IEEE 802.11ax TECHNOLOGY INTRODUCTION

White paper | Version 01.00 | Lisa Ward

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Make ideas real

CONTENTS

This white paper introduces the technology used in the IEEE 802.11ax amendment to the IEEE 802.11 standard and gives an overview of receiver and transmitter test requirements. IEEE 802.11ax, also known as high efficiency wireless (HEW), provides mechanisms to more efficiently utilize the unlicensed spectrum bands (2.4 GHz, 5 GHz and 6 GHz) and improve user experience.

1 INTRODUCTION

IEEE 802.11 is the IEEE working group developing wireless local area network specifications. The group began work in the late 1990s and since then has created several successful standards/amendments, including IEEE 802.11a, b and g.

WLAN is now ubiquitous, with one or more WLAN technologies included as standard capabilities on most laptops and many smartphones. The IEEE 802.11 group has continued to build and improve on the earlier IEEE 802.11a/b and g with the official approval of IEEE 802.11n in 2009 and IEEE 802.11ac in 2013. There is a drawback to this success, however. Because WLAN is everywhere, it is common to find many access points and stations located in dense locations such as apartment buildings and stadiums. Since WLAN uses spectrum in the unlicensed ISM band, it is likely that several connections may interfere each other and cause some capacity crunch. There is no common scheduler in WLAN, and the channel access uses a CSMA scheme that has some drawbacks in high occupancy scenarios. In addition, users utilize WLAN for many different applications such as video streaming and offloading.

To accommodate the challenging applications and the large number of WLAN users in dense locations, the IEEE 802.11 working group formed the high efficiency wireless (HEW) study group in 2013 to find ways to improve the user experience for these applications and to more efficiently use the 2.4 GHz and 5 GHz spectrum. In March 2014, the HEW study group became an official task group, Task Group IEEE 802.11ax, to develop the IEEE 802.11ax amendment to IEEE 802.11-2016.

This white paper contains four parts:
1. Core documents for the IEEE 802.11ax amendment development
2. IEEE 802.11ax goals and features
3. Technology overview that covers key parts of the IEEE 802.11ax draft
4. Test requirements for measuring key metrics such as EVM and adjacent channel rejection

2 IEEE 802.11ax CORE DOCUMENTS

Much of the information in this paper comes from two key IEEE 802.11ax core documents. The IEEE 802.11ax draft and the IEEE 802.11ax specification framework document version 17.

The IEEE 802.11ax amendment draft [1] contains the proposed changes to IEEE 802.11-2016 in order to meet the IEEE 802.11ax requirements and goals. These changes include a new clause for the PHY specifications and a new MAC clause for supporting the new PHY features. In addition, the IEEE 802.11ax amendment contains modifications to the current IEEE 802.11 MAC layer in order to maintain compatibility with legacy devices. The 802.11ax amendment is expected to be published end of 2020.

The IEEE 802.11ax specification framework document contains the features and requirements that were agreed to by the IEEE 802.11ax task group members and is used as the framework or outline of the IEEE 802.11ax amendment. The specification framework document can be obtained by all at this link:
https://mentor.ieee.org/802.11/dcn/15/11-15-0132-17-00ax-spec-framework.docx
While all IEEE 802.11ax draft versions are only available to voting members of the IEEE 802.11 working group, the IEEE 802.11ax draft v6.0 is available for

purchase by non-members at this link: https://www.techstreet.com/ieee/standards/ieee-p802-11ax?gateway_code=ieee&vendor_id=7180&product_id=2019792

The IEEE 802.11 task groups provide public status updates of their work. The IEEE 802.11ax status can be found at:
http://www.ieee802.org/11/Reports/tgax_update.htm

3 IEEE 802.11ax GOALS AND FEATURES

The main goal of IEEE 802.11ax is to improve the user experience and network performance in dense deployments in the unlicensed bands. Specific targets (as defined in the project authorization request [2]) are:

- At least four times improvement in the average throughput per station (measured at the MAC data service access point) in a dense deployment scenario, while maintaining or improving the power efficiency per station
- Backwards compatibility and coexistence with legacy IEEE 802.11 devices operating in the same band

IEEE 802.11ax will use the spectrum efficiency, area throughput and performance improvements to target several usage models including (see [3]):

- Airports/train stations
- E-education
- Public transportation
- Dense apartment buildings
- Picocell street deployments

A high-level overview of new IEEE 802.11ax features and their key benefits can be found in Table 1.

Table 1: IEEE 802.11ax features and key benefits

Feature	Key benefits
Uplink MU-MIMO	Higher throughput upstream
Downlink OFDMA	Overhead reduction
Uplink OFDMA	Higher aggregate throughput
	Uplink range extension
	Overhead reduction
4 × symbol duration	Increased robustness for outdoor operation
1024QAM	Higher maximum data rate
Extended range preamble and MCS0 rep2	Range extension

4 IEEE 802.11ax (HIGH EFFICIENCY PHY)

A high efficiency (HE) device will have to comply with mandatory requirements of the legacy WLAN PHY layers. This means that an HE device operating in the 2.4 GHz band will need to comply with the IEEE 802.11n PHY requirements and an HE device operating in the 5 GHz band will be required to be in line with the IEEE 802.11n and IEEE 802.11ac PHY specifications.

Despite this compliance requirement, there are significant changes in IEEE 802.11ax from previous IEEE 802.11 generations. One of the main differences is the addition of support for multi-user MIMO (MU-MIMO) in both the uplink and downlink and orthogonal frequency division multiple access (OFDMA). Another change in IEEE 802.11ax is the symbol time, which is 12.8 µs – four times the legacy symbol time of 3.2 µs.

Three main reasons for increasing the symbol time are [4]:
- Robustness in outdoor channels
- Greater tolerance to timing jitter across users in UL MU-MIMO/OFDMA
- Higher indoor efficiency (by lowering CP overhead)

Along with the increased symbol time, IEEE 802.11ax mandates support for three cyclic prefix (CP) times:
- 0.8 µs: using this legacy CP time with the longer symbol time improves efficiency since there is less overhead from the CP
- 1.6 µs: targeting high efficiency in outdoor channels and indoor UL MU-MIMO/OFDMA
- 3.2 µs: targeting robustness in the more demanding case of outdoor UL MU-MIMO/OFDMA

In consequence of the higher symbol time, the subcarrier spacing decreases from 312.5 kHz to 78.125 kHz and the FFT size for a channel bandwidth of 20 MHz increases from 64 to 256. A narrow subcarrier spacing allows better equalization and thus higher channel robustness. Although a larger FFT size could have been used, the implementation complexities increase as FFT increases. In addition, as the subcarrier spacing becomes smaller, the carrier frequency offset (CFO) correction needs to be more precise.

Table 2: Overview comparison between IEEE 802.11n, 11ac and 11ax

	IEEE 802.11n	IEEE 802.11ac	IEEE 802.11ax
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 (µs)	3.2	3.2	12.8
Cyclic prefix (us)	0.8	0.8, 0.4	0.8, 1.6, 3.2
MU-MIMO	no	downlink	uplink and downlink
Modulation	OFDM	OFDM	OFDM, OFDMA
Data subcarrier modulation	BPSK, QPSK, 16QAM, 64QAM	BPSK, QPSK, 16QAM, 64QAM, 256QAM	BPSK, QPSK, 16QAM, 64QAM, 256QAM, 1024QAM
Coding	BCC (mandatory), LDPC (optional)	BCC (mandatory), LDPC (optional)	BCC (mandatory), LDPC (mandatory)

4.1 PPDU formats

IEEE 802.11ax distinguishes itself from the legacy frames at the PHY layer by introducing four new PPDU (packet protocol data unit) formats:

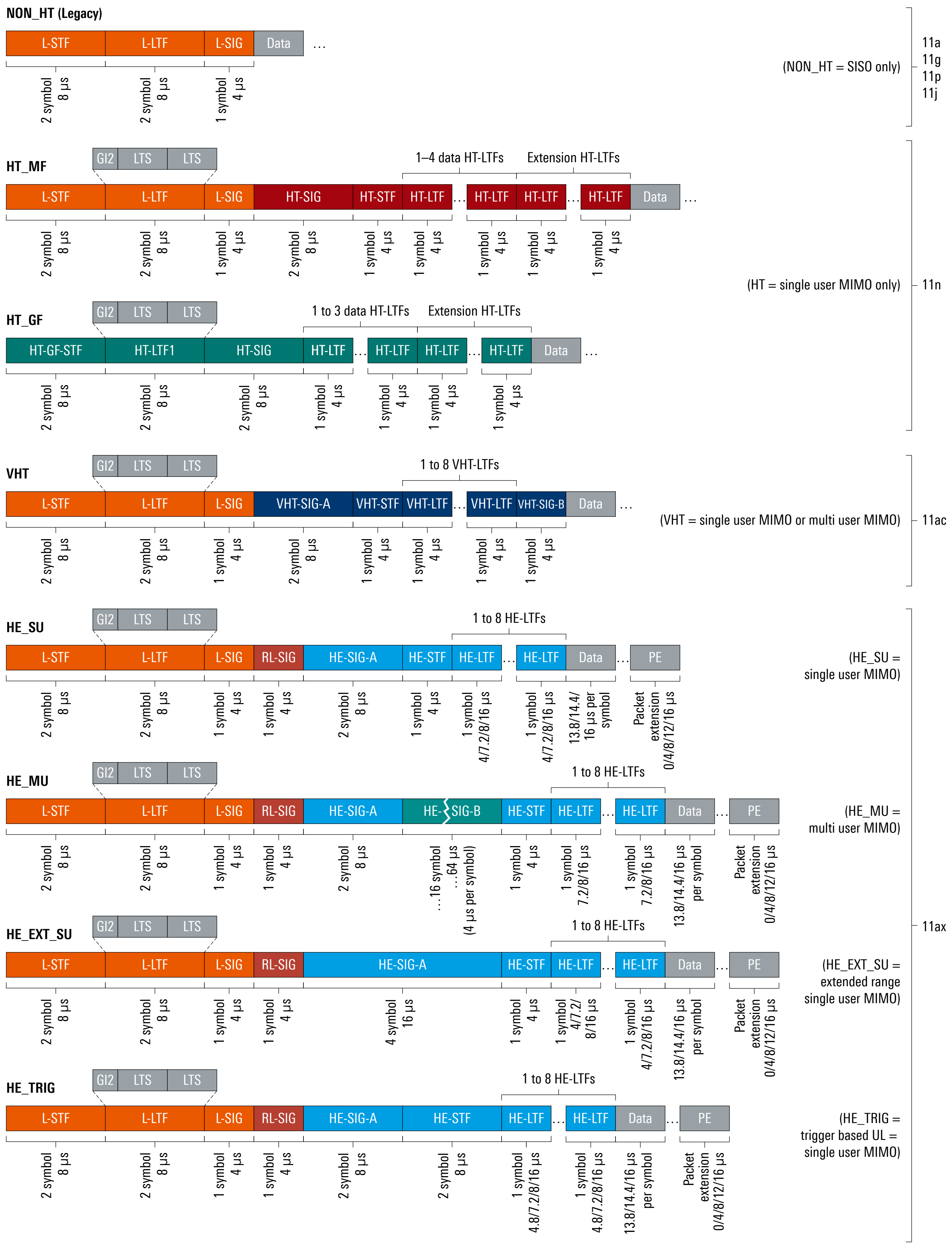
- Single user PPDU (HE_SU), which is used when transmitting to a single user
- HE extended range PPDU (HE_EXT_SU). This is also intended for transmitting to a single user but is intended for a user that may be further away from the AP such as in outdoor scenarios. The HE_EXT_SU will only be transmitted in 20 MHz channel bandwidths. Further, the HE_EXT_SU will use only 1 spatial stream and either MCS0 (BPSK ½), MCS1 (QPSK ½) or MCS2 (QPSK ¾).
- Multi-user PPDU (HE-MU), which carries one or more transmissions to one or more users
- HE trigger based PPDU (HE_Trig), which carries a single transmission and is sent in response to a trigger frame. This frame format is sent in an OFDMA and/or MU MIMO uplink transmission. MU UL transmissions typically require devices that are carefully calibrated and can meet strict requirements in terms of power and measurement accuracy. However, the IEEE 802.11 specification allows device implementations with a wide range of capabilities. In order to accommodate both high and low end devices, devices that support HE_Trig will also be required to declare whether they are a class A device that is carefully calibrated and can meet stricter power and measurement accuracy requirements or a class B device that is a low cost device with limited capabilities and more relaxed requirements [5].

While it is still yet to be determined whether support for the full PPDU for all of these PPDU formats will be required, all devices will be required to understand the preamble for all of the transmission modes.

Table 3: PPDUs field descriptions

Field	Description
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
Data	data
PE	packet extension field
GI	guard interval
LTS	legacy training sequence

Fig. 1: Legacy PPDU formats and new HE PPDU formats

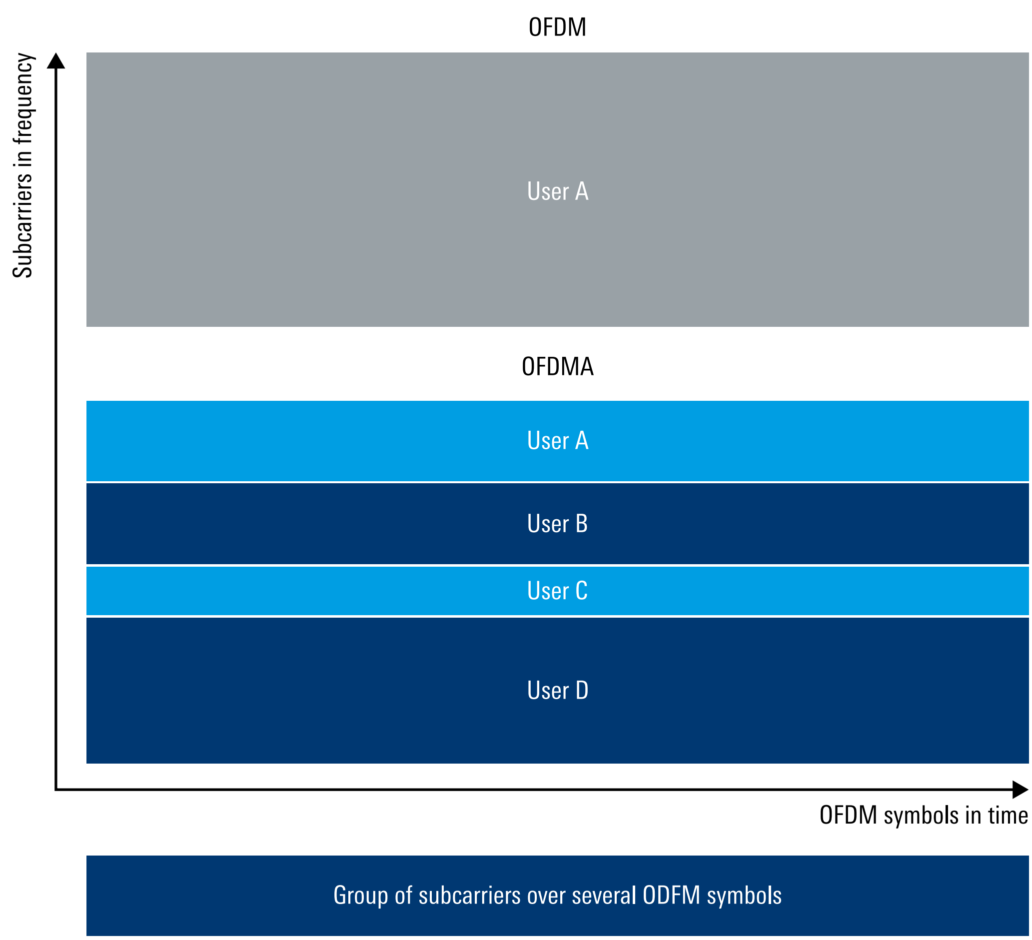


4.2 From single user to multiple users (MU)

Legacy IEEE 802.11 technologies used orthogonal frequency division multiplexing (OFDM), where transmissions are intended for a single user. IEEE 802.11ac added support for transmission to multiple users in the downlink using MU-MIMO, and IEEE 802.11ax adds support for uplink MU-MIMO as well and also adds OFDMA for multiple users in the uplink and downlink. Devices will be required to support OFDMA in the uplink and downlink but it is likely that UL-MU-MIMO will not be required for initial IEEE 802.11ax devices. Therefore, the focus of this section will be on OFDMA.

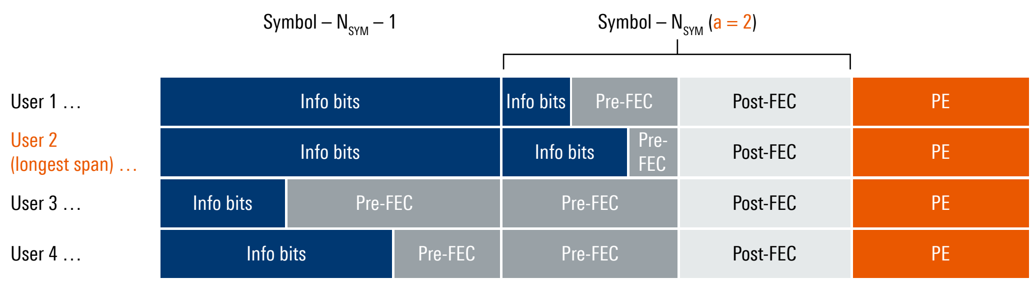
In OFDMA, the resources are allocated in two dimensional regions over time and frequency, referred to as a resource unit. Thus, different sets of subcarriers of the OFDM signal are allocated to different users as shown in Fig. 2.

Fig. 2: OFDM versus OFDMA [1]



Note that all users in IEEE 802.11ax OFDMA will have the same time allocations and will end at the same time. In the downlink, this will be achieved by adding padding bits to the shorter packets and requiring that the extra bits be transmitted at the same power level as the data portion of the packet. While this decreases the efficiency, it makes the requirement for backwards compatibility with legacy IEEE 802.11 networks easier to achieve. This can be understood by recalling that legacy devices might use carrier sense multiple access (CSMA) to determine if the channel is free to use. If, for example, one of the users had a longer packet than the other three users, the amount of signal power that will be sensed when the remainder of the longer packet is transmitted alone will be lower than when all users are transmitting together. In that case, a legacy device might determine that the channel is available and begin transmission. In addition to backwards compatibility, it may make synchronization of the signals less complex and reduce the amount of overhead information required in the preamble. An illustration of the DL OFDMA in the time domain is shown in Fig. 3.

Fig. 3: DL-OFDMA padding example [6] *a = a-factor



In the MU uplink case, the AP will not know how much data the individual users have to transmit. Therefore, the AP uses a control frame called a trigger frame to provide information to the user about how long it would like the uplink packet to be.

For the OFDMA (DL and UL) frequency allocations, the resource units (RU) can contain 26, 52, 106, 242, 484 or 996 tones (subcarriers) and are in fixed locations. The tones in the resource units are adjacent and contiguous except in the middle of the channel where DC null carriers are present. The locations of the 26-, 52-, 106-, 242-, 484- and 996-tone resource units that depend on the channel bandwidth are shown in Fig. 4 (for 20 MHz), Fig. 5 (for 40 MHz) and Fig. 6 (for 80 MHz). Note that while the location of the resource units themselves are fixed, it is possible to have a mix of different RU sizes.

Fig. 4: 20 MHz resource units and tone allocation [7]

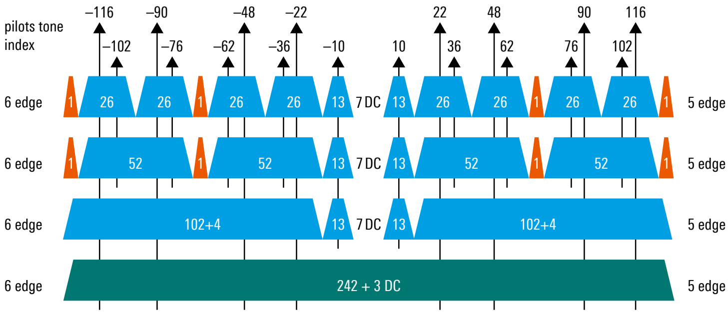


Fig. 5: 40 MHz resource unit and tone allocations [7]

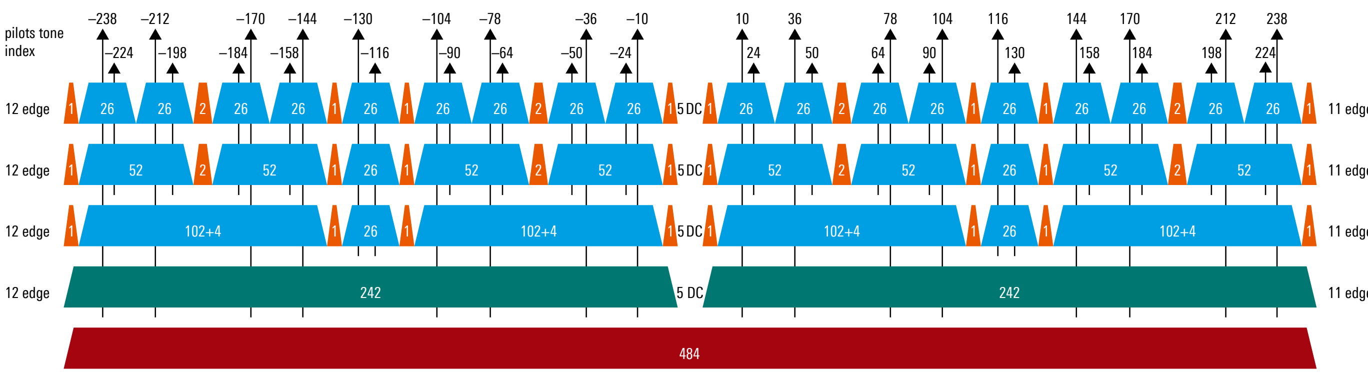
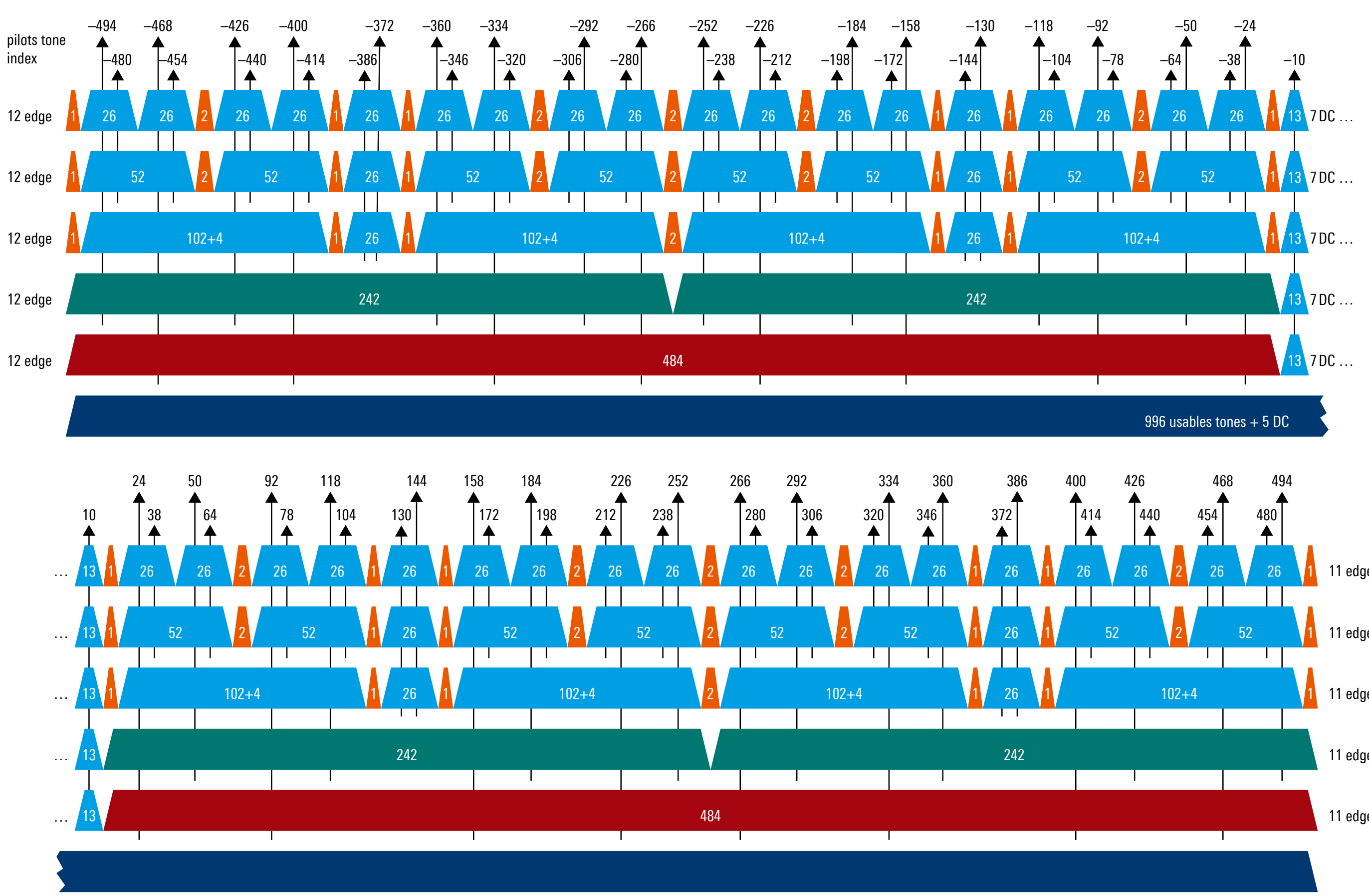


Fig. 6: 80 MHz resource unit and tone allocations [7]



4.2.1 Subcarrier types

4.2.1.1 Unused subcarriers

Three types of subcarriers are present: data subcarriers, pilot subcarriers (for phase information and parameter tracking) and unused subcarriers. The unused subcarriers are the DC subcarrier, the guard band subcarriers and the null subcarriers. While they do not transmit information, these unused subcarriers do serve useful purposes in the transmission of the OFDMA signal. There are 11 guard band subcarriers at the channel edges for 20 MHz and 23 guard band subcarriers for the 40 MHz and 80 MHz case as shown in Fig. 4, Fig. 5 and Fig. 6. These guard bands help protect against interference from adjacent channels.

Doing the math (for example in the 20 MHz resource unit allocation: 256 subcarriers – 11 edge subcarriers – 9 resource units × 26 subcarriers : RU = 11) shows that there are 11 subcarriers unaccounted for in each 242 subcarrier block. These 11 subcarriers will transmit no energy. A few of the 11 subcarriers were judiciously placed to serve as a separator between RUs, especially smaller size RUs, to reduce leakage from the adjacent block (shown in orange in Fig. 4, Fig. 5 and Fig. 6 [7]). In addition, some of these subcarriers are used as DC subcarriers. Null DC subcarriers are important for recovery of the OFDMA signal, especially in the case of smaller resource units near DC. In the downlink, the additional DC subcarriers will help mitigate problems due to receiver LO leakage and carrier frequency offset (CFO). In the uplink, the DC null subcarriers are even more critical since the STAs will need to synchronize to the AP's carrier frequency. If the frequency compensation is done in the digital domain, TX carrier leakage may not be at the center of the transmitted OFDMA waveform, which could cause interference with data tones. The AP will not be able to calibrate these carrier leaks when it receives the signal since it will not know the frequencies or magnitude of the STA transmissions [8].

4.2.1.2 Data subcarriers

The data subcarriers in IEEE 802.11ax will use the modulation and coding schemes (MCS) from IEEE 802.11ac and add two new MCS with 1024QAM. The four coding rates used in IEEE 802.11ac were studied as possibilities for the 1024QAM MCS, and two (3/4 and 5/6) were selected because 1024QAM using the other two coding rates (1/2 and 2/3) did not yield an increase in the information bit throughput that is already possible with the IEEE 802.11ac MCS. The two new 1024QAM MCS are MCS 10 and 11 and along with the 256QAM MCS 8 and 9 will likely be optional. 1024QAM will only be used in resource units (RU) having 242 or more tones. Table 4 provides the modulation and coding rate for the IEEE 802.11ax MCS.

Based on simulations, in most indoor scenarios, the 1024QAM MCS is selected with a high probability and results in over 20 % average throughput gain. However, 1024QAM does present some additional challenges for real equipment, for instance:

- Nonlinearity of power amplifier (PA)
- Higher crest factor or peak-to-average power ratio
- Quantization error of analog-to-digital converter (ADC)
- Phase noise and I/Q imbalance of local oscillator (LO)
- Residual center frequency offset (CFO) effect

Table 4: IEEE 802.11ax MCS indices

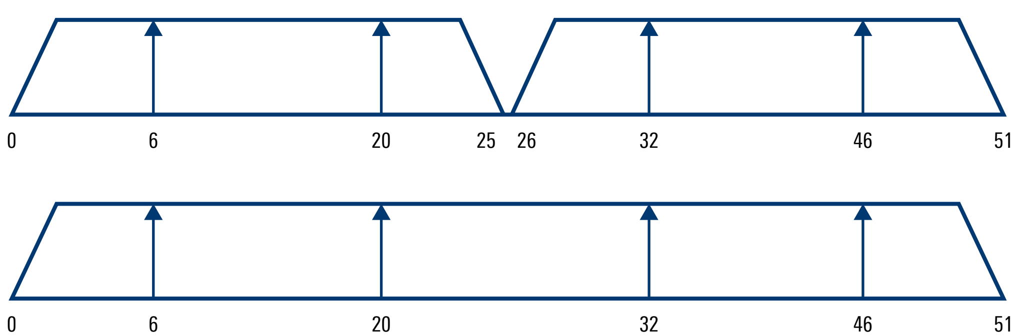
MCS	Modulation	Coding rate
0	BPSK	1/2
1	QPSK	1/2
2	QPSK	3/4
3	16QAM	1/2
4	16QAM	3/4
5	64QAM	2/3
6	64QAM	3/4
7	64QAM	5/6
8	256QAM	3/4
9	256QAM	5/6
10	1024QAM	3/4
11	1024QAM	5/6

4.2.1.3 Pilot subcarriers

Pilots are subcarriers that transmit a known signal. They are used by the OFDM demodulator to compensate for frequency errors, etc., and are critical to proper demodulation of the received signal. They are an important part of the transmission. Since they transmit no data information, the number of pilots should be kept at a minimum while still having enough to properly demodulate the signal. Because IEEE 802.11ax supports several bandwidths and resource unit sizes, the IEEE 802.11ax group needed to carefully consider the best location for the pilots in order to keep the implementation/computational requirements as simple as possible. To achieve that goal, IEEE 802.11ax will use pilots that are fixed and aligned in location across all of the resource allocation sizes.

To see what that means, a simplified picture of the pilot placement for 26- and 52-tone resource units is shown in Fig. 7. The 26-tone RU will use 2 pilots, and the 52-tone RU will use 4 pilots. Note that the pilot locations for the two cases are aligned.

Fig. 7: IEEE 802.11ax pilots for 26- and 52-tone RUs [7]



While it might be guessed that 8 pilots would be used for the 106-tone case in order to match the pilots in the 52-tone RU, instead only 4 pilots are really needed. Therefore pilot puncturing is done. To determine which of the 4 pilots to puncture out in the 106-tone case, it was necessary to consider how the remaining pilots would align with the 242-tone case in the 80 MHz bandwidth. As a result, the pilot selection was done so that the pilots would be more evenly distributed in the 242-tone RU. The exact pilot locations can be found in Table 5 and seen for the various RUs for the 20 MHz bandwidth in Fig. 4, for the 40 MHz bandwidth in Fig. 5, and for the 80 MHz bandwidth in Fig. 6.

Table 5: Pilot tone indices

Channel width	RU size	Pilot tone indices
20 MHz	26, 52	±10, ±22, ±36, ±48, ±62, ±76, ±90, ±102, ±116
	106, 242	±22, ±48, ±90, ±116
40 MHz	26, 52	±10, ±24, ±36, ±50, ±64, ±78, ±90, ±104, ±116, ±130, ±144, ±158, ±170, ±184, ±198, ±212, ±224, ±238
	106, 242, 484	±10, ±36, ±78, ±104, ±144, ±170, ±212, ±238
80 MHz	26, 52	±10, ±24, ±38, ±50, ±64, ±78, ±92, ±104, ±118, ±130, ±144, ±158, ±172, ±184, ±198, ±212, ±226, ±238, ±252, ±266, ±280, ±292, ±306, ±320, ±426, ±440, ±454, ±468, ±480, ±494, ±334, ±346, ±360, ±372, ±386, ±400, ±414,
	106, 242, 484	±24, ±50, ±92, ±118, ±158, ±184, ±226, ±252, ±266, ±292, ±334, ±360, ±400, ±426, ±468, ±494
	996	±24, ±92, ±158, ±226, ±266, ±334, ±400, ±468

4.2.2 OFDMA downlink resource unit assignments

Since multiple users are intended recipients in the OFDMA downlink, the AP needs to tell the STAs which resource units belong to them. In IEEE 802.11ax, the AP uses the HE-SIG-B field in the HE_MU_PPDU to do this. The SIG-B field is only found in the downlink HE-MU-PPDU (see Fig. 1).

The SIG-B contains two fields:

- ▶ Common field, where RU allocation info is included (see Table 6 for complete details of common field. The section for CRC calculation is found in the IEEE 802.11ax draft.)
- ▶ User-specific field, where per-STA info belongs to (e.g. STA-ID, MCS, Nsts)

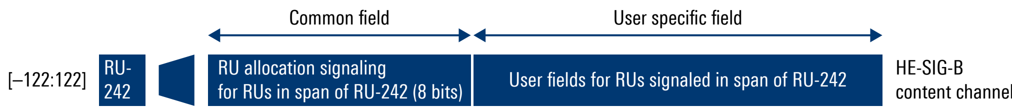
It is encoded on a per 20 MHz basis using BCC and is sent on the STA's preferred band so that the STA's signaling information (e.g. HE-SIG-B) is sent on the same band as the payload [9].

Table 6: SIG-B common info field [10]

Field	# of bits	Description
RU allocation	N×8	Indicates the RU arrangement in the frequency domain. It also indicates number of user fields in each RU. For 106-tone and larger RUs that support MU-MIMO, it indicates the number of users multiplexed using MU-MIMO. N = 1 for 20 MHz and 40 MHz HE MU PPDU, N = 2 for 80 MHz HE MU PPDU, N = 4 for 160/80+80 MHz HE MU PPDU
Center 26-tone RU	1	This field is present only for full 80 MHz bandwidth and full 160/80+80 MHz bandwidth. For full 80 MHz bandwidth: Set to 1 to indicate that center 26-tone RU is allocated in the common block fields of both SIGB content channels with same value. Set to 0 otherwise. For full 160/80+80 MHz bandwidth: Set to 1 to indicate that center 26-tone RU is allocated for one individual 80 MHz in common block fields of both SIGB content channels. Set to 0 otherwise.
CRC	4	See CRC computation (section 27.3.11.7.3 in IEEE 802.11ax draft v6)
Tail	6	Used to terminate the trellis of the convolutional decoder. Set to 0.

The most straightforward case for showing the HE-SIG-B mapping is the 20 MHz case.

Fig. 8: HE-SIG-B content for 20 MHz channel [1]



As shown in Fig. 8 for the 20 MHz case, the common field, which contains 8 bits for the RU allocation signaling, is followed by the user-specific field, which contains the user-specific information. Table 8 shows the values of the 8 bits and the corresponding allocation. For example, if there are 9 users each being assigned 26-tone RUs, the common field would contain 00000000. Another example, if there are 6 users with 1 user allocated 106-tone RU and the remaining 5 users assigned 26-tone RU each, then the common field would contain 01000000. In IEEE 802.11ax, a user can be assigned to only one RU.

The user-specific information comes after the common field in the HE-SIG-B. Fig. 9 shows the format of the user field, and Table 7 provides the details of each of the subfields in the user field. Based on the resource allocation provided in the common field and the relative location of the user field, the STA now knows which resource unit it is allocated and where to receive its data.

Fig. 9: HE-SIG-B user field format for OFDMA

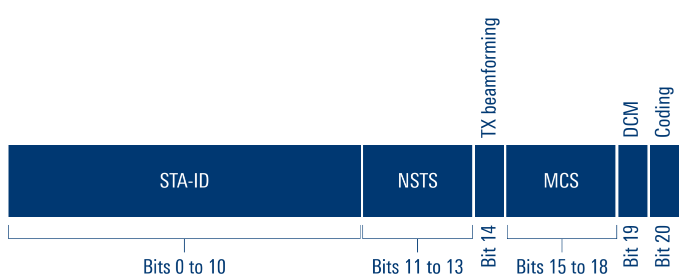
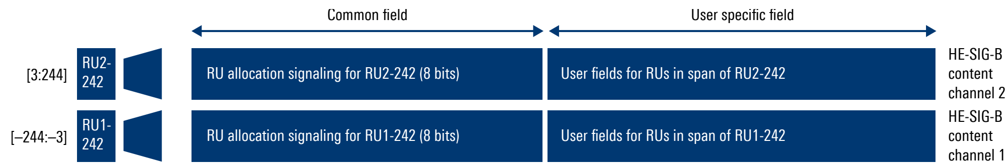


Table 7: HE-SIG-B user-specific fields (OFDMA)

Field	Description/value
STA-ID	The 11 least significant bits of the association identifier (AID). An AP assigns an AID to a STA during association. If the resource unit is not assigned to any STA, the STA-ID is set to 2046.
NSTS	Number of spatial streams. Set to the number of space time streams minus 1.
TX beamforming	Use of transmit beamforming: 1: beamforming is applied 0: otherwise
MCS	Modulation and coding scheme: 0: BPSK 1/2 1: QPSK 1/2 2: QPSK 3/4 3: 16QAM 1/2 4: 16QAM 3/4 5: 64QAM 2/3 6: 64QAM 3/4 7: 64QAM 5/6 8: 256QAM 3/4 9: 256QAM 5/6 10: 1024QAM 3/4 11: 1024QAM 5/6
DCM	Dual carrier modulation: 0: DCM is not used 1: DCM is used
Coding	Indicates whether BCC or LDPC is used: 0: BCC 1: LDPC

For the 40 MHz bandwidth, the HE-SIG-B has two 20 MHz channels, each with different information, so that each 20 MHz channel carries control information for users scheduled in that 20 MHz segment as shown in Fig. 10.

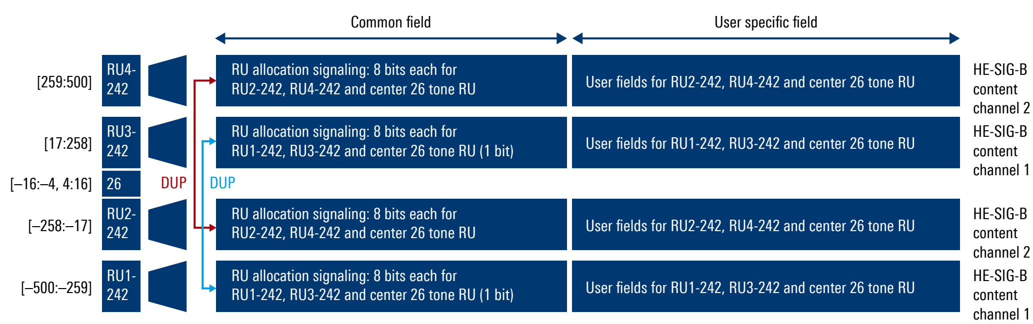
Fig. 10: HE-SIG-B content channel for 40 MHz bandwidth [1]



The 80 MHz bandwidth case will also use two HE-SIG-B content channels and signal the RU allocation per 242-tone segment. This means that the common field will now contain 16 bits by concatenating two 8-bit indices from Table 8 so that each of the two 20 MHz content channels define in total the resource allocation for 40 MHz. The implication of this is that a STA will need to decode information from two subbands.

These two content channels are then duplicated in the other 40 MHz of the 80 MHz bandwidth (see Fig. 11). The decision for this scheme was made based on a tradeoff between implementation complexity and efficiency: more subbands means more parallel decoders, but as the bandwidth increases, more users can be supported without increasing the size of the HE-SIG-B field [9].

Fig. 11: HE-SIG-B content channel format for 80 MHz bandwidth [1]



As seen in Fig. 6 and Fig. 11, the 80 MHz bandwidth may have an allocation for a 26-tone resource unit straddling the DC subcarriers. Therefore, in content channel 1 of the 80 MHz bandwidth, there is an additional bit to signal whether a user has been assigned that resource unit.

The 160 MHz bandwidth also uses two HE-SIG-B content channels and signals the RU allocation per 242-tone segment. This means that each channel will need to signal 4 RUs so that the common field will contain 32 bits by concatenating four 8-bit indices from Table 8. Again, the content channels are duplicated similarly to the 80 MHz case as illustrated in Fig. 12.

Fig. 12: HE-SIG-B content channel format for 160 MHz bandwidth [10]

Table 8: 8-bit indices for RU allocation per 242-tone segment for OFDMA

<table>
<tr><th>8-bit indices (b7 to b0)</th><th>#1</th><th>#2</th><th>#3</th><th>#4</th><th>#5</th><th>#6</th><th>#7</th><th>#8</th><th>#9</th></tr>
<tr><td>00000000</td><td>26</td><td>26</td><td>26</td><td>26</td><td>26</td><td>26</td><td>26</td><td>26</td><td>26</td></tr>
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<tr><td>00000110</td><td>26</td><td>26</td><td colspan="2">52</td><td>26</td><td colspan="2">52</td><td>26</td><td>26</td></tr>
<tr><td>00000111</td><td>26</td><td>26</td><td colspan="2">52</td><td>26</td><td colspan="2">52</td><td colspan="2">52</td></tr>
<tr><td>00001000</td><td colspan="2">52</td><td>26</td><td>26</td><td>26</td><td>26</td><td>26</td><td>26</td><td>26</td></tr>
<tr><td>00001001</td><td colspan="2">52</td><td>26</td><td>26</td><td>26</td><td>26</td><td>26</td><td colspan="2">52</td></tr>
<tr><td>00001010</td><td colspan="2">52</td><td>26</td><td>26</td><td>26</td><td colspan="2">52</td><td>26</td><td>26</td></tr>
<tr><td>00001011</td><td colspan="2">52</td><td>26</td><td>26</td><td>26</td><td colspan="2">52</td><td colspan="2">52</td></tr>
<tr><td>00001100</td><td colspan="2">52</td><td colspan="2">52</td><td>26</td><td>26</td><td>26</td><td>26</td><td>26</td></tr>
<tr><td>00001101</td><td colspan="2">52</td><td colspan="2">52</td><td>26</td><td>26</td><td>26</td><td colspan="2">52</td></tr>
<tr><td>00001110</td><td colspan="2">52</td><td colspan="2">52</td><td>26</td><td colspan="2">52</td><td>26</td><td>26</td></tr>
<tr><td>00001111</td><td colspan="2">52</td><td colspan="2">52</td><td>26</td><td colspan="2">52</td><td colspan="2">52</td></tr>
<tr><td>00010000</td><td colspan="2">52</td><td colspan="2">52</td><td>–</td><td colspan="4">106</td></tr>
<tr><td>00011000</td><td colspan="4">106</td><td>–</td><td colspan="2">52</td><td colspan="2">52</td></tr>
<tr><td>00100000</td><td>26</td><td>26</td><td>26</td><td>26</td><td>26</td><td colspan="4">106</td></tr>
<tr><td>00101000</td><td>26</td><td>26</td><td colspan="2">52</td><td>26</td><td colspan="4">106</td></tr>
<tr><td>00110000</td><td colspan="2">52</td><td>26</td><td>26</td><td>26</td><td colspan="4">106</td></tr>
<tr><td>00111000</td><td colspan="2">52</td><td colspan="2">52</td><td>26</td><td colspan="4">106</td></tr>
<tr><td>01000000</td><td colspan="4">106</td><td>26</td><td>26</td><td>26</td><td>26</td><td>26</td></tr>
<tr><td>01001000</td><td colspan="4">106</td><td>26</td><td>26</td><td>26</td><td colspan="2">52</td></tr>
<tr><td>01010000</td><td colspan="4">106</td><td>26</td><td colspan="2">52</td><td>26</td><td>26</td></tr>
<tr><td>01011000</td><td colspan="4">106</td><td>26</td><td colspan="2">52</td><td colspan="2">52</td></tr>
<tr><td>01100000</td><td colspan="4">106</td><td>–</td><td colspan="4">106</td></tr>
<tr><td>01110000</td><td colspan="2">52</td><td colspan="2">52</td><td>–</td><td colspan="2">52</td><td colspan="2">52</td></tr>
<tr><td>01110001</td><td colspan="9">242-tone RU empty</td></tr>
<tr><td>01110010</td><td colspan="9">484-tone RU with zero HE-SIG-B user-specific field in the corresponding HE-SIG-B content channel</td></tr>
<tr><td>01110011</td><td colspan="9">996-tone RU with zero HE-SIG-B user-specific field in the corresponding HE-SIG-B content channel</td></tr>
<tr><td>011101x_1x_0</td><td colspan="9">definition tbd.</td></tr>
<tr><td>011111x_1x_0</td><td colspan="9">definition tbd.</td></tr>
<tr><td>10000000</td><td colspan="4">106</td><td>26</td><td colspan="4">106</td></tr>
<tr><td>11000000</td><td colspan="9">242</td></tr>
<tr><td>11001000</td><td colspan="9">484</td></tr>
<tr><td>11010000</td><td colspan="9">996</td></tr>
<tr><td>11011000</td><td colspan="9">2 × 996</td></tr>
<tr><td>111$x_4x_3x_2x_1x_0$</td><td colspan="9">definition tbd.</td></tr>
</table>

4.2.3 OFDMA uplink resource unit assignments

To solicit uplink multi-user transmissions, the IEEE 802.11ax AP sends a control frame known as a trigger frame. This frame solicits and allocates resources for UL MU transmissions a short interframe space (SIFS) after the PPDU that carries the trigger frame in the downlink. The SIFS is the shortest interframe space between transmissions from different STAs defined in the IEEE 802.11 standard. This is enough time for the responding STAs to prepare the data to send to the AP, but it is too short for other STAs to attempt to use the channel since they would need to wait a longer time for the channel to be considered idle to begin transmission.

Although the trigger frame is a new control frame added to support IEEE 802.11ax, it is not required to transmit this frame using an HE frame format. In fact, transmitting the control frame using a legacy frame format may be beneficial since this provides the legacy stations info on the TXOP time, etc. and uses less overhead than the HE frame format.

The frame contains a field called common info that provides, as the name implies, information that is the same for all responding STAs. For information that is specific to a particular STA, the user info field is used.

4.2.3.1 Contents of trigger frame common field

Information contained in the common field of the trigger frame includes:

- Length: length in units of 1.33 µs of the expected uplink packet
- Number of HE-LTF symbols: number of long training fields the responding UL MU STAs should use
- GI and LTF: possible values are
  - 0 if 1 × HE-LTF + 1.6 µs GI
  - 1 if 2 × HE-LTF + 1.6 µs GI
  - 2 if 4 × HE-LTF + 3.2 µs GI
- Bandwidth: specifies the bandwidth for the trigger based uplink PPDU

4.2.3.2 Contents of trigger frame user field

Information that is unique for a responding UL MU STA is contained within the user field of the trigger fame. The user field starts with a STA AID to indicate the intended STA and is followed by user-specific information such as:

- RU allocation: indicates the resources units allocated for the STA
- Coding type: indicates whether BCC or LDPC coding is used
- MCS: indicates the MCS the STA should use in the trigger based PPDU

The RU allocation is done using 7 bit encoding in the RU allocation subfield of the user field. Table 9 provides the encoding for a 20 MHz PPDU.

Table 9: RU allocation encoding for trigger frame user field in 20 MHz

Encoding for RU allocation in user field of trigger frame for 20 MHz PPDU									
26-tone RU	**RU1**	**RU2**	**RU3**	**RU4**	**RU5**	**RU6**	**RU7**	**RU8**	**RU9**
Subcxr index	–121:–96	–95:–70	–68:–43	–42:–17	–16:–4, 4:16	17:42	43:68	70:95	96:121
RU allocation bits	0000000	0000001	0000010	0000011	0000100	0000101	0000110	0000111	0001000
52-tone RU	**RU1**		**RU2**			**RU3**		**RU4**	
Subcxr index	–121:–70		–68:–17			17:68		70:121	
RU allocation bits	0100101		0100110			0100111		0101000	
106-tone RU	**RU1**					**RU2**			
Subcxr index	–122:–17					17:122			
RU allocation bits	0110101					0110110			
242-tone RU	**RU1**								
Subcxr index	–122:–2, 2:122								
RU allocation bits	0111101								

Fig. 13: Example frame exchange using trigger frame in 20 MHz

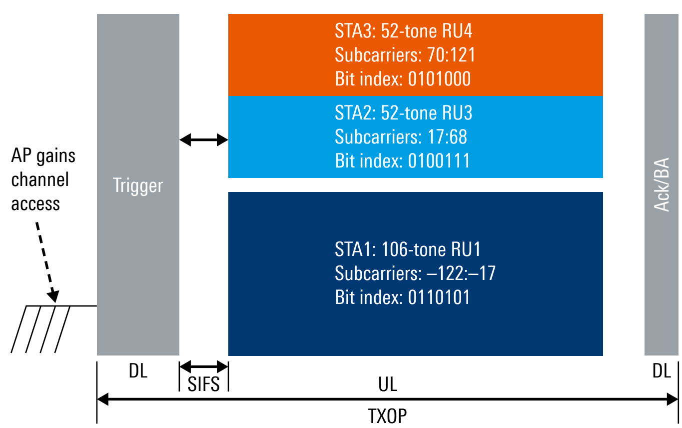


Fig. 13 provides a simple example of the frame exchange for a 20 MHz PPDU. In this example, there are three responding STAs. STA1 (in dark blue) is allocated a 106-tone resource block; STA2 (in cyan) and STA3 (in orange) are each assigned a 52-tone resource. In this case, the AP assigned the 106-tone resource block for STA1 to subcarriers –122:–17 (shown in dark blue in Table 9) and this corresponds to the 7-bit encoding of 0110101. The AP assigned the 52-tone resource block for STA2 to subcarriers 17:68 (shown in cyan). This is RU3 of the 52-tone RUs and corresponds to the 7-bit encoding 0100111. Similarly, the AP assigned the 52-tone resource block for STA3 to subcarriers 70:121 (shown in orange). This is RU4 of the 52-tone RUs and corresponds to 0101000.

The AP sends the trigger frame to the three STAs. The STAs respond a short interval later with identical size packets using the length information transmitted in the common field and they decode the bits in their user-specific RU allocation subfield to know which subcarriers to use to transmit their data.

RU allocations for 40 MHz, 80 MHz and 160 MHz bandwidths are given in Table 10 and Table 11. The 2×996-tone RU in the last rows of Table 11 is only applicable for the 160 MHz bandwidth.

Table 10: RU allocation encoding for trigger frame user field in 40 MHz

Encoding for RU allocation in user field of trigger frame for 40 MHz PPDU									
26-tone RU	**RU1**	**RU2**	**RU3**	**RU4**	**RU5**	**RU6**	**RU7**	**RU8**	**RU9**
Subcxr index	–243:–218	–217:192	–189:–164	–163:–138	–135:–111	–109:–84	–83:–58	–55:–30	–29:–4
RU allocation bits	0000000	0000001	0000010	0000011	0000100	0000101	0000110	0000111	0001000
26-tone RU	**RU10**	**RU11**	**RU12**	**RU13**	**RU14**	**RU15**	**RU16**	**RU17**	**RU18**
Subcxr index	4:29	30:55	58:83	84:109	111:136	138:163	164:189	192:217	218:243
RU allocation bits	0001001	0001010	0001011	0001100	0001101	0001110	0001111	0010000	0010001
52-tone RU	**RU1**	**RU2**	**RU3**	**RU4**	**RU5**	**RU6**	**RU7**	**RU8**	
Subcxr index	–243:–192	–189:–138	–109:–58	–55:–4	4:55	58:109	138:189	192:243	
RU allocation bits	0100101	0100110	0100111	0101000	0101001	0101010	0101011	0101100	
106-tone RU	**RU1**		**RU2**		**RU3**		**RU4**		
Subcxr index	–243:–138		–109:–4		4:109		138:243		
RU allocation bits	0110101		0110110		0111011		0111100		
242-tone RU	**RU1**					**RU2**			
Subcxr index	–244:–3					3:244			
RU allocation bits	0111101					0111110			
484-tone RU	**RU1**								
Subcxr index	–244:–3, 3:244								
RU allocation bits	1000001								

Table 11: RU allocation for trigger frame user field in 80 MHz, 80+80 MHz and 160 MHz

Encoding for RU allocation in user field of trigger frame for 80, 80+80 and 160 MHz PPDU									
26-tone RU	**RU1**	**RU2**	**RU3**	**RU4**	**RU5**	**RU6**	**RU7**	**RU8**	**RU9**
Subcxr index	–499:–474	–473:–448	–445:–420	–419:–394	–392:–367	–364:–340	–339:–314	–311:–286	–285:–260
RU allocation bits	0000000	0000001	0000010	0000011	0000100	0000101	0000110	0000111	0001000
26-tone RU	**RU10**	**RU11**	**RU12**	**RU13**	**RU14**	**RU15**	**RU16**	**RU17**	**RU18**
Subcxr index	–257:–232	–231:–206	–203:–178	–177:–152	–150:–125	–123:–98	–97:–72	–69:–44	–43:–18
RU allocation bits	0001001	0001010	0001011	0001100	0001101	0001110	0001111	0010000	0010001
26-tone RU	**RU19**	**RU20**	**RU21**	**RU22**	**RU23**	**RU24**	**RU25**	**RU26**	**RU27**
Subcxr index	–16:–4, 4:16	18:43	44:69	72:97	98:123	125:150	152:177	178:203	206:231
RU allocation bits	0010010	0010011	0010100	0010101	0010110	0010111	0011000	0011001	0011010
26-tone RU	**RU28**	**RU29**	**RU30**	**RU31**	**RU32**	**RU33**	**RU34**	**RU35**	**RU36**
Subcxr index	232:257	260:285	286:311	314:399	340:365	367:392	394:419	420:445	448:473
RU allocation bits	0011011	0011100	0011101	0011110	0011111	0100000	0100001	0100010	0100011
26-tone RU	**RU37**								
Subcxr index	474:499								
RU allocation bits	0100100								
52-tone RU	**RU1**	**RU2**	**RU3**	**RU4**	**RU5**	**RU6**	**RU7**	**RU8**	
Subcxr index	–499:–448	–445:–394	–365:–314	–311:–260	–257:–206	–203:–152	–123:–72	–69:–18	
RU allocation bits	0100101	0100110	0100111	0101000	0101001	0101010	0101011	0101100	
52-tone RU	**RU9**	**RU10**	**RU11**	**RU12**	**RU13**	**RU14**	**RU15**	**RU16**	
Subcxr index	18:69	72:123	152:203	206:257	260:311	314:365	394:445	448:499	
RU allocation bits	0101101	0101110	0101111	0110000	0110001	0110010	0110011	0110100	
106-tone RU	**RU1**		**RU2**		**RU3**		**RU4**		
Subcxr index	–499:–394		–365:–260		–257:–152		–123:–18		
RU allocation bits	0110101		0110110		0110111		0111000		
106-tone RU	**RU5**		**RU6**		**RU7**		**RU8**		
Subcxr index	18:123		152:257		260:365		394:499		
RU allocation bits	0111001		0111010		0111011		0111100		
242-tone RU	**RU1**		**RU2**			**RU3**		**RU4**	
Subcxr index	–500:–259		–258:–17			17:258		259:500	
RU allocation bits	0111101		0111110			0111111		1000000	
484-tone RU	**RU1**					**RU2**			
Subcxr index	–500:–17					17:500			
RU allocation bits	1000001					1000010			
996-tone RU	**RU1**								
Subcxr index	–500:–3, 3:500								
RU allocation bits	1000011								
2x996-tone RU	**RU1**								
Subcxr index	–1012:–515, –509:–12, 12:509, 515:1012								
RU allocation bits	1000100								

5 IEEE 802.11ax MEASUREMENTS

IEEE 802.11ax reuses many of the specifications from the IEEE 802.11ac amendment. Differences from the IEEE 802.11ac specification are given in this section. Devices that support the IEEE 802.11ax trigger based PPDU have many requirements that need to be met in order for the uplink MU transmissions to behave properly. These requirements are included here as well. For application notes and information on testing IEEE 802.11ac, see: https://www.rohde-schwarz.com/wlan/11ac

5.1 IEEE 802.11ax transmitter specification

5.1.1 Transmit spectrum mask

The IEEE 802.11ax device must meet the spectral mask given in the IEEE 802.11ax amendment and any applicable regulatory requirements. The measurement for the IEEE 802.11ax mask is made using a 100 kHz resolution bandwidth (RBW) and a 7.5 kHz video bandwidth (VBW). The mask for 20 MHz, 40 MHz, 80 MHz and 160 MHz transmissions is shown in Fig. 14 with the values of A, B, C and D given in Table 12. The mask amplitude is given in units of dBr, which means dB relative to the maximum spectral density of the signal.

Fig. 14: Spectral mask for 20 MHz, 40 MHz, 80 MHz and 160 MHz channels

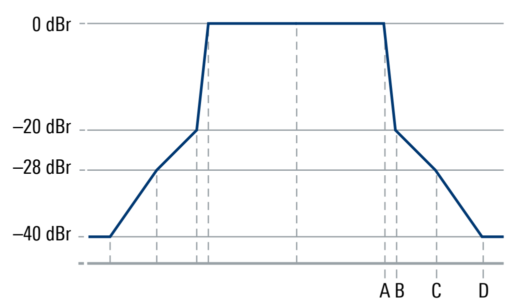


Table 12: Frequency offsets for spectral mask requirement

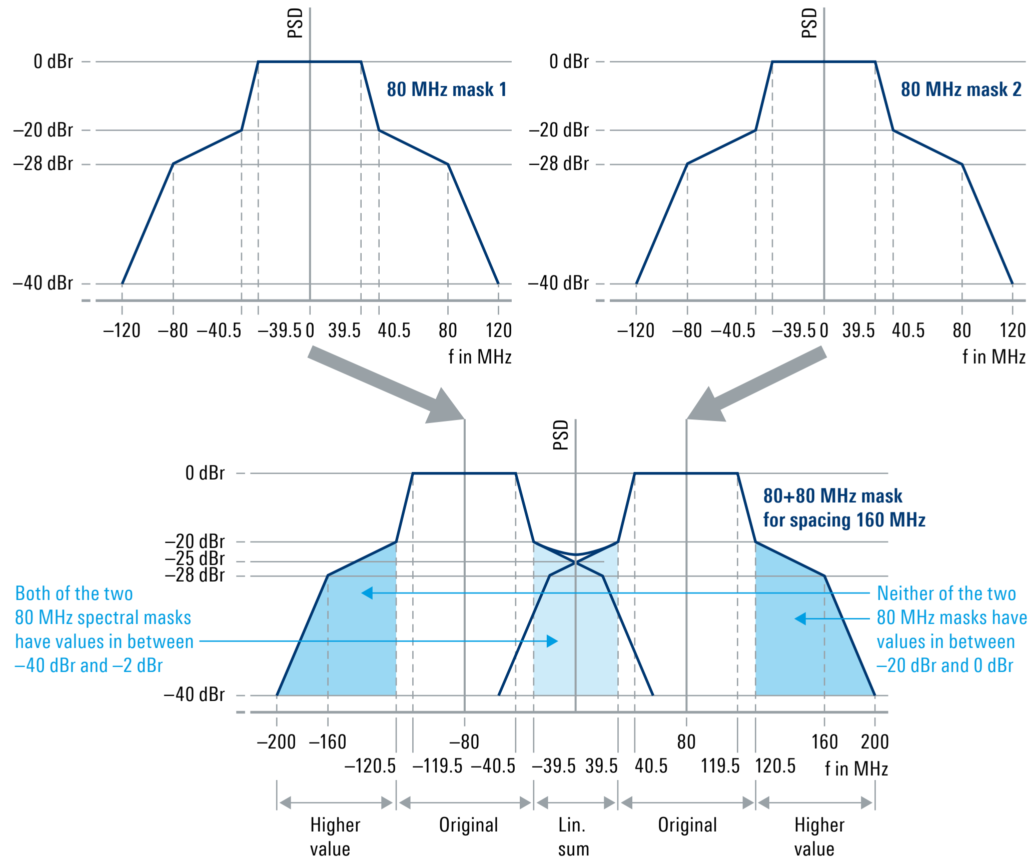
Channel size	A	B	C	D
20 MHz	9.75 MHz	10.25 MHz	20 MHz	30 MHz
40 MHz	19.5 MHz	20.5 MHz	40 MHz	60 MHz
80 MHz	39.5 MHz	40.5 MHz	80 MHz	120 MHz
160 MHz	79.5 MHz	80.5 MHz	160 MHz	240 MHz

In the case of non-contiguous 80+80 MHz, the 80 MHz masks are used for each 80 MHz signal. The values where the two non-contiguous 80 MHz masks overlap are given in Table 122. The mask construction for two 80 MHz non-contiguous signals separated by 160 MHz is shown in Fig. 15.

Table 13: 80+80 MHz non-contiguous spectrum mask values

Step	Frequency overlap mask values	Resulting mask value
1	Both masks have values from –20 dBr to –40 dBr	Sum of the two mask values in the linear domain
2	Neither mask has a value from 0 dBr to –20 dBr	The higher value of the two masks
3	No mask value defined	Linear interpolation in dB domain between the two nearest frequency points with defined mask values

Fig. 15: Example 80+80 MHz spectral mask



5.1.2 Spectral flatness

Spectral flatness provides a way to measure whether the subcarriers have a similar amount of power. This is done by determining the average energy of a range of subcarriers and verifying that no individual subcarrier's energy in that range deviates by more than the value specified.

Fig. 16 provides the IEEE 802.11ax spectral flatness specification for the 20 MHz, 40 MHz and 80 MHz signals as a function of subcarrier with the values for A, B, C and D given in Table 14. For example, if measuring the spectral flatness for the 20 MHz channel width, the subcarrier measured at subcarrier index 5 should be within ±4 dB of the average energy of the subcarriers from 2 to 84 and –84 to –2, and the energy at subcarrier 100 should be within +4 dB/–6 dB of the average energy of the subcarriers from 2 to 84 and –84 to –2. The outer subcarriers energy is not included in the calculation of the average energy (the blue dotted line in Fig. 16) because transmit filters may have higher attenuation at the band edges, which would unfairly skew the $E_{i,avg}$ value.

The IEEE 802.11ax spectral flatness measurement is made using BPSK modulated OFDM subcarriers. The test signal should contain at least 20 PPDUs with each PPDU containing at least 16 data symbols. Unoccupied subcarriers should be ignored during testing and averaging. In addition, resource unit power boosting and beamforming should not be used during this test.

Fig. 16: Spectral flatness requirement for 20 MHz, 40 MHz and 80 MHz bandwidths

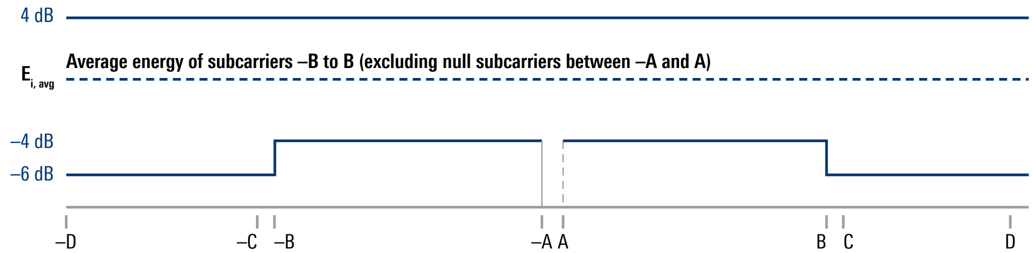
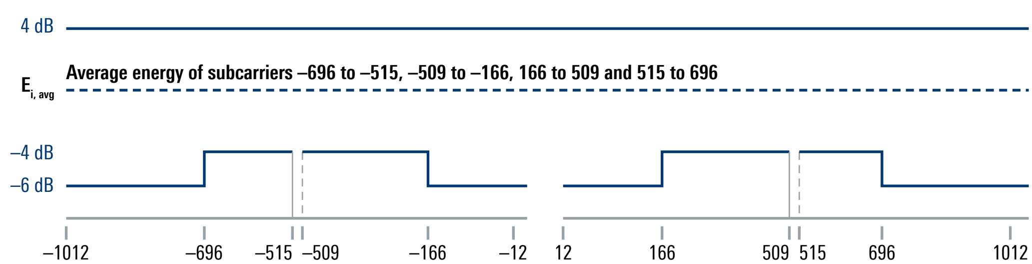


Table 14: Subcarrier index values for A, B, C, D and $E_{i,avg}$

Channel size	A	B	C	D	Subcarriers used to determine $E_{i,avg}$
20 MHz	2	84	85	122	2 to 84 and –2 to –84
40 MHz	3	168	169	244	3 to 168 and –3 to –168
80 MHz	3	344	345	500	3 to 344 and –3 to –384

For an 80+80 MHz transmission, each segment needs to meet the 80 MHz spectral flatness requirement. In the case of 160 MHz bandwidth transmission, subcarriers –696 to –515, –509 to –166, 166 to 509, and 515 to 696 are used to determine the average energy. Those subcarriers are required to be within ±4 dB of the average energy. Subcarriers –1012 to –697, –165 to –12, 12 to 165, and 697 to 1012 are required to be within +4 dB/–6 dB of the average energy (see Fig. 17).

Fig. 17: 160 MHz spectral flatness requirements



5.1.3 Transmitter modulation accuracy

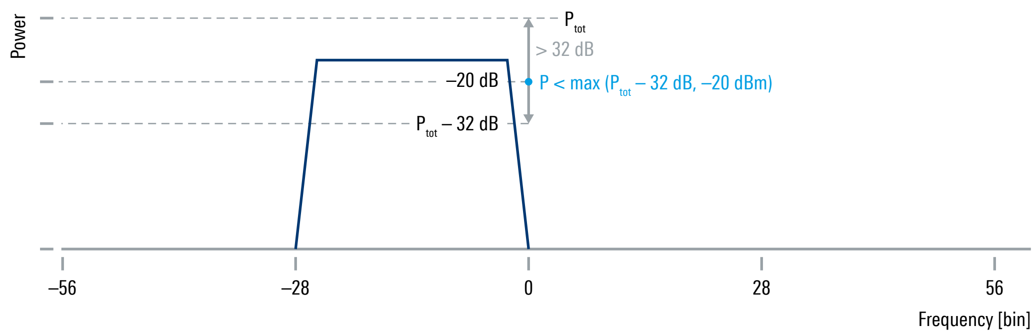
Two measurements are used to characterize modulation accuracy: transmitter local oscillator leakage and error vector magnitude (EVM).

5.1.3.1 Transmitter local oscillator (LO) leakage

This measures the amount of energy that leaks through and appears at the RF LO frequency. This measurement is needed because, depending on the type of receiver used, too much power leakage at this frequency may lead to poor demodulator performance. Further, if the power level is too high, a receiver may falsely trigger on the signal.

For IEEE 802.11ax, the specification requires that the power be measured at the location of the RF LO using resolution bandwidth 78.125 kHz, and the measured power should not exceed the greater value of –20 dBm or the transmit power per antenna in dBm minus 32 dB. An illustration of this specification is given in Fig. 18.

Fig. 18: IEEE 802.11ax TX LO leakage illustration

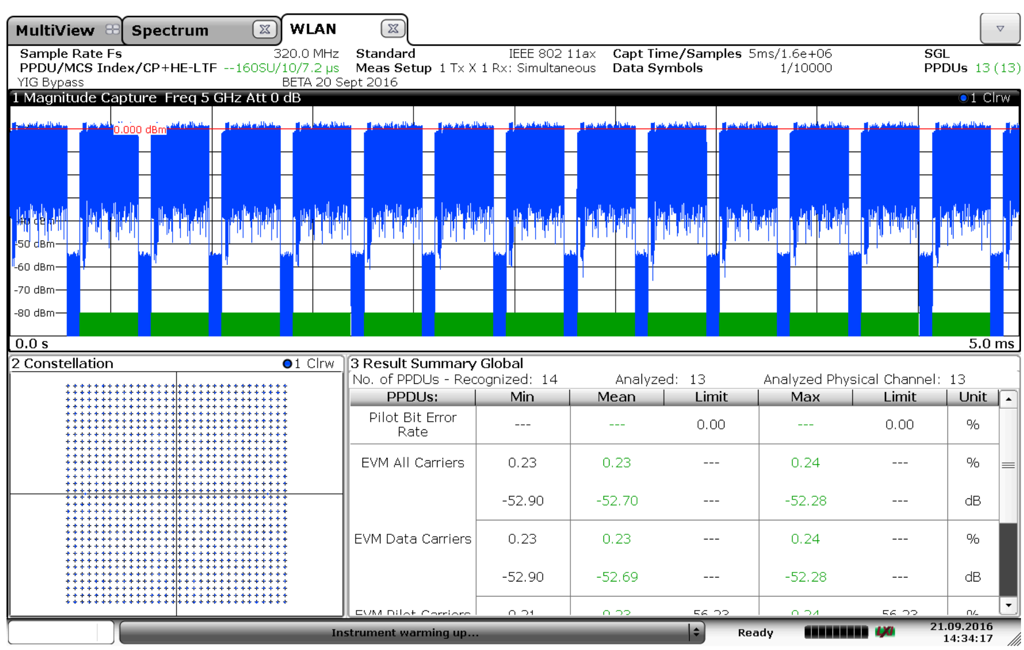


The center frequency leakage is measured using a 78.125 kHz resolution bandwidth.

5.1.3.2 Error vector magnitude

The EVM requirements for HE SU PPDU, HE extended range PPDU, and HE MU PPDU for MCS 0 to 9 are the same as in IEEE 802.11ac. For the new MCS 10 and 11, the EVM requirement will be –35 dB if amplitude drift compensation is enabled in the test equipment and –32 dB if amplitude drift compensation is disabled. Table 15 summarizes the EVM requirements for all MCS levels. Test equipment used for this measurement should have a residual EVM of 10 dB or less. This means that the analyzer should be capable of measuring lower than –45 dB for the 1024QAM case. Fig. 18 shows a screenshot from the R&S®FSW signal and spectrum analyzer achieving –52 dB EVM for a 160 MHz 1024QAM WLAN signal.

Fig. 19: 1024QAM WLAN constellation and EVM



The procedure for calculating EVM is very similar to IEEE 802.11ac. The test is performed using a minimum of 20 PPDUs with at least 32 data symbols containing random data if the occupied RU has 26 tones. If the occupied RU has more than 26 tones, then the PPDUs shall be at least 16 data symbols long.

The result is determined by averaging over the subcarriers, frequency segments, HE PPDUs and spatial streams. The signal should not use STBC (i.e. number of spatial streams should equal the number of space-time streams). IEEE 802.11ax EVM calculation is done using compensation of both estimated frequency offset and sampling offset drift. This is different than IEEE 802.11ac which only compensated for frequency offset, but this is important for IEEE 802.11ax which has much longer symbol times. Longer symbol times could lead to a larger timing drift, and this timing error causes intercarrier interference (ICI). [11]

For HE TB PPDU, the EVM requirements need to account for multiple STAs transmitting at the same time. The AP will see the noise from the multiple sources as total cumulative noise and network performance will decrease if this noise becomes too large. In addition, a STA transmitting power unintentionally outside of its allocated RU will negatively affect the EVM of other STAs. Therefore, the HE TB PPDU EVM requirement [12]:

- Tightens the EVM limit for low MCS because those MCS can contribute the highest amount of EVM noise to adjacent STAs in UL OFDMA
- Requires better EVM when the transmit power is below a predefined level – makes sure that EVM improves with reduced transmit power
- Includes an EVM requirement for the unused tones to measure if the STA is causing interference to adjacent RUs

The EVM limits for HE TB PPDU are given in the last two columns of Table 15. The two columns are necessary to provide two different EVM requirements depending on the transmit power as discussed in the second bullet above. In addition, the first rows of the table show the more stringent EVM limits for the lower MCS levels as described in the first bullet.

Table 15: Relative constellation error versus MCS for EVM

MCS	Modulation	Coding rate	EVM in dB for HE SU PPDU, HE ER SU PPDU and HE MU PPDU	EVM in dB for HE TB PPDU, transmit power > MCS 7 maximum power	EVM in dB for HE TB PPDU, transmit power ≤ MCS 7 maximum power
0	BPSK	1/2	–5	–13	–27
1	QPSK	1/2	–10	–13	–27
2	QPSK	3/4	–13	–13	–27
3	16QAM	1/2	–16	–16	–27
4	16QAM	(13)3/4	–19	–19	–27
5	64QAM	2/3	–22	–22	–27
6	64QAM	3/4	–25	–25	–27
7	64QAM	5/6	–27	–27	–27
8	256QAM	3/4	–30	–30	–30
9	256QAM	5/6	–32	–32	–32
10	1024QAM	3/4	–35	–35/–32	–35/–32
11	1024QAM	5/6	–35	–35/–32	–35/–32

For the unused tone EVM for the HE TB PPDU (discussed in the third bullet above), the limits are specified as a staircase mask. Although the requirement applies to any allocated RU size, the unused tone error is measured and averaged in 26-tone RU blocks to avoid frequency dependent variations. Therefore, the equations in the standard are defined in units of 26-tone RUs as shown in equation 1 and equation 2. [13]

Equation 1: UnusedToneError for $-i_{RU26,start} + 1 \le m \le -1$

$$UnusedToneError\left(i_{RU26,start}+m\right) \le \begin{Bmatrix} max\left(\varepsilon-2,-35\ dB\right), & if\ -r \le m \le -1 \\ max\left(\varepsilon-12,-35\ dB\right), & if\ -2r \le m \le -r-1 \\ max\left(\varepsilon-22,-35\ dB\right), & if\ -3r \le m \le -2r-1 \\ -35\ dB, & otherwise \end{Bmatrix}$$

Equation 2: UnusedToneError for $1 \le m \le N_{RU26} - i_{RU26,end}$

$$UnusedToneError\left(i_{RU26,end}+m\right) \le \begin{Bmatrix} max\left(\varepsilon-2,-35\ dB\right), & if\ 1 \le m \le r \\ max\left(\varepsilon-12,-35\ dB\right), & if\ r+1 \le m \le 2r \\ max\left(\varepsilon-22,-35\ dB\right), & if\ 2r+1 \le m \le 3r \\ -35\ dB, & otherwise \end{Bmatrix}$$

where:

m	defines the gap in the units of 26-tone RU to the occupied RU from either side with m = ±1 being the adjacent 26-tone RUs
r	is the scaling factor per allocated RU size (see Table 16)
$i_{RU26,start}$	is equal to i_{RU} if the occupied RU is a 26-tone RU, and is defined in Table 17 for other RU sizes
$i_{RU26,end}$	is equal to $i_{RU26,start} + r - 1$
i_{RU}	is the index of the occupied RU
N_{RU26}	is the maximum number of 26-tone RUs for the given bandwidth of the HE TB PPDU, i.e. ► 20 MHz bandwidth: $N_{RU26} = 9$ ► 40 MHz bandwidth: $N_{RU26} = 18$ ► 80 MHz bandwidth: $N_{RU26} = 37$ ► 80+80 MHz bandwidth or 160 MHz bandwidth: $N_{RU26} = 74$
ε	is the relative constellation error requirement for the occupied RU in an HE TB PPDU as defined in Table 15.

Table 16: Scaling factor r per occupied RU size

Scaling factor r	Allocated RU size
1	26-tone
2	52-tone
4	106-tone
9	242-tone
18	484-tone
37	996-tone

Table 17: $i_{RU26,Start}$ for each RU size

i_{RU}	52-tone RU	106-tone RU	242-tone RU	484-tone RU	996-tone RU
1	1	1	1	1	1
2	3	6	10	20	38
3	6	10	20	38	–
4	8	15	29	57	–
5	10	20	38	–	–
6	12	25	47	–	–
7	15	29	57	–	–
8	17	34	66	–	–
9	20	38	–	–	–
10	22	43	–	–	–
11	25	47	–	–	–
12	27	52	–	–	–
13	29	57	–	–	–
14	31	62	–	–	–
15	34	66	–	–	–
16	36	71	–	–	–
17	38	–	–	–	–
18	40	–	–	–	–
19	43	–	–	–	–
20	45	–	–	–	–
21	47	–	–	–	–
22	49	–	–	–	–
23	52	–	–	–	–
24	54	–	–	–	–
25	57	–	–	–	–
26	59	–	–	–	–
27	62	–	–	–	–
28	64	–	–	–	–
29	66	–	–	–	–
30	68	–	–	–	–
31	71	–	–	–	–
32	73	–	–	–	–

The following example illustrates how to determine the UnusedToneError limits for a 52-tone allocated RU at index 5 in a 40 MHz PPDU. The MCS is 2 and the transmit power is greater than the MCS 7 maximum power.

The variables used in the equations can be found as follows:

▶ From Table 15: ε in this case is –13 dB
▶ From Table 16: find the scaling factor; for a 52-tone RU, r = 2
▶ N_{RU26} for a 40 MHz bandwidth is 18
▶ From Table 17: find $i_{ru26,start}$; for this example, the i_{RU} is 5, for a 52-tone RU, this corresponds to an $i_{ru26,start}$ index of 10
▶ $i_{RU26,end}$ is now also known because $i_{RU26,end} = i_{RU26,start} + r - 1 = 10 + 2 - 1 = 11$
▶ m is a counting variable

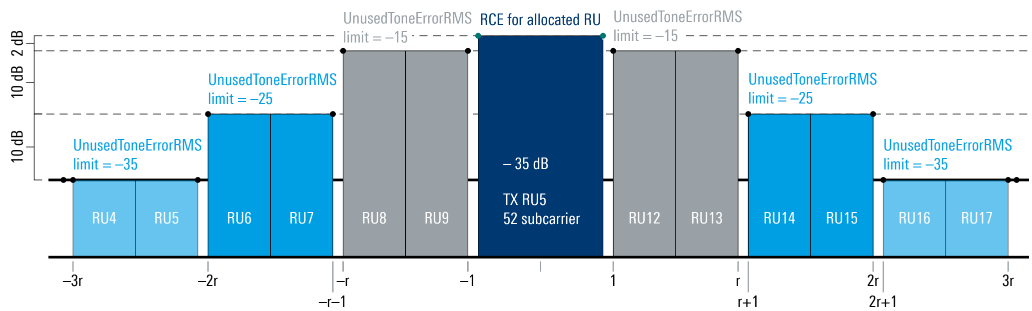
For this example, the 52-tone RU with index 5 corresponds to two 26-tone RUs with index 10 and 11 (Fig. 20 shows the allocated RU in dark blue).

The steps of the mask can now be found using equation 1 and equation 2. Table 18 provides the limits for each of the three stair steps. The adjacent step (step 1) is highlighted in gray; step 2 is highlighted in cyan; step 3 is highlighted in light cyan. Fig. 20 shows the pictorial representation of the results found in Table 18.

Table 18: UnusedToneError limits for 40 MHz PPDU, 56-tone RU at i_{RU} = 5 with MCS = 2

Stair step	m	Eqn index ($i_{RU26,start}$ – m)	Eqn index ($i_{RU26,end}$ + m)	UnusedToneError limit in dB
Step 1	1, –1	9	12	–15
(limit = ε – 2)	2, –2	8	13	–15
Step 2	3, –3	7	14	–25
(limit = ε – 12)	4, –4	6	15	–25
Step 3	5, –5	5	16	–35
(limit = ε – 22)	6, –6	4	17	–35

Fig. 20: Resulting limits for 40 MHz PPDU, 56-tone RU at i_{RU} = 5



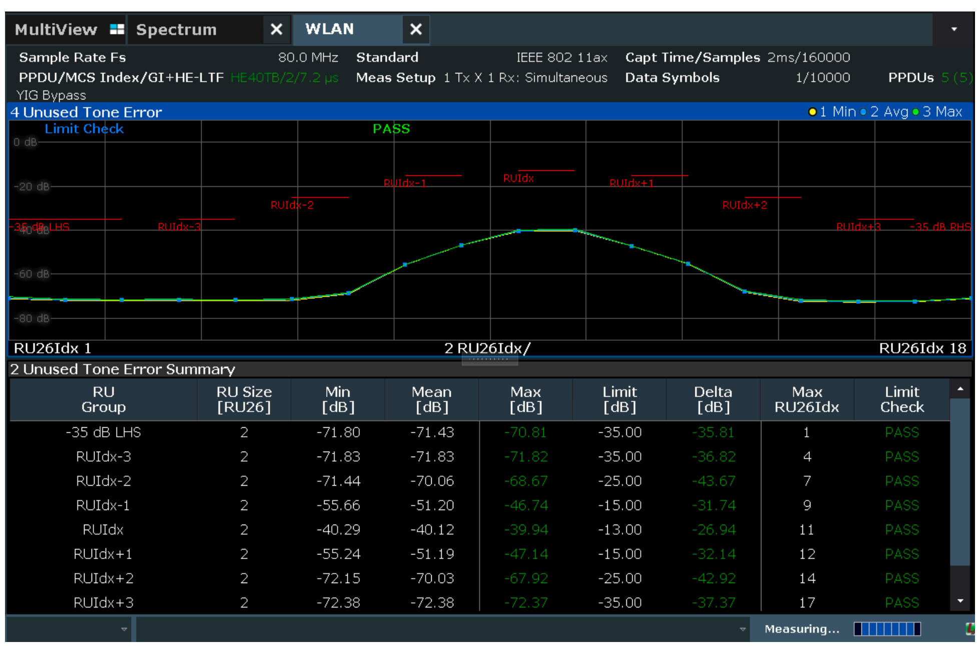
Fortunately, signal analyzers such as the R&S®FSW calculate the limits automatically and provide the measurement results easily. Fig. 21, Fig. 22 and Fig. 23 show screenshots from the R&S®FSW displaying the UnusedToneError measurement and limits for the example illustrated above. In the first screenshot (Fig. 21), the signal generated with the R&S®SMW200A vector signal generator is a clean signal. In the second screenshot (Fig. 22), a 0.04 dB I/Q gain imbalance was added to the generated signal. The gain imbalance product is a mirrored spectrum of the active RU around DC. As shown in the screenshot, it occurs at i_{RU26} = {8,9}. In the third screenshot (Fig. 23), the signal was generated with high R&S®SMW200A output power resulting in compression and degradation of the EVM.

Fig. 21: R&S®FSW UnusedToneError for 40 MHz PPDU with 56-tone RU at i_{ru} = 5 and MCS = 2

Fig. 22: R&S®FSW UnusedToneError for 40 MHz PPDU with 56-tone RU at i_{ru} = 5, MCS = 2 and added I/Q gain imbalance impairment

RU Group	RU Size [RU26]	Min [dB]	Mean [dB]	Max [dB]	Limit [dB]	Delta [dB]	Max RU26Idx	Limit Check
-35 dB LHS	2	-71.67	-71.21	-70.44	-35.00	-35.44	1	PASS
RUIdx-3	2	-71.57	-71.52	-71.47	-35.00	-36.47	4	PASS
RUIdx-2	2	-71.19	-71.19	-71.18	-25.00	-46.18	6	PASS
RUIdx-1	2	-52.97	-52.82	-52.68	-15.00	-37.68	8	PASS
RUIdx	2	-58.17	-58.10	-58.04	-13.00	-45.04	10	PASS
RUIdx+1	2	-70.64	-68.54	-66.44	-15.00	-51.44	12	PASS
RUIdx+2	2	-71.93	-71.87	-71.80	-25.00	-46.80	14	PASS
RUIdx+3	2	-72.24	-72.14	-72.03	-35.00	-37.03	17	PASS

Fig. 23: R&S®FSW UnusedErrorTone for 56-tone RU, i_{RU} = 5, MCS = 2 using a high power input signal



RU Group	RU Size [RU26]	Min [dB]	Mean [dB]	Max [dB]	Limit [dB]	Delta [dB]	Max RU26Idx	Limit Check
-35 dB LHS	2	-71.80	-71.43	-70.81	-35.00	-35.81	1	PASS
RUIdx-3	2	-71.83	-71.83	-71.82	-35.00	-36.82	4	PASS
RUIdx-2	2	-71.44	-70.06	-68.67	-25.00	-43.67	7	PASS
RUIdx-1	2	-55.66	-51.20	-46.74	-15.00	-31.74	9	PASS
RUIdx	2	-40.29	-40.12	-39.94	-13.00	-26.94	11	PASS
RUIdx+1	2	-55.24	-51.19	-47.14	-15.00	-32.14	12	PASS
RUIdx+2	2	-72.15	-70.03	-67.92	-25.00	-42.92	14	PASS
RUIdx+3	2	-72.38	-72.38	-72.37	-35.00	-37.37	17	PASS

5.2 HE receiver requirements

The IEEE 802.11ax receiver testing requirements and limits are similar to those defined in the IEEE 802.11ac specification and will be covered in this section. For information and details on how to generate signals for IEEE 802.11ax receiver testing see the application note "Generating WLAN IEEE 802.11ax Signals" (1GP115). It provides information on how to generate signals for IEEE 802.11ax and also covers additional important features for receiver tests, such as adding fading and imperfections to the generated signal.

5.2.1 Receiver minimum input sensitivity

The minimum input sensitivity test verifies that a receiver is able to successfully demodulate a signal at a given minimum input level. Successful demodulation is determined by a packet error rate (PER) of less than 10%. For IEEE 802.11ax, the minimum input sensitivity level depends on the modulation, coding rate and bandwidth (Table 19). The IEEE 802.11ax packets used for this test should be HE SU PPDUs 4096 bytes in length with an 800 ns guard interval. BCC is used if the PPDU bandwidth is 20 MHz, and LDPC is used if the bandwidth is greater than 20 MHz.

Table 19: Minimum sensitivity limits

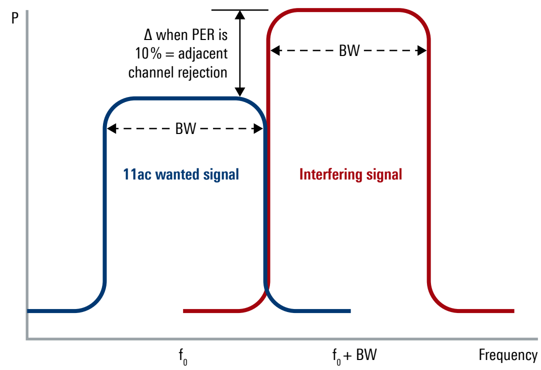
Modulation	Coding rate (R)	Minimum sensitivity (20 MHz PPDU) in dBm	Minimum sensitivity (40 MHz PPDU) in dBm	Minimum sensitivity (80 MHz PPDU) in dBm	Minimum sensitivity (160 MHz or 80+80 MHz PPDU) in dBm
BPSK	1/2	–82	–79	–76	–73
QPSK	1/2	–79	–76	–73	–70
QPSK	3/4	–77	–74	–71	–68
16QAM	1/2	–74	–71	–68	–65
16QAM	3/4	–70	–67	–64	–61
64QAM	2/3	–66	–63	–60	–57
64QAM	3/4	–65	–62	–59	–56
64QAM	5/6	–64	–61	–58	–55
256QAM	3/4	–59	–56	–53	–50
256QAM	5/6	–57	–54	–51	–48
1024QAM	3/4	–54	–51	–48	–45
1024QAM	5/6	–52	–49	–46	–43

5.2.2 Adjacent and nonadjacent channel rejection

The adjacent channel rejection test measures the ability of an IEEE 802.11ax receiver to detect and demodulate a signal in the presence of a stronger signal in a nearby channel (Fig. 24). The receiver is demodulating the wanted IEEE 802.11ax signal at f_0 with a bandwidth (BW) of 20 MHz, 40 MHz, 80 MHz or 160 MHz and power set 3 dB higher than the value of the minimum sensitivity level given in Table 19. An interfering HE compliant signal with a duty cycle (on/off ratio) greater than 50% and the same bandwidth as the wanted signal is centered 'BW in MHz' from the wanted signal (f_0 + 'BW in MHz') but with a power set higher than the wanted signal. The packet error rate is measured as the interferer's signal power is increased. When the packet error rate reaches 10%, the delta between the interferer's power and the wanted signal's power is measured. This delta is called the adjacent channel rejection and must be great than the value provided in Table 20. The adjacent channel rejection test can be skipped when a 160 MHz receiver is being tested but the regulatory domain does not allow an adjacent 160 MHz channel.

For the IEEE 802.11ax adjacent and nonadjacent channel rejection test, the desired signal uses HE SU PPDUs 4096 byte in length with an 800 ns guard interval. BCC is used if the PPDU bandwidth is 20 MHz, and LDPC is used if the bandwidth is greater than 20 MHz.

Fig. 24: Adjacent channel rejection



The nonadjacent channel rejection is similar, but the interfering signal is 2 × BW in MHz from the wanted signal as shown in Fig. 25.

Fig. 25: Nonadjacent channel rejection

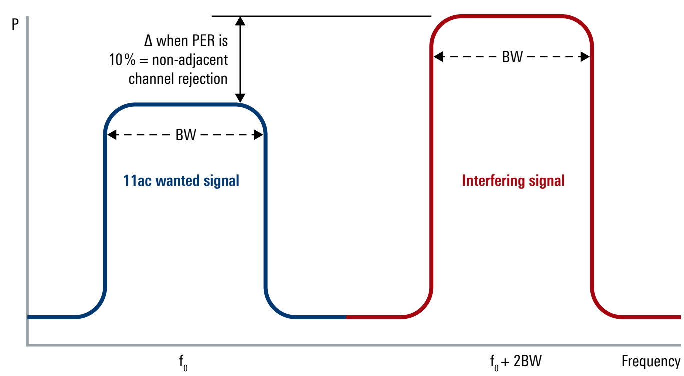


Table 20: Minimum adjacent and nonadjacent channel rejection requirements

Modulation	Rate (R)	Adjacent channel rejection in dB		Nonadjacent channel rejection in dB	
		20/40/80/160 MHz channel	80+80 MHz channel	20/40/80/160 MHz channel	80+80 MHz channel
BPSK	1/2	16	13	32	29
QPSK	1/2	13	10	29	26
QPSK	3/4	11	8	27	24
16QAM	1/2	8	5	24	21
16QAM	3/4	4	1	20	17
64QAM	2/3	0	–3	16	13
64QAM	3/4	–1	–4	15	12
64QAM	5/6	–2	–5	14	11
256QAM	3/4	–7	–10	9	6
256QAM	5/6	–9	–12	7	4
1024QAM	3/4	–12	–15	4	1
1024QAM	5/6	–14	–17	2	–1

5.2.3 Receiver maximum input level

Receiver maximum input level tests the ability of the receiver to demodulate an IEEE 802.11ax signal with an input level of –30 dBm if operating in the 5 GHz and 6 GHz bands and –20 dBm if operating in the 2.4 GHz band. HE SU PPDUs 4096 byte in length with an 800 ns guard interval are used. BCC is used if the PPDU bandwidth is 20 MHz, and LDPC is used if the bandwidth is greater than 20 MHz. The signal is applied at each antenna; the PER is measured and must be below 10%.

5.3 HE trigger based PPDU precorrection specifications

IEEE 802.11ax adds many new requirements for the HE trigger based (HE_Trig) PPDU case. These specifications are needed because UL OFDMA and UL MU-MIMO rely on transmission accuracy and user device synchronization for effective operation.

5.3.1 Transmit power accuracy and RSSI

Transmit power and RSSI measurement inaccuracies can result in excessive interference during the uplink multi-user transmissions. Table 21 provides the power and RSSI requirements for the HE trigger based PPDU. Note that there are different requirements depending on the device class. Because the high capability devices (class A) will be well calibrated, they should be able to meet a more stringent requirement. Low cost devices (class B) may not be calibrated and therefore need a less stringent requirement. [5]

The RSSI is measured over the legacy preamble for the RSSI accuracy requirement. In the 2.4 GHz band, this requirement is applicable for receive signals in the range of –82 dBm to –20 dBm, and in the 5 GHz band for receive signals in the range of –82 dBm to –30 dBm.

Table 21: Power and RSSI accuracy requirement for HE trigger based PPDU

Parameter	IEEE 802.11ax minimum requirements		Comments
	Class A devices	**Class B devices**	
Absolute transmit power accuracy	±3dB	±9 dB	Accuracy of achieving a specified transmit power level
Relative transmit power accuracy	not applicable	±3 dB	Accuracy of the change in transmit power for consecutive HE TB PPDUs
RSSI measurement accuracy	±3 dB	±5 dB	Difference between the RSSI and the received power. Requirements are valid from minimum RX to maximum RX input power.

Because class B devices have relaxed absolute transmit power accuracy specifications, an additional requirement is added for them: relative transmit accuracy, which measures the accuracy of the change of transmit power in consecutive HE TB PPDU transmissions [5]. The current requirement is that the class B devices support ±3 dB relative accuracy.

5.3.2 Carrier frequency offset (CFO) error and timing drift

Carrier frequency offset error contributes to interference between users. IEEE 802.11ax requires user devices to perform CFO correction relative to the trigger frame frequency to reduce the amount of residual CFO at the AP during the UL MU transmission. For the CFO requirement, the CFO error statistics are measured. At the 10% point of the CCDF curve, the CFO error must be less than 350 Hz. The measurement is made in the primary 20 MHz channel at a received power of –60 dBm. The CFO is measured after the HE-SIG-A field in the HE_Trig PPDU.

In order for the AP to decode packets from multiple users, the UL OFDMA and MU-MIMO transmissions need to be synchronized when the AP receives them. After the users receive information from the AP to trigger the uplink transmissions, they transmit the HE_Trig PPDU at a specified time. At the STA's antenna connector, the accuracy of this time is required to be ±0.4 µs + 16 µs from the end of the last OFDM symbol of the triggering PPDU sent by the AP to trigger the UL transmissions.

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7 ABBREVIATIONS/ACRONYMS/INITIALISMS

Abbreviation	Description
ADC	analog to digital converter
AP	access point
AWGN	average white Gaussian noise
BCC	binary convolutional coding
BPSK	binary phase shift keying
BW	bandwidth
CCA	clear channel assessment
CCDF	complementary cumulative distribution function
CFO	carrier frequency offset
CRC	cyclic redundancy check
CSMA	carrier sense multiple access
EVM	error vector magnitude
GI	guard interval
HE	high efficiency
IEEE	Institute of Electrical and Electronics Engineers
LDPC	low density parity check
L-LTF	legacy long training field
L-STF	legacy short training field
LO	local oscillator
LTF	long training field
MIMO	multiple input multiple output
MU	multi user
MU-MIMO	multi-user MIMO
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiplexing access
PA	power amplifier
PE	packet extension
PER	packet error rate
PLCP	physical layer convergence procedure
PPDU	PLCP protocol data unit
PPM	parts per million
PS	power save (mode)
QAM	quadrature amplitude modulation
RBW	resolution bandwidth
RSSI	receive signal strength indicator
RU	resource unit
STBC	space time block coding
STF	short training field
SU	single user
TBD	to be determined
TG	task group
TXOP	transmission opportunity
UL	uplink
VHT	very high throughput
WLAN	wireless local area network

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