-STF and L-LTF, and channel estimation to decode 11ax preamble. Legacy STA can detect the PPDU existence and defer their transmission by the length indicated in L-SIG. It is more reliable (−82 dBm) and energy efficient than ED to prevent the unexpected interference from legacy STA [12].

HE-SIG-A: All intended 11n/ac receivers decode HT-SIG/VHT-SIG-A following legacy preamble to obtain common configuration information of the following PPDU; 11ax PPDU should also contain HE-SIG-A to carry some similar fields as in HT-SIG/VHT-SIG-A of 11n/ac, e.g., BW and GI. HE-SIG-A uses 64-FFT on each 20-MHz channel, and receiver can perform coherent detection of HE-SIG-A based on the CSI estimation from L-LTF. Legacy STA can be spoofed to receive an 11a/ac PPDU by specific design of modulation scheme. Like 11n/11ac, the legacy preamble and HE-SIG-A shall be duplicated on each 20 MHz in order to maintain the reliability of carrier sensing and low PAPR at transmitter.

802.11ax is the first WLAN standard to use OFDMA to enable transmissions with multiple users at the same time. This technology has been used in other standards, including WiMAX and LTE, and is also being used in 5G NR. With OFDMA, the bandwidth is divided into resource units (RUs) of various sizes, and different numbers and sizes of RUs can be allocated to transmissions to different users,

Figure 1. (a) HE PPDU formats. (b) RU locations in a 20-MHz HE PPDU.

based on the data throughput requirements [12–15]. The size of an RU can be 26, 52, 106, 242, 484, 996 or 2×996 tones or subcarriers, and the location of the RUs is defined for 20-, 40- and 80-MHz channels. The 20-MHz RU structure is used for each 20-MHz segment of one 40-MHz transmission. Figure 1b shows the location of RUs for a 20-MHz channel [16].

3.1 MU aggregation

In legacy WLAN, different access category (AC) traffic cannot be transmitted in an A-MPDU for contention fairness consideration. In high-efficiency case OFDMA/MU-MIMO, the airtime of scheduled DL/UL OFDMA RU is set by the STA that requires the longest airtime. Remaining STAs will and may have long idle time. Allowing AP or

Table 2. PPDU field representation.

Field	Representation
L-STF	Legacy short training field
L-LTF	Legacy long training field
L-SIG	Legacy signal field
RL-SIG	Repeated legacy signal field
HE-SIG-A	HE signal A field
HE-SIG-B	HE signal B field
HE-STF	HE short training field
HE-LTF	HE long training field
PE	Packet extension field
GI	Guard interval
LTS	Legacy training sequence

STA to aggregate frames from different ACs will improve the utilization of the scheduled RUs. In DL OFDMA/MU-MIMO, AP aggregates frames from secondary ACs of the same STA, whereas in UL OFDMA/MU-MIMO, STA aggregates frames from secondary ACs. The VHT-SIG-B length field for each user indicates the number of octets, rounded to the next 4 octet boundary, in the A-MPDU excluding padding. This value allows the PHY to stop processing receive once all the useful MAC data have been received [12].

When compared with LTE, WLAN does not have mandatory MU aggregation mechanisms and is less suited for short packets. Considering an application with a high likelihood of short packets/bursts, MU aggregation mechanisms help enhance MAC efficiency and reduce medium access overhead mainly in dense environments. Another prime requirement of MU aggregation is to have efficient aggregation for ACK/BA. Although such aggregation can be made available in DL with some specification changes except for UL direction, there is no efficient ACK aggregation mechanism. If UL OFDMA gets adopted in HEW, it can be used for ACK aggregation. However, consideration needs to be made to make it robust in case of error or missing ACK/BA (see figure 2).

The polled-ACK mechanism was added in 802.11ac for DL MU-MIMO, and it could be reused for DL OFDMA as well. Sequential-ACK procedures were considered in 11ac, but due to error recovery issues, none was adopted. Although polled-ACK is robust, it reduces the efficiency of the MU aggregation mechanism, particularly for short packets/bursts. While polled-ACK is suitable, it is not an

Figure 2. HE MU PPDU transmission with ACK/BA.

efficient mechanism for short payloads, or to poll ACK from many STAs in case of DL OFDMA. Finding a new more efficient and yet robust ACK/BA aggregation improves the overall efficiency of MU aggregation. The UL OFDMA and UL MU might be used in 802.11ax, which are suitable candidates. Considering UL MU for ACK aggregation, although it is feasible and offers good error recovery, it is less favourable since it is likely to be an optional feature. UL OFDMA is likely to be considered for HEW if UL OFDMA can be used for ACK aggregation in UL direction [17].

Another alternative for ACK/BA aggregation in UL direction is to use CDMA-based signalling. CDMA-based signalling would also offer excellent trade-offs for ACK aggregation in UL direction, as well as for bandwidth/air-time request, which would be necessary for UL OFDMA and UL MU mechanisms. Use of CDMA-based signalling is also well known in OFDMA-based cellular technologies [18].

In LTE/WiMAX, there are dedicated common channels where STAs can put their request for UL airtime, where such resource is available to all STAs. Smartphone traffic measurements for the variety of applications such as YouTube, web browsing, Facebook, Skype, etc. are shown in figure 3. In this figure we can easily observe that packet sizes are mostly short, the number of packets per burst is mostly a few and burst inter-arrival time is mostly on the order of milliseconds [19]. For instance, traffic measurement on packet size reveals that packet size is <66 B with >75% chance for UL, and <1500 B with 40% chance for DL.

3.2 HE sounding protocol

Transmit beamforming and DL MU-MIMO need information about the channel state to calculate a steering matrix that is given to the transmit signal to improve reception at

Figure 3. Distribution of uplink and downlink packet size for random web browsing.

Figure 4. Transmit beamforming sounding protocol with more than one HE beamformee.

one or more receivers. Figure 4 shows that HE STAs use the HE sounding protocol to look for the channel state information. Just like the VHT sounding protocol, the HE sounding protocol uses an explicit feedback mechanism in which the HE beamformee estimates the channel using a training signal sent by the HE beamformer and forwards back a transformed assessment of the channel state. The HE beamformer uses this estimation to derive the steering matrix [2].

The HE beamformee provides an estimate information of the channel state in a HE compressed beamforming feedback. The HE compressed beamforming feedback is a HE compressed beamforming report field for SU-type feedback concatenation with the high-efficiency multi-user (HE MU) distinctive beamforming report field for MU-type feedback, and a channel quality information (CQI) only report field for CQI-type feedback [7]. The HE compressed

beamforming feedback is taken in a single-HE compressed beamforming and CQI report frame if the induce frame is ≤ 11454 octets in length. Otherwise, the HE beamforming feedback is segmented and each segment is taken in a HE compressed beamforming and CQI report frame. For CQI-type feedback the HE compressed beamforming feedback is probably not segmented because induce MPDU size will always be < 11454 octets.

4. High-efficiency MAC

To improve the system level effectiveness further and also for better use of spectrum resources in dense deployment scenarios, the 802.11ax standard uses an enhanced CCA that proposes to increase CCA-SD (signal detection)

Figure 5. Using DSC (increased CCA) plus colour codes for spatial reuse.

Figure 6. (a) Spatial reuse operation, (b)–(d) throughput comparison using BSS colour filter and DSC and (e) adjustment rule.

threshold to higher than -82 dBm for better SR. This new feature is known as DSC [20]. Using DSC, STAs can distinguish signals from OBSSs and make decisions on medium contention and interference management. As an alternative to carrier sense threshold (CSth), the transmit power control is adapted.

4.1 Improving SR by increased CCA with BSS colouring

To increase capacity in the dense environment, we need to improve frequency reuse between BSSs. BSS colouring was a mechanism introduced in 802.11ah to assign a different colour per BSS, which will be extending to dot11ax. New channel access behaviour will be awarded based on the colour detected. It identifies SR opportunities of acquiring knowledge from OBSSs using the BSS colour codes (see figure 5); SR operation is shown in figure 6a.

Increased CCA: The 802.11ax AP/STA applies increased $\text{CCA-SD}_{\text{ax}}$ level on any received frame [20]. However, the problems are the following: SR on MYBSS frame is not protected, reduction of DL/UL coverage due to the increased CCA and unfair to legacy STAs; it is not

trivial to find the optimal $\text{CCA-SD}_{\text{ax}}$ level that satisfies all scenarios.

Increased CCA plus BSS colour: A frame received under $\text{CCA-SD}_{\text{ax}}$ level is inspected for BSS colour (MYBSS frame), and OBSS frame is not protected. This case works only when there are no legacy STAs. HEW STA will require a longer time to inspect received frame's BSS colour while legacy STA will finish regular CCA in much shorter time on the same frame, which is a drawback of HEW STA. In this case also, OBSS legacy STA is unfair.

Increased CCA plus BSS colour plus legacy: A frame received under $\text{CCA-SD}_{\text{legacy}}$ and $\text{CCA-SD}_{\text{ax}}$ is inspected for BSS colour, excluding OBSS_{ax} frames. A frame received below $\text{CCA-SD}_{\text{legacy}}$ is also not protected. In this case, there are no significant problems like sacrificing MYBSS frame, legacy STA being unfairly treated and UL/DL coverage reduction, but we need to work on SR for OBSS_{ax} frames only. In future enhancement, we need to protect frames received under $\text{CCA-SD}_{\text{legacy}}$.

As an alternative to CSth, adapt the transmission power of the secondary user to minimize any harmful interference to the primary user. The duration of the SR opportunity is lower than the duration of the transmission from the primary user [8, 9, 12, 14, 15, 21]. From the literature we find

that there is not much improvement in BSS total throughput using only BSS colour filtering alone; it is shown in figure 6b. However, we can easily observe that DSC provides more gain than colour filtering noted in figure 6c. Finally, when BSS colour filtering is used along with DSC, it can provide additional benefit when the offset of Rx sensitivity level is relatively small, which is acceptable for different application scenarios.

4.2 Improving SR by OA-CCA

OA-CCA is a technique used for SR. STA detects valid OBSS PPDU and retrieves the SR field parameters that are an asset to SR. STA adjusts its transmit power to meet the SR operation before an SR attempt. In this situation, the HE STA may discard the OBSS PPDU if the SR condition is satisfied, i.e., the SR condition ensures that the receiving STA of the on-going OBSS transmission is not affected by the SR transmission, or else we just protect the receiver of the on-going frame exchange under TBD conditions. Two modes of SR operation are proposed by task group IEEE 802.11ax (TGax). First, OBSS_PD threshold is based on an adjustment of the transmit power and the OBSS_PD threshold without using spatial reuse parameter (SRP) in SR field, which allows simple semi-static implementation where an STA can set its OBSS_PD. For example, an STA can determine its TxPWR based on the path loss to the intended receiver (in our case STA2) and environment and raise the OBSS_PD threshold. Second is OA-CCA; this mode is based on an SR field in HE-SIG-A and per link detection. First, we need to adjust the transmit power based on the specific information of path losses and acceptance receiver interference level to protect the receiver of the on-going transmission, based on the specific link detected like one PPDU at a time, which allows gathering of per BSS colour information to operate on a per colour and per SRP basis; this is more accurate and specific to dense deployment [8, 9, 12].

OA-CCA for Trigger frame and uplink MU: Trigger frame from AP (in our case STA2) for uplink multi-user carries SRP, OBSS colour and the uplink duration; meanwhile uplink STA1 copies SRP of the trigger frame ($RSSI_{trigger\ frame}$) into the SR field. STA3, which is denoted as an SR initiator, can initiate an SR transmission during the uplink PPDU duration after receiving the SRP. 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 figure 6e.

Mathematical analysis of the SR operation: STA1, which is also noted as UL STA, transmits to STA2 and STA1's transmission is detected by STA3 as it is above the baseline CCA level; STA3 identifies OBSS transmission and tries to initiate an SR transmission to STA4. For STA3 not to interfere with AP reception named as STA2, here we have the condition

$$TxPWR_{STA3} - \text{Space Loss} < \text{Acceptable Receiver Interference Level}_{STA2(AP)} \quad (4.1)$$

$$\text{where Space Loss} = TxPWR_{STA2(AP)} - RSSI_{trigger\ frame@STA3}. \quad (4.2)$$

Define SR parameter (SRP) as follows:

$$SRP = TxPWR_{STA2(AP)} + \text{Acceptable Receiver Interference Level}_{STA2(AP)}. \quad (4.3)$$

$$\begin{aligned} &\text{The required transmit power back - off is simplified} \\ &\text{to } TxPWR_{STA3} < SRP - RSSI_{triggerframe@STA3}. \end{aligned} \quad (4.4)$$

$$\begin{aligned} &\text{All power levels are normalized to that of 20 MHz:} \\ &\text{power} - 10 \times \log(BW/BW_{20\text{ MHz}}). \end{aligned} \quad (4.5)$$

4.3 Access efficiency (MAC efficiency)

The efficiency of WLAN channel use can be as low as 10% in certain conditions, which means that successful WLAN data transmission is lessened to 10% while ~90% of the channel is used for control, management frames and lost transmissions (collisions). HEW must permanently greet this problem [7]. An access efficiency requirement for HEW would provide significant improvements for overloaded hotspots. Access efficiency is calculated by dividing the BSS average total throughput by the BSS throughput time-averaged data rate. This metric provides the unit-less percentage of time over which the channel is occupied by data packets that are successfully transmitted and received. Control frames, management frames and collision frames are excluded from access efficiency calculation. The HEW amendment provides a mechanism to increase BSS channel access efficiency in overloaded channel scenarios with many associated STAs. The HEW amendment includes at least one mode of operation capable of achieving 60% or greater access efficiency when compared with scenarios providing 20–25% access efficiency [3, 4, 8, 9] when using existing IEEE 802.11 standard and its amendments operating in the same band in the same deployments with the same number of STAs and equal traffic loading. Figure 7 shows that the HEW requires both MAC efficiency and PHY data rate to achieve the functional requirements.

4.4 Enhanced TWT operation

TWTs allow STAs to maintain activity in the BSS by scheduling STAs to operate at different times to minimize contention between STAs and to reduce the required amount of time that an STA in power save (PS) mode needs

Figure 7. Throughput enhancement using MAC efficiency plus PHY data rate.

to be awake. The new proposal made by TGax to enhance TWT operation is a three-way approach. First, signalling a schedule when an STA is not able to transmit or receive, second, TWT flow set-up for power savings and constrained periods, and third, TWT set-up response. The first approach, a TWT requesting STA, requires listing the repeating times, i.e., constrained periods when it is not able to transmit or receive. If needed, the TWT receiving STA should use this information to select the TWT SP times, i.e., select the times when the requesting STA can transmit and receive. In the second approach, one TWT set-up frame requests a single-TWT agreement. To set up a TWT flow for power save and TWT flow to avoid operation at times when STA is not available (see figure 8), the STA should transmit two TWT set-up request frames: one TWT set-up frame requesting a TWT flow for power save and one TWT set-up frame requesting a TWT flow for constrained periods to provide information on the times when STA is not available. The two set-up frames may be aggregated to the same PPDU and transmitted at the same time. In the third approach, the AP may accept or reject the TWT-

constrained periods agreement, i.e., schedule when the requesting STA is not available. If accepted, the requesting STA shall update the constrained periods agreement if its availability changes. When constrained periods and TWT agreement for power save are transmitted in the same PPDU, the AP may accept only TWT agreement for power save, but the STA shall not update its availability information to the AP. The AP may propose alternative parameters for TWT agreement for power save. The TWT parameter set on constrained periods, i.e., when STA is not available, helps in selecting a suitable schedule.

5. Throughput analysis

In this section, we study the single-AP throughput analysis for four user downlink scenarios using HE MU PPDU frame format that supports the three MU-MIMO, OFDMA and combination of both configurations. The HE MU configuration is used to configure the transmission (Tx) of a HE MU packet. The HE MU PPDU format shown in the

Figure 8. Enhanced TWT operation.

Table 5. Throughput and access efficiency using MCS 4.

Path loss (dB)	Payload size = 1508 B, PHY rate = 52 Mbps/STA			
	OFDMA configuration		MU-MIMO configuration	
	Throughput (Mbps)	MAC efficiency (%)	Throughput (Mbps)	MAC efficiency (%)
96	71.6	84.44*	130	62.5
98	71.6	84.44*	130	62.5
100	71.6	84.44*	130	62.5
102	53.7	63.33*	65	31.25
104	35.8	42.22*	0	0
106	26.8	31.6*	0	0

then transmits a signal with power equal to the target RSSI plus estimated path loss. STAs closer to the AP transmit less power while STAs farther away transmit more power to overcome the higher path loss. The RSSI values provisions by the vendors and chipset makers like Aruba HPE, Cisco and so on, and not by IEEE standard. Generally, -50 dBm RSSI value provides 100% quality, also called as excellent signal strength. However, once RSSI value decreases to the noise floor, for example, -100 dBm, quality will be 0% (table 5); this leads to data corruption and requires a more significant number of retransmissions, adversely affecting throughput and latency. Table 6 shows the predefined values of RSSI, which define the path loss and SNR.

SNR is not a ratio but the difference in decibels between the received signal and the background noise level (noise floor). For example, if a radio (client device) receives a signal of -67 dBm and the noise floor is measured at -90 dBm, the SNR is 23 dB. In this scenario, SNR will vary between 24 and 14 dB when path loss varies from 96 to 106 dB, and this is because RSSI value ranges from -66 to -76 dBm. The -67 dBm signal strength is very good for voice over Wi-Fi and non-HD streaming video applications that satisfy functional requirements observed in figures 10 and 11 having high SNR value of 23 dB, and 97 dB low path loss.

Scheme 1: In this scheme, the APEP length is set to 1508 B for all users in all configurations, which is considered as transmission of large size packet under the conditions of AP throughput analysis. Eight transmit antennas (AP side) and two receive antennas (STA side) are used in this scheme (8×2). The result is shown in figure 10; in high SNR region (low path loss), MU-MIMO configuration gives better AP throughput value of 130 Mbps when compared with OFDMA configuration, which achieves 71.6 Mbps. The packet duration of the MU-MIMO configuration is approximately 50% that of the OFDMA configuration, which gives throughput gain. As the SNR decreases (high path loss), OFDMA configuration gets more effective with the help of transmit beamforming. The

Table 6. Relationship among path loss, SNR and RSSI.

RSSI (dBm)	Path loss (dB)	SNR (dB)	Informative with respect to RSSI
-30	60	60	Perfect signal strength, not acceptable in the real world; the client can be touching feet from AP to achieve this
-50	80	40	Anything down to this level can be considered an excellent signal strength
-60	90	30	Good and reliable signal
-67	97	23	Minimum signal strength for VoWiFi and non-HD streaming video applications that are very reliable, timely packet delivery
-70	100	20	Minimum signal strength for reliable packet delivery; e-mail and web applications
-80	110	10	Minimum signal strength for basic connectivity; packet delivery may be unreliable
-90	120	0	Equalling or drowning in the noise floor; any functionality is highly implausible

packet durations of OFDMA and mixed configuration are relatively same [24].

Scheme 2: In this scheme, the APEP length is set to 36 B for all users in all configurations, which is considered as transmission of small size packet under the conditions of AP throughput analysis. The 8×2 matrix is the same as in scheme 1. The result is shown in figure 11; for small packet size, Tx OFDMA and mixed configuration provide better AP throughput irrespective of high/low-SNR region. MU-MIMO configuration suits only at high SNR (low path loss). The four-user cumulative throughput of OFDMA configuration in high SNR region is 8.8 Mbps and it maintains half of the value till the end; because of this behaviour, OFDMA configuration outperforms in the entire SNR region [24].

Special case: This scheme belongs to performance evaluation of 5th percentile STAs usually present in the high-path-loss or low-SNR region, to meet functional requirements as discussed in section 2. Here the APEP length is set to 1000 B for all MU-MIMO users, and 100 B for all OFDMA users in all configurations. Six transmit antennas (AP side) and two receive antennas (STA side) are used in this scheme (6×2). From figure 12, it is easily understood that solitary MU-MIMO configuration (802.11ac) cannot resist the high path loss; however, in other configurations like OFDMA and mixed mode (802.11ax), throughput is consistently maintained till the end, which means even in the 5th percentile, STAs can get desirable throughput as per norms ($4 \times$).

Figure 10. Scheme 1—performance of large size packet transmission.

Figure 11. Scheme 2—performance of small size packet transmission.

As explained in the access efficiency section, 60% efficiency is easily obtainable in 802.11ax for dense environments as shown in table 5; also the calculation efficiency using PHY rate for each user or STA is 52 Mbps. For low path loss, 62.5% efficiency is obtained in MU-MIMO configuration and OFDMA configuration can maintain the average efficiency of 26.5% till the end. Calculation of efficiency performed using Eqs. (5.1) and (5.2) defines the MAC throughput as the ratio of total MAC payload (bits) to the time consumed for transmitting total MAC payload (s) [11, 25]. For example, at 96 dB path loss, OFDMA configuration can send

a payload of 1508 bytes for 4 users with a burst of 10 packets equal to 482.56 kB. Hence, the total time required to transmit 482.56 kB is 6.74 ms. This time duration is very much acceptable to satisfy the functional requirements in dense scenarios using high efficiency Wi-Fi or wireless.

MAC throughput =

$$\frac{\text{total MAC payload for each path loss(B)}}{\text{time consumed for transmitting total MAC payload(s)}}, \quad (5.1)$$

Figure 12. Performance of 5th percentile STAs.

$$\text{MAC efficiency} = \frac{\text{MAC throughput}}{\text{PHY rate}}. \quad (5.2)$$

6. Conclusion

In this article, we briefly reviewed a few technological building blocks of IEEE 802.11ax-2019 (HEW) amendment being designed to increase capacity in dense environments. Interactive video transmission latency requirements provide QoS in overloaded APs for AC_VI. Trigger-based OFDMA transmissions and uplink MU-MIMO are the most disruptive improvements in high-efficiency PHY from previous approved 802.11n/ac amendments. HEW may solely outperform VHT WLANs in scenarios with many STAs associated with a single AP, as shown in table 5. High-efficiency MAC works on improving SR by DSC; BSS colouring and OA-CCA seem very promising approaches to reduce the exposed node problem in high-density WLANs, and hence improve the area throughput. The throughput analysis result shows that for large packets, MU-MIMO is the most efficient in high-SNR region. OFDMA is the most efficient over the entire SNR range for a small packet. In future, WLAN scenarios will have coexistence with unlicensed LTE; to avoid this we need to combine HEW and IEEE 802.11ad/ay WLANs, and many other legacy features.

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