802.11ac Technology Introduction

White Paper

This white paper provides a brief technology introduction on the 802.11ac amendment to the successful 802.11-2007 standard. 802.11ac provides mechanisms to increase throughput and user experience of existing WLAN and will build on 802.11n-2009.

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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 802.11a, b and g. WLAN is now ubiquitous, with one or more of these 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 a/b and g with the official approval of 802.11n in 2009 and other enhancements such as 802.11w, 11k, etc. An IEEE Standards in Communications and Networking article, "The IEEE 802.11 Universe" [1] provides a very good overview of past and current 802.11 projects. For more insight into 802.11 technology and test solutions, please see application note “WLAN 802.11n: From SISO to MIMO” [2] and application note “Measurement of WLAN 802.11 ac signals” [15].

Late in 2008, two new task groups, TGad for the 802.11ad amendment and TGac for the 802.11ac amendment, were started with the goal of significantly improving the data throughput of 802.11 so that performance of a wireless network can be equivalent to a wired network. 802.11ad will use very wide bandwidths in the 60GHz band and 802.11ac will use frequencies in the 5GHz. Both amendments are scheduled for completion at the end of 2012.

This technology introduction paper covers the 802.11ac (also known as VHT, Very High Throughput) amendment and is divided into several main topics: important 802.11ac documents, key requirements, and the 802.11ac PHY which is further broken into sections describing the channel structure, frame formats, preamble fields, and data fields. This is followed by a description of PHY layer test specifications.

2 802.11ac Core Documents

- **TGac Usage Models R2 [4]**, approved during May 2010 802.11 working group meeting. This document contains 6 usage models that are expected to be used for 11ac.
- **TGac Feature Requirements and Evaluation Methodology Document v16 [5],** approved during the January 2011 meeting: The main purpose is to define the functional requirements that the 802.11ac amendment must meet.
- **TGac Channel Model Addendum v12 [6]**, approved during the March 2010 meeting: This document defines the channel models that 11ac will use. They are primarily modifications to the 802.11n channel models. These models are used in simulations (along with other parameters specified in the Evaluation Methodology Document) to show that inputs to the 802.11ac amendment meet the feature requirements.
- **Specification Framework Document, currently at v21 [7].** Approved January, 2011. Members of TGac have developed the higher level requirements in this document and it is used as the ‘framework’ or outline of the 802.11ac amendment.

- **TGac Draft Amendment v1.1 [16]**. Draft version 1.1 of the 11ac amendment. This document contains the necessary changes to 802.11mb draft v9 to meet the 802.11ac requirements. (802.11mb is the revision project of the 802.11-2007 standard. It incorporates all approved 802.11 amendments since the release of 802.11-2007 and fixes any ambiguities found since the release of these standards.) These changes include a new clause for the PHY specifications and modifications to the 802.11 MAC specifications. P802.11ac Draft Version 1.1 was released August, 2011. The expected completion date for the final amendment version is in early to mid 2012.

3 802.11ac Key Requirements

The main requirements/goals for the 802.11ac amendment are (see [5]):

- **Backwards Compatibility**: 11ac shall provide backwards compatibility with 802.11a and 802.11n devices operating in the 5GHz band. This means that 11ac must interwork with 11a and 11n and care is being taken in the 11ac to define frame structures to accommodate the 11a and 11n devices.
- **Coexistence**: 11ac will provide mechanisms to ensure coexistence with 11a and 11n devices operating in the 5GHz band.
- **Single-STA (station) throughput:** A station (a device compliant with 802.11ac PHY and MAC) shall be capable of throughput greater than 500Mbps as measured at the MAC Service Access Point (SAP) while using no more than an 80 MHz channel.
- **Multi-STA throughput** (measured at the MAC SAP): The throughput when the 11ac system has multiple stations shall be greater than 1Gbps while using no more than an 80 MHz channel.

802.11ac will use the higher throughput and data rates to address several categories of usage models (see [4]):

1. Wireless display
2. In home distribution of HDTV and other content
3. Rapid upload/download of large files to/from servers
4. Backhaul traffic (mesh, point to point, etc.)
5. Campus and auditorium deployments
6. Manufacturing floor automation

It is anticipated that the top three markets/usage models of very high throughput devices shipping in 2012 will be: In room gaming (category 1), Rapid sync-n-go file transfer (category 3) and Projection to TV or projector in conference room (category 1).

4 802.11ac PHY

802.11ac plans to re-use 11n (&11a) details where possible. This is advantageous for ensuring backwards compatibility and co-existence and also allows the 11ac developers to focus on the new features that are needed to achieve the throughput requirements. For example, the 11ac PHY is based on the well known OFDM (Orthogonal Frequency Division Multiplexing) PHY used for 11a and 11n and will maintain the same modulation, interleaving and coding architecture of 11n. However, some modifications and new 11ac features/parameters are necessary to meet 11ac's goals.

802.11ac (aka VHT, Very High Throughput) devices are required to support 20, 40, and 80 MHz channels and 1 spatial stream. Several optional features are also defined in 802.11ac:

- Wider channel bandwidths (80+80 MHz and 160 MHz)
- Higher modulation support (optional 256QAM)
- 2 or more spatial streams (up to 8)
- MU-MIMO (Multi-User MIMO)
- 400 ns short guard interval
- STBC (Space Time Block Coding)
- LDPC (Low Density Parity Check)

An 11ac device making use of only the mandatory parameters (80 MHz bandwidth, 1 spatial stream, and 64 QAM 5/6) will be capable of a data rate of ~293 Mbps while a device that implements all optional parameters (8 spatial streams and 256 QAM 5/6 with a short guard interval) will be able to achieve almost 3.5Gbps.

4.1 Channelization

When the OFDM PHY was introduced to 802.11, the channel bandwidth was 20MHz with later amendments adding support for 5 and 10MHz bandwidths. The 802.11n amendment added support for an optional 40MHz channel. 802.11ac will include support for 80MHz bandwidth as well as an optional 160MHz bandwidth. The 11ac device is required to support 20, 40, and 80 MHz channel bandwidth reception and transmission. The 80MHz channel will consist of two adjacent, non-overlapping 40MHz channels. The 160MHz channels will be formed by two 80MHz channels which may be adjacent (contiguous) or non-contiguous.

"Channelization for 11ac" (See [8]) provides a nice background of the 11ac channel allocation for the US (Figure 1) and for Europe and Japan (Figure 2). Since the release of that contribution, the FCC has approved the use of channel 144 in the US. (See Annex E of [16].) Figure 1 reflects this additional 20 MHz channel and the resulting additional 40 MHz channel and 80 MHz channel for 11ac for US and for the global operating class.

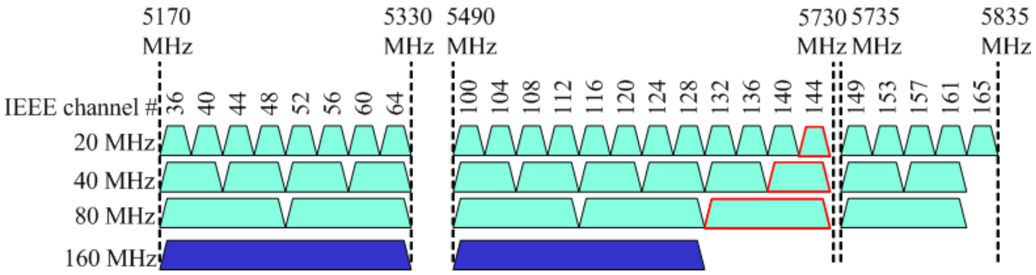


Figure 1: US and Global Operating Class Channel Allocation

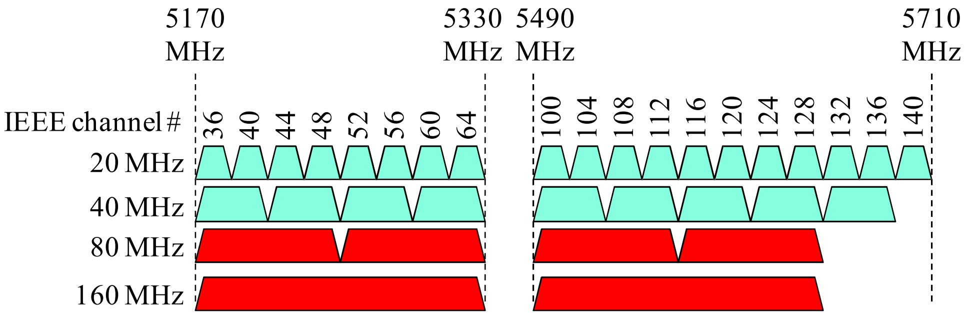


Figure 2: Europe and Japan Class Channel Allocation

To signal the VHT bandwidth and operating frequencies 4 fields are used:

- *Current Channel Bandwidth*: Provides the channel bandwidth and could be 20MHz, 40 MHz, 80 MHz, 160 MHz, and 80+80 MHz.
- *Current Channel Center Frequency Index 1*:
  - For 20, 40, 80 or 160 MHz bandwidths, this provides the channel center frequency
  - For 80+80 MHz, this provides the center frequency of the primary segment.
- *Current Channel Center Frequency Index 2*:
  - For 20, 40, 80 or 160 MHz bandwidths, this is undefined.
  - For 80+80 MHz, this provides the center frequency of the secondary segment.
- *Current Primary 20 MHz Channel*: Provides the location of the primary 20MHz channel. All channel bandwidths will have a primary 20 MHz channel assigned.

These parameters are sent in the PLME MIB (Physical Layer Management Entity Management Information Base) and are used along with the *channel starting frequency* given in the Country Information and Regulatory Classes Annex of the 802.11 standard [13] in the following equations to determine channel center frequency and the frequency for the 20MHz primary subchannel:

Channel center frequency [MHz]=
Channel starting frequency+5 * Current Channel Center Frequency Index

Primary 20 MHz channel center frequency [MHz]
=Channel starting frequency+5 * Current Primary 20 MHz Channel

A few examples (from [9]) will help to illustrate how these parameters work to provide the center frequency and bandwidth: (Since a VHT STA operates in 5GHz band, the examples will assume a regulatory class that has a channel starting frequency = 5 GHz.)

Example 1:
A channel specified by

CurrentChannelBandwidth = 80 MHz
CurrentChannelCenterFrequencyIndex1 = 42
CurrentPrimary20MHzChannel = 36

is an 80 MHz channel with

Channel center frequency	= 5 GHz + 5 * 42 = 5210 MHz
Primary 20 MHz center freq	=5 GHz + 5 * 36 = 5180 MHz

Example 2:
A channel specified by

CurrentChannelBandwidth = 80+80 MHz
CurrentChannelCenterFrequencyIndex1 =155
CurrentChannelCenterFrequencyIndex2 = 106
CurrentPrimary20MHzChannel = 161

is an 80+80 MHz channel with

Channel center freq (Primary)	= 5 GHz + 5 * 155 = 5775 MHz
Channel center freq (Secondary)	= 5 GHz + 5 * 106 = 5530 MHz
Primary 20 MHz channel center freq	= 5 GHz + 5 * 161 = 5805 MHz

4.2 From Bandwidth to OFDM Subcarriers

802.11ac uses OFDM (Orthogonal Frequency Division Multiplexing) just as 802.11a and 802.11n do. (In fact 11ac ‘reuses’ much of the existing (legacy) 802.11a and 802.11n specifications modifying where necessary to achieve the 11ac goals.) OFDM uses equally spaced subcarriers to transmit data, and the number of subcarriers in the 11ac signal depends on the bandwidth as shown in Table 1. The subcarriers that are not used for transmitting the signal are null subcarriers which are used for DC subcarrier(s) or guard subcarriers. The DC subcarrier (subcarrier 0) is nulled to reduce problems from analog/digital converters and carrier feedthrough.

Table 1: Subcarriers per 11ac Transmission Bandwidth

Bandwidth (MHz)	Number of Subcarriers	Subcarriers Transmitting Signal
20	64	-28 to -1 and 1 to 28
40	128	-58 to -2 and 2 to 58
80	256	-122 to -2 and 2 to 122
160	512	-250 to-130, -126 to -6, 6 to 126 and 130 to 250
80+80	256 per 80MHz Chan	-122 to -2 and 2 to 122

Because VHT devices are required to co-exist with existing legacy devices (e.g. 11a and 11n) and because 11ac devices will support 20, 40, and 80 MHz bandwidths, VHT will send the same preamble in each 20 MHz sub band so that all 802.11 devices will be able to synchronize to the packet. (See 4.3.1 for more information on the preambles.) This introduces a problem of high PAPR (Peak to Average Power Ratio) which reduces the efficiency of power amplifiers. To mitigate this effect, the subcarriers of the upper 20 MHz subbands are rotated as shown in Table 2:

Table 2: Subcarrier Rotation per Signal Bandwidth

Bandwidth (MHz)	Rotated Subcarriers	Rotation Value
20	N/A	
40	≥0	90 degrees (j)
80	≥-64	180 degrees (-1)
160	-192 to -1 and ≥64	180 degrees (-1)
80+80	Same as 80 MHz for each 80 MHz segment	Same as 80MHz

Those familiar with the 802.11n-2009 will recognize the 40 MHz subcarrier rotation as the same as the 11n 40MHz bandwidth case.

4.3 Frame Format

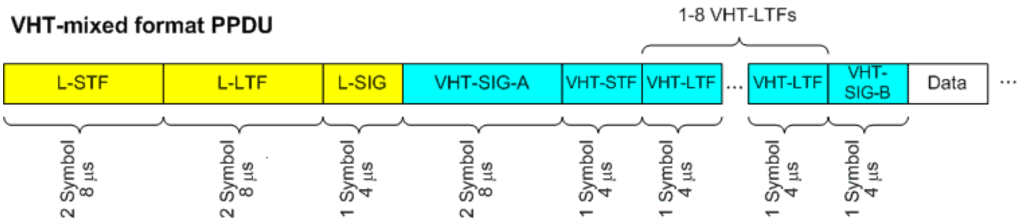


Figure 3: VHT Mixed Format PPDU

The 802.11ac frame format is shown in Figure 3 and begins as expected with a preamble. The first 3 fields are L-STF (Short Training Field), L-LTF (Long Training Field) and L-SIG (Signal). The L-STF and L-LTF contain information that allows the device to detect the signal, perform frequency offset estimation, timing synchronization, etc. The 'L-' stands for 'legacy' and the details of the sequences used in these fields for the 20 MHz signals are the same as the legacy 11a and 11n preamble fields which allows for all 802.11 devices to synchronize to the signal. In addition, the L-SIG field includes information regarding the length of the rest of the packet. This means that all devices including the legacy devices will know that a packet of a given length is being transmitted.

The next fields in the packet beginning with VHT are new to 11ac. (VHT = 11ac and stands for Very High Throughput.) The VHT-SIG-A field contains two OFDM symbols. The first symbol is modulated using BPSK, so any 11n device listening will think that the packet is an 11a. The second symbol uses a 90 degree rotated BPSK which allows the VHT device to know that this is an 11ac packet. Important information is contained in the bits of these two symbols such as bandwidth mode, MCS (Modulation and Coding Scheme) for the single user case, number of space time streams, etc.

The legacy fields and the VHT-SIG-A fields are duplicated over each 20 MHz of the bandwidth and the appropriate phase rotation is applied (see 4.2)

After the VHT-SIG-A, the VHT-STF is sent. The primary function of the VHT-STF is to improve automatic gain control estimation in a MIMO transmission.

The next 1 to 8 fields of the packet are the VHT-LTFs. These are used for estimating the MIMO channel and then equalizing the received signal. Because the number of LTFs sent is greater than or equal to the number of spatial streams per user, they are called ‘resolvable LTFs’.

The VHT-SIG-B is the last field in the preamble before the data field is sent. VHT-SIG-B is BPSK modulated and provides information on the length of the useful data in the packet and in the case of MU-MIMO provides the MCS. (The MCS for single user case is transmitted in VHT-SIG-A.)

Appropriate phase rotation is applied to each 20 MHz subband in the VHT-STF, VHT-LTF, and VHT-SIG-B. (See 4.2)

Following the preamble, the data symbols are transmitted. These, too, implement the phase rotation in the upper 20 MHz subbands.

4.3.1 VHT Preamble fields in detail

4.3.1.1 VHT SIG-A

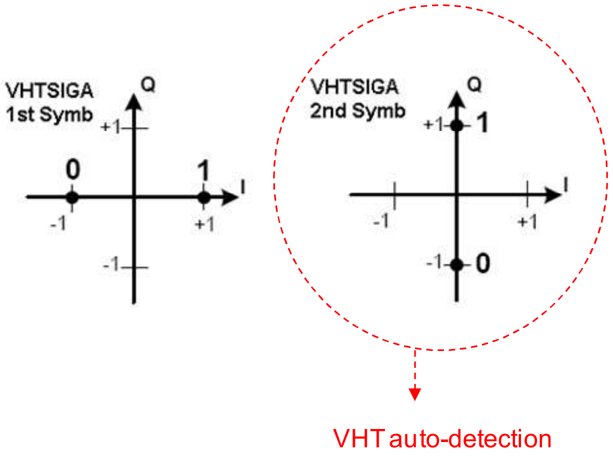


Figure 4: VHT SIG-A symbols modulation

The VHT SIG A symbols immediately follow the legacy portion of the preamble and contains information needed by all STAs (stations) and for the 11ac devices to decode the rest of the VHT packet. The SIG-A symbols use the long GI (Guard Interval) and are BCC encoded with R=1/2 The first symbol is BPSK modulated and means that an 11n receiver will think that the packet is an 11a packet and will ignore. The second symbol is BPSK rotated by 90 degrees (QBPSK) (as shown in Figure 4) and allows for auto-detection of VHT packet by the VHT STA (because the VHT device will know that it is an 11ac packet based on the QBPSK modulation.)

The VHT-SIG-A symbols contain 24 bits each. 8 bits are used for CRC (Cyclic Redundancy Check) and 6 bits are tail bits for the encoder. The information provided in the remaining 34 bits of the VHT-SIG A are needed for VHT devices to read the VHT packet. Figure 5 shows the VHT-SIG-A format for the single user case with the number of bits used for each of the fields and Table 3 describes the field values.

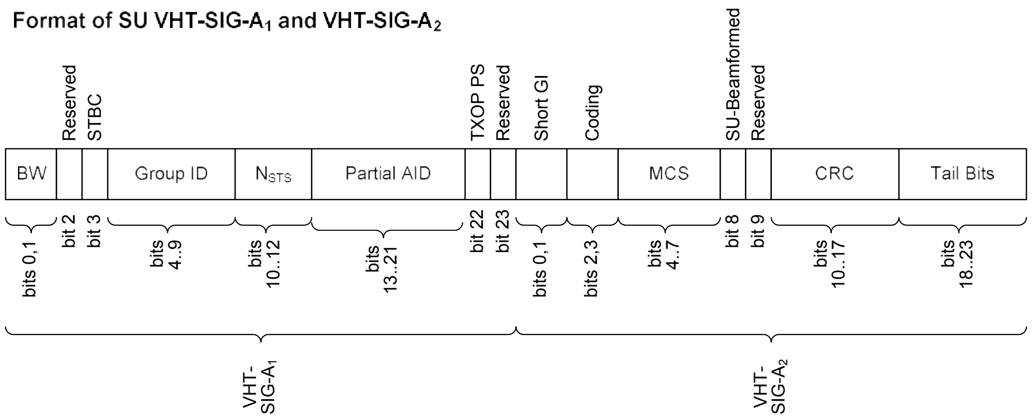


Figure 5: VHT SIG-A Format (Single User)

Table 3: VHT SIG-A Fields (Single User)

VHT-SIG-A1 Fields (Single User)	
Field	**Description/Value**
BW	PPDU Bandwidth 00: 20 MHz 01: 40 MHz 10: 80 MHz 11: 160 MHz or 80+80 MHz
Reserved	Set to 1.
STBC	Space Time Block Coding 1 if all streams use STBC 0 otherwise
Group ID	0 if packet is addressed to an AP or for a mesh STA 0 if packet is addressed to a mesh STA 111111 (63) otherwise
NSTS	Provides the number of space time streams (STS) 0: 1 STS 1: 2 STS 2: 3 STS 3: 4 STS 4: 5 STS 5: 6 STS 6: 7 STS 7: 8 STS
Partial AID	Partial Association Identifier an abbreviated indication of the intended recipient of the frame An AP assigns an AID to a STA during association
TXOP_PS NOT_ALLOWED	If non-AP VHT STA, Reserved. Set to 1. If VHT AP, 0: AP allows STAs to enter doze state in TXOP PS 1: Otherwise
Reserved	Set to 1.

VHT-SIG-A2 Fields (Single User)	
Field	**Description/Value**
Short GI	
Bit 0 (B0)	0: Data Field does not use short guard interval 1: Data Field uses short guard interval
Bit 1 (B1)	1: short GI is uses and number of symbols mod 10 = 9 0: otherwise
Coding	
Bit 2 (B2)	0: BCC 1: LDPC
Bit 3 (B3)	1: if LDPC encoding results in extra OFDM symbol 0: otherwise
MCS	MCS Index 0: BPSK 1/2 1: QPSK 1/2 2: QPSK 3/4 3: 16-QAM 1/2 4: 16-QAM 3/4 5: 64-QAM 2/3 6: 64-QAM 3/4 7: 64-QAM 5/6 8: 256-QAM 3/4 9: 256-QAM 5/6
Beamformed	1: Beamforming steering matrix is applied 0: otherwise
Reserved	Set to 1.
CRC	Cyclic Redundancy Check
Tail	Set to 0. (used to end the trellis of the convolutional decoder)

To accommodate multi-users (up to 4 are possible) some of the VHT-SIG-A fields are modified to signal user specific information. Figure .. shows the number of bits per field with bits that are intended for a specific user indicated with colors (user 0 specific bits are shaded in plum; user 1 specific bits are shaded in red; user 2 specific bits are shaded in green; and user 3 specific bits are in blue). Table … explains the fields in more detail.

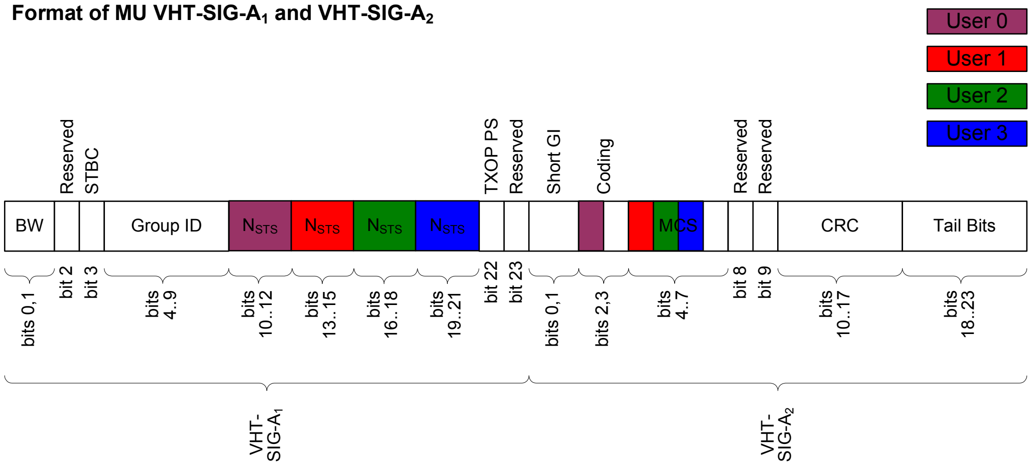

Format of MU VHT-SIG-A$_1$ and VHT-SIG-A$_2$

Figure 6: VHT-SIG-A Format (Multi-User)

Table 4: VHT-SIG-A Fields (Multi-User)

VHT-SIG-A1 Fields (Multi-User)	
Field	**Description/Value**
BW	PPDU Bandwidth 00: 20 MHz 01: 40 MHz 10: 80 MHz 11: 160 MHz or 80+80 MHz
Reserved	Set to 1.
STBC	Space Time Block Coding 1 if all streams use STBC 0 otherwise
Group ID	Value range: 1-62; indicates intended MU group (The group definitions are established by AP before transmission of a MU frame and provide information such as a user's position within a group.)
NSTS (Per User)	Provides the number of space time streams (STS) per user 0: 0 STS 1: 1 STS 2: 2 STS 3: 3 STS 4: 4 STS values 5-7 are reserved
TXOP_PS NOT_ALLOWED	If non-AP VHT STA, Reserved. Set to 1. If VHT AP, 0: AP allows STAs to enter doze state in TXOP PS 1: Otherwise
Reserved	Set to 1.

VHT-SIG-A2 Fields Multi User)	
Field	**Description/Value**
Short GI	
Bit 0 (B0)	0: Data Field does not use short guard interval 1: Data Field uses short guard interval
Bit 1 (B1)	1: short GI is uses and number of symbols mod 10 = 9 0: otherwise
Coding	
Bit 2 (B2)	If packet intended for user 0 (ie if NSTS field is non-zero) 0: User 0 uses BCC 1: User 0 uses LDPC If packet is not intended for user 0 (ie if NSTS field zero) Reserved. Set to 1.
Bit 3 (B3)	1: if LDPC results in extra OFDM symbol for at least 1 user 0: otherwise
MCS	If data is present for user n (ie if NSTS field for that user (user n) is non-zero) 0: User n uses BCC 1: User n uses LDPC If packet is not intended for user 0 (ie if NSTS field zero) Reserved. Set to 1. Bit 4 is for user 1 Bit 5 is for user 2 Bit 6 is for user 3 Bit 7 is reserved and set to 1.
Reserved	Set to 1.
Reserved	Set to 1.
CRC	Cyclic Redundancy Check
Tail	Set to 0. (used to end the trellis of the convolutional decoder)

4.3.1.2 VHT STF

The VHT STF (Short Training Field) is used to improve the automatic gain control in a MIMO transmission. The frequency domain sequence for the 20MHz and 40 MHz bandwidth are the same as in 20.3.9.3.3 of Standard 802.11n-2009:

$$
\begin{aligned}
S_{-26,26} = {} & \sqrt{1/2} \\
& \{0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, \\
& 0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0\}
\end{aligned}
$$

$$
\begin{aligned}
S_{-58,58} = {} & \sqrt{1/2} \\
& \{0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, \\
& 0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 0, 0, \\
& 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, \\
& 0, 0, 0, 0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0\}
\end{aligned}
$$

The VHT STF for the 80MHz case is formed by using the $S_{-58,58}$ sequence as follows:

$$VHTS_{-122,122} = \{VHTS_{-58,58}, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, VHTS_{-58,58}\}$$

In the 80+80 MHz case, each 80 MHz segment uses the $VHTS_{-122,122}$.

In the 160MHz case, the sequence is:

$$VHTS_{-250,250} = \{VHTS_{-122,122}, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, VHTS_{-122,122}\}$$

What does this look like in the 'real world'? The numbered subscripts refer to the subcarrier. So, S-26,26 denote the subcarriers -26, -25, -24 …., 0, … 24, 25, 26 and the values in parenthesis gives the corresponding value of that subcarrier. For example, subcarrier -26 has 0 amplitude, subcarrier -25 has 0 amplitude, subcarrier -24 has amplitude sqrt(1/2)(1+j) and so forth. If one observed the signal in the frequency domain on a spectrum analyzer, one would only 'see' the subcarriers that have a non-zero value as shown in Figure 7.

Sig. Lvl Set -40 dBm
Frequency 2.4 GHz
Fs 80 MHz
SGL GAT:EXT
Time 500.01 µs
Data Symbols 1/1366
Samples 40001
Standard IEEE 802.11n
PPDU/MCS Index/GI Mixed40/7/16
Burst 0 (0)
B Spectrum FFT / dBm Rx1
Marker[1] -67.89 dBm 2.40024 GHz
sts are shorter than minimal numbe
Measurement Complete
11.04.2011
11:02:15

Figure 7: VHT STF Preamble Field Spectrum Analyzer Display

Note that the VHT STF always uses the long guard interval.

4.3.1.3 VHT LTF

The VHT LTF (long training fields) are used by the receiver to estimate the MIMO channel and equalize the received signal. The number of LTF symbols sent in a packet depends on the number of space time streams: one LTF for one space time stream, two LTFs for two space time streams, four LTFs for three or four space time streams, six LTFs for five or six space time streams, eight LTFs for seven or eight space time streams.

The VHT-LTF consists of data subcarriers with a value (-1, 0, or 1) applied to each tone (i.e. subcarrier). (The sequence of values is defined in the 11ac amendment). The VHT-LTF may be quite long as the number of space time streams increase (i.e. the MIMO order increases). Unlike the legacy LTF, pilot tones are inserted into the VHT-LTF symbols for phase tracking to compensate for residual frequency error and phase noise that can degrade the OFDM signal and lead to channel estimation errors at the receiver. ([14])

The location of the pilots depends on the bandwidth of the signal (from [9]) and is given in Table 5:

Table 5: Subcarrier Indices for VHT-LTF Pilots

Transmission Bandwidth	Subcarrier Indices of Pilot Tones
20 MHz	±7, ±21
40 MHz	±11, ±25, ±53
80 MHz	±11, ±39, ±75, ±103
160 MHz	±25, ±53, ±89, ±117, ±139, ±167, ±203, ±231

The tone (subcarrier) is then mapped to each space time stream using a matrix P for data subcarriers or a matrix R for pilot subcarriers. The R matrix is simply a row repetition matrix which means that all space-time streams of the pilot subcarriers in VHT-LTF symbols will have the same pilot values.

After mapping, the receiver is able to use the pilot subcarriers to track the phase and frequency offset of the LTF symbols so that a more accurate channel estimation is possible from the data subcarriers.

Similar to the VHT-STF, the VHT-LTF will always use the long guard interval.

4.3.1.4 VHT SIG-B

The VHT-SIG-B follows the VHT-LTF. It is one symbol that is BPSK modulated and contains 26 bits in a 20MHz packet, 27 bits in a 40MHz packet and 29 bits in an 80 MHz, 160 MHz, or 80+80 MHz packet. The format for the VHT-SIG-B depends on whether the packet is for a SU-MIMO or for a MU-MIMO as shown in Figure 8.

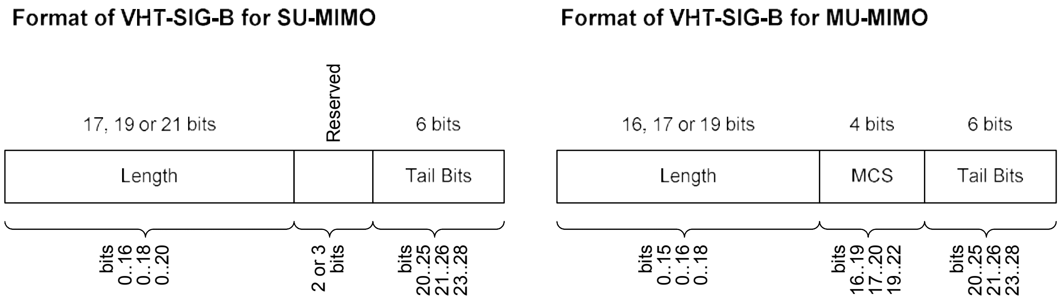


Figure 8: VHT-SIG-B Format

By varying the size of the length fields, a consistent packet duration of 5.46 ms can be maintained regardless of channel width or if it is for a SU or MU.

These bits are repeated for the higher bandwidths as shown in Figure 9 (from [9]). A pad bit is necessary at the end of the 80MHz repetition to accommodate all 117 tones (29*4+1).

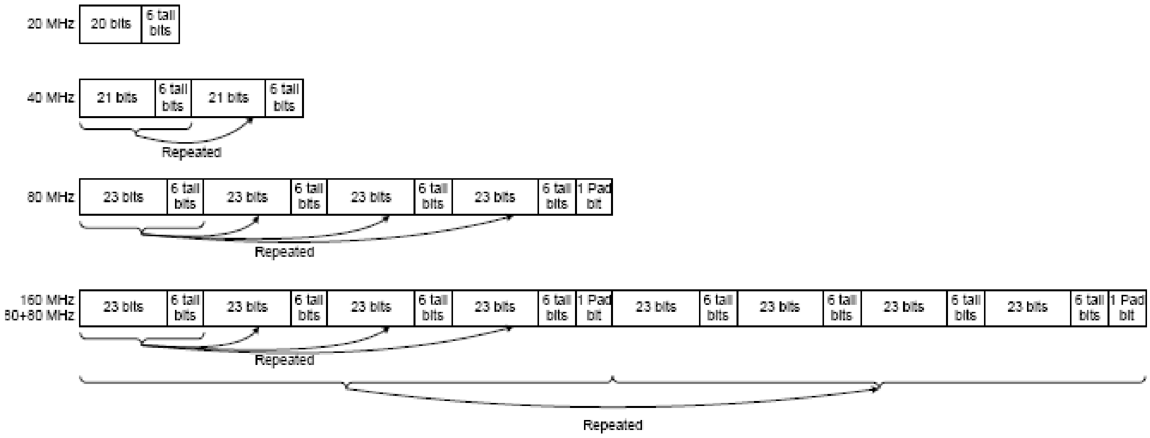


Figure 9: SIG-B bits for 20, 40, 80, 80+80 and 160 MHz

4.4 802.11ac Data Field for Single User with BCC

802.11ac will use the 802.11n modulation, interleaving and coding architecture. However, there are a few differences to the 11n specification. 11ac and 11n requires device support for BPSK, QPSK, 16QAM and 64QAM modulation, but 11ac adds an optional 256 QAM. The second difference is in the number of defined MCS Indices. 10 single user MCS are defined in 11ac as shown in Table 6. Note that this is significantly lower than the 77 MCS indices specified in 11n. 11n required 77 because 11n supported "unequal" modulations, e.g. a single user might get BPSK on one stream and 16QAM on another. (See tables 20-38 to 20-43 of [10]). For 11ac, the decision to only allow equal modulations makes sense because in practice no 11n devices supported unequal modulations and given the additional options in .11ac (e.g. 256-QAM, 160MHz bandwidth), the number of possibilities would be impractical.

MCS	Modulation	Coding Rate
0	BPSK	1/2
1	QPSK	1/2
2	QPSK	3/4
3	16-QAM	1/2
4	16-QAM	3/4
5	64-QAM	2/3
6	64-QAM	3/4
7	64-QAM	5/6
8	256-QAM	3/4
9	256-QAM	5/6

Table 6: 11ac Single User MCS Indices

4.5 802.11ac Transmitter Specification

4.5.1 Transmit Spectrum Mask

The 11ac device must meet the spectral mask given in the 11ac amendment and any applicable regulatory requirements. The measurement for the 11ac mask is made using a 100 KHz resolution bandwidth (RBW) and a 30 KHz video bandwidth (VBW). The mask for 20, 40, 80, and 160 MHz transmissions is shown in Figure 10 with the values of A, B, C, and D given in Table 7. The mask 'amplitude' is given in units of dBr which means dB relative to the maximum spectral density of the signal.

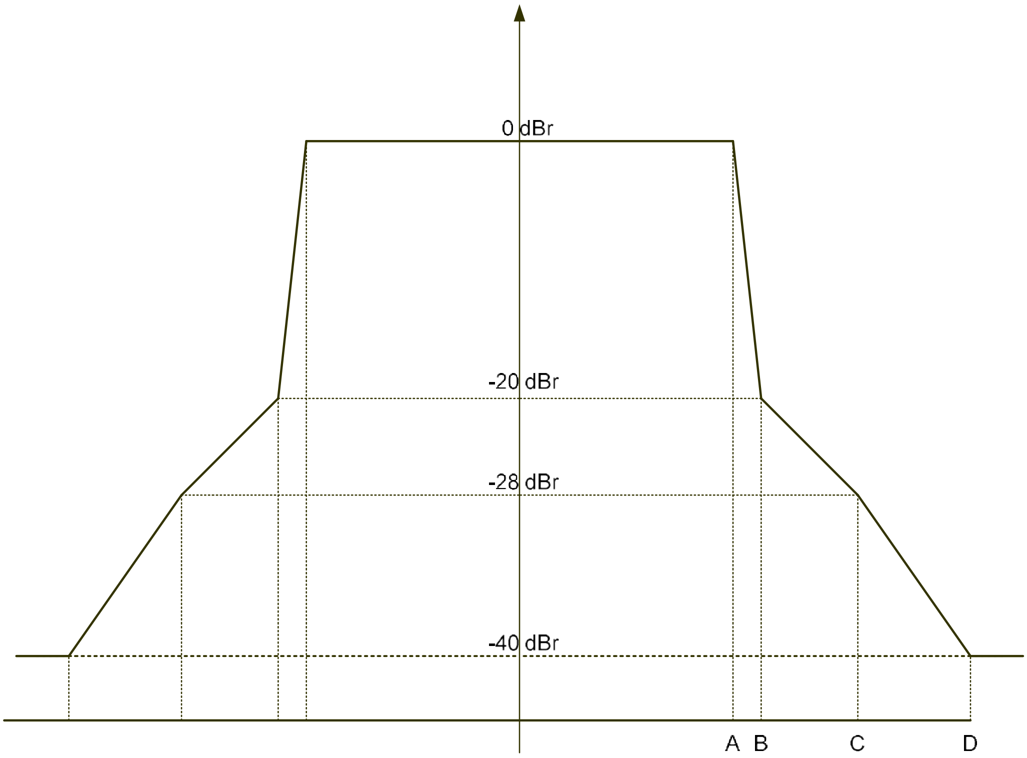


Figure 10: Spectral Mask for 20, 40, 80 and 160 MHz Channels

Table 7: Frequency Offsets for Spectral Mask Requirement

Channel Size	A	B	C	D
20 MHz	9 MHz	11 MHz	20 MHz	30 MHz
40 MHz	19 MHz	21 MHz	40 MHz	60 MHz
80 MHz	39 MHz	41 MHz	80 MHz	120 MHz
160 MHz	79 MHz	81 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 and the value of the mask where the two non-contiguous 80 MHz masks overlap are given in Table 8. The mask construction for two 80 MHz non-contiguous signals separated by 160 MHz is shown in Figure 11.

Table 8: 80 + 80 MHz Non-Contiguous Spectrum Mask Values

Step	Frequency Overlap Mask Values	Resulting Mask Value
1	Both masks have values between -20 dBr and -40 dBr	Sum of the two mask values in the linear domain
2	Neither mask has a value between 0 dBr and -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.

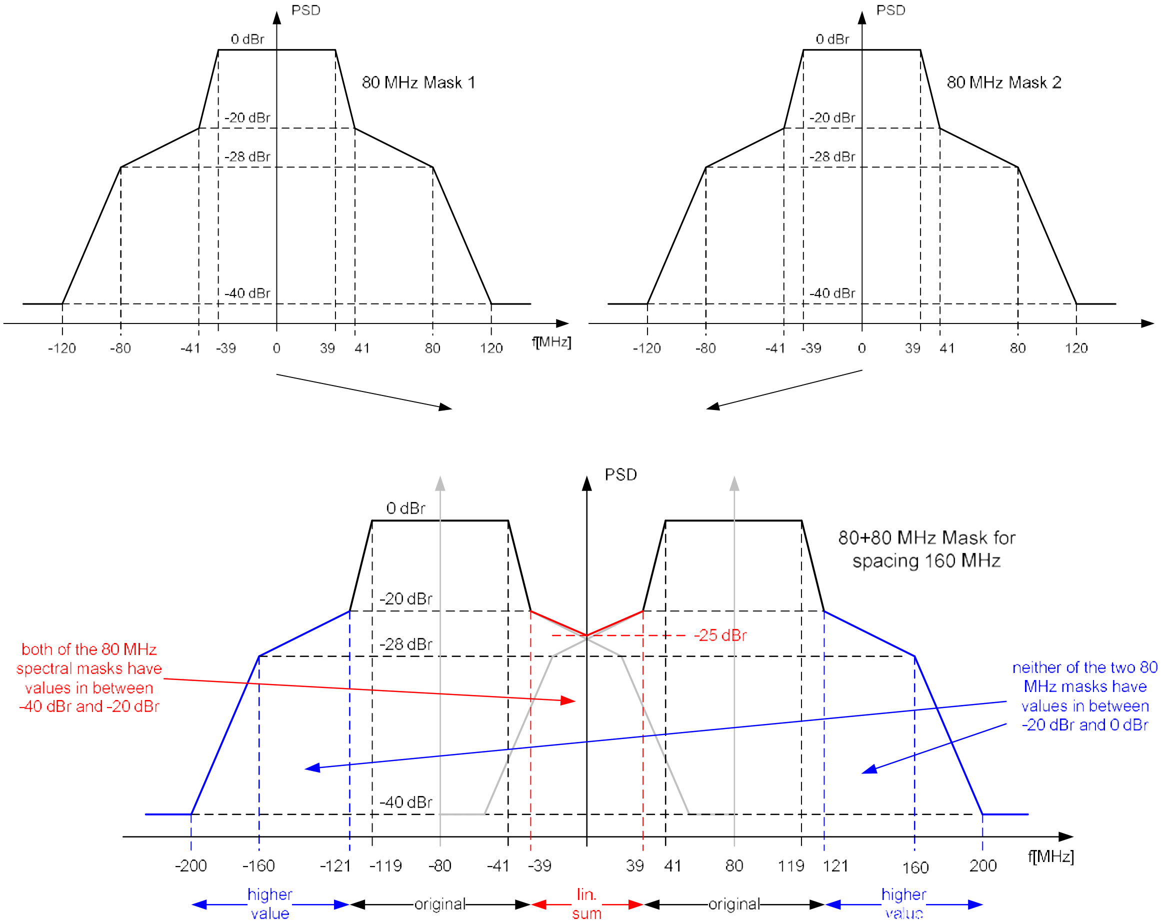


Figure 11: 80 + 80 MHz Non Contiguous Channel Mask When the 80 MHz Channels Center Frequencies are separated by 160 MHz

After the mask value in dBr is determined, this should be checked along with the transmit power to ensure that no mask value is below -59 dBm/MHz. (In other words, the lowest possible mask value will be -59 dBm/MHz.)

4.5.2 Transmit 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. .

Figure 12 provides the 802.11ac spectral flatness specification for the 20, 40 and 80 MHz signals as a function of subcarrier with the values for A, B, C and D given in Table 9. For example, if measuring the spectral flatness for the 20MHz channel width, the subcarrier measured at subcarrier index 5 should be within +/-4 dB of the average energy of the subcarriers from 1 to 16 and -1 to -16 and the energy at subcarrier 20 should be within +4/-6 dB of the average energy of the subcarriers from 1 to 16 and -1 to -16. The outer subcarriers energy is not included in the calculation of the average energy (the blue dotted line in …) because transmit filters may have higher attenuation at the band edges which would unfairly skew the Ei,avg value.

The 802.11ac spectral flatness measurement is made using BPSK modulated OFDM subcarriers.

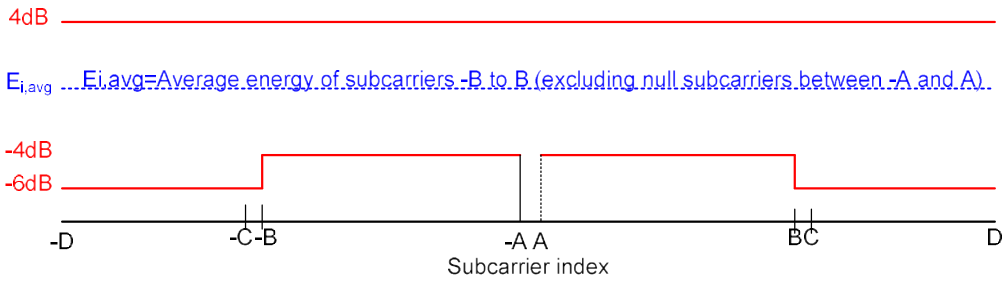


Figure 12: Spectral Flatness Requirement for 20, 40 and 80 MHz Bandwidths

Table 9: Subcarrier Index values for A, B, C, D and Ei,avg in Spectral Flatness Requirement Figure

Channel Size	A	B	C	D	Subcarriers used to determine $E_{i,avg}$
20 MHz	1	16	17	28	1 to 16 and -1 to -16
40 MHz	2	42	43	58	2 to 42 and -2 to -42
80 MHz	2	84	85	122	2 to 84 and -2 to -84

The 160 MHz spectral flatness specification takes a bit more thought because the contiguous 160 MHz is designed to interoperate with the 80 + 80 MHz signal. This means that an 80+80 MHz transmitter can transmit the two 80 MHz segments adjacent to each other for reception by a 160 MHz receiver and a 160 MHz transmitter may be received by 80 + 80 MHz receiver. So, both cases (80+80 MHz adjacent signals and 160 MHz signals) need to be considered when deriving the 160 MHz spectral flatness test. (See [11] for more details.)

The top picture in Figure 13 illustrates what the spectral flatness specification would be if only the 160 MHz case is considered. It is found by scaling the 80 MHz spec by 250/122. This scaling factor comes from the number of subcarriers in the 160 MHz case (250) divided by the number of subcarriers in the 80 MHz case (122).

The middle picture in Figure 13 illustrates what the spectral flatness specification would be if only the adjacent 80 MHz + 80 MHz case were considered. It is found by placing the two non-contiguous 80 MHz signals next to each other (remembering that there are 6 null carriers on the band edges.) The 80 MHz specification is then used for each part and the subcarriers are renumbered to match the 160 MHz tone allocation.

Now the final spectral flatness specification for 160 MHz can be determined by intersecting these two cases as shown in the bottom picture in Figure 13. In words, then, the average energy is determined by averaging subcarriers -172 to -130, -126 to -44, +44 to +126, and +130 to +172. Subcarriers -172 to -130, -126 to -44, +44 to +126, and +130 to +172 are required to be with +/- 4 dB of the average energy and subcarriers -250 to -173, -43 to -6, +6 to +43, and +173 to +250 are required to be within +4/-6 dB of the average energy.

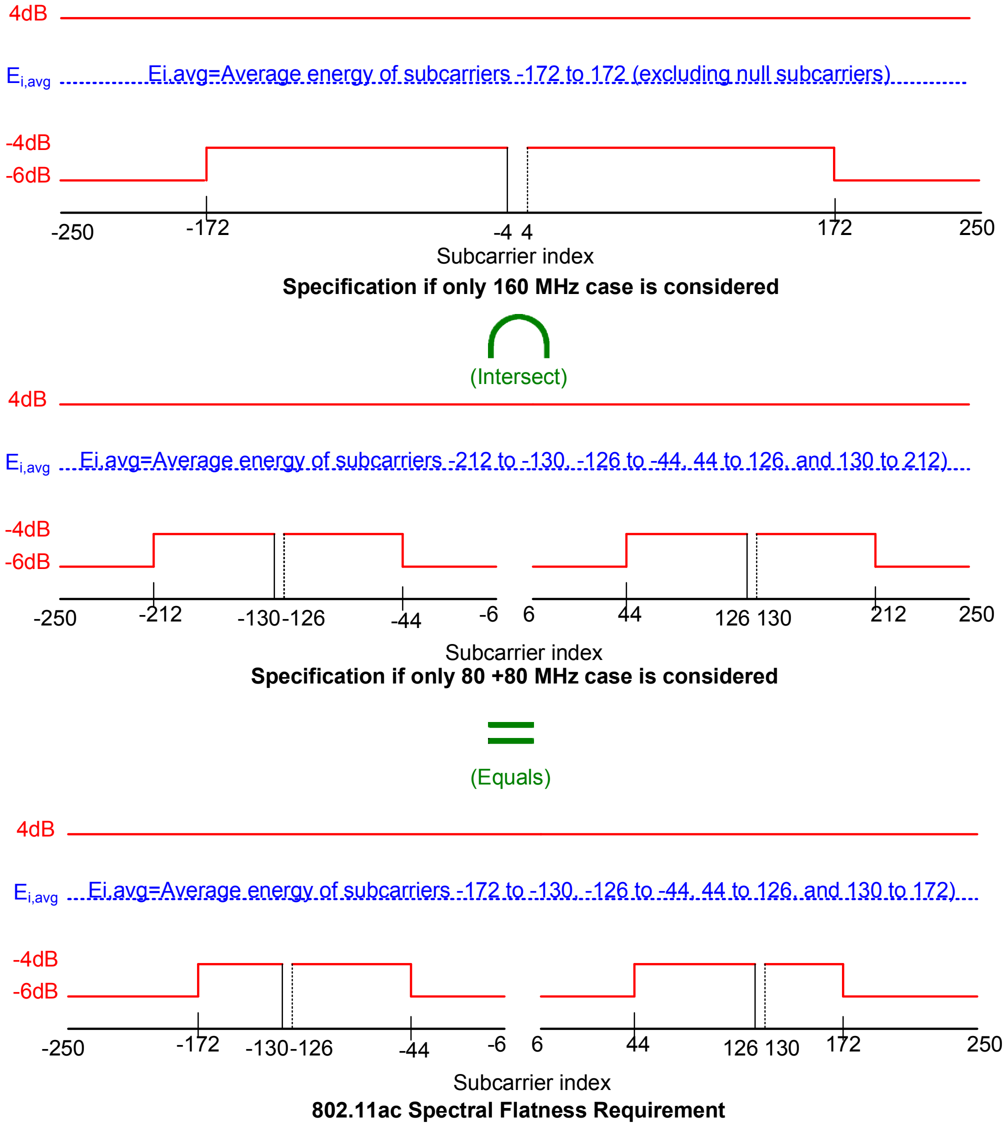


Figure 13: Derivation of 160 MHz spectral flatness specification

4.5.3 Transmit Center Frequency and Symbol Clock Tolerance

In both cases, the tolerance shall be within 20 ppm (parts per million). As indicated in [3], an OFDM signal with inaccuracies in symbol clock frequency or center frequency can lead to high constellation error. Transmitter frequency inaccuracy may also result in failed spectrum mask and/or failure of the station to connect to an access point or to another station.

4.5.4 Transmitter Modulation Accuracy

Two measurements are used to characterize modulation accuracy: center frequency leakage and relative constellation error (RCE)

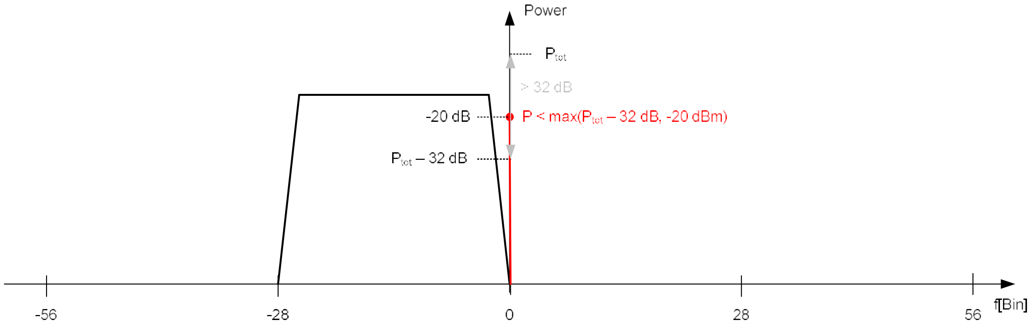
4.5.4.1 Transmitter Center Frequency Leakage

As the name suggests, this measures the amount of energy that 'leaks' through and appears at the center 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 at the center is too high, a receiver may false trigger on the signal.

For 802.11ac, the center frequency leakage specification differs depending on the location of the RF LO (Local Oscillator) in relation to the transmitted signal bandwidth. (See [16])

- For an 80 + 80 MHz non contiguous signal where the RF LO falls outside of both channels, meeting the spectral mask specification is sufficient. (See Figure 11)
- For the case where the RF LO falls into the center of the signal transmission bandwidth, the power measured at the center of the bandwidth should not be greater than the signal's average subcarrier power. (See Figure 14.)

For the case where the RF LO does not fall at the center of the signal transmission bandwidth, the power at the RF LO location is measured. The measured power should not exceed -20 dBm or total transmitted power minus 32 dB whichever is greater. This case occurs when a 20 MHz PPDU is transmitted in the 80 MHz channel
(



- Figure 15) or a 40 MHz PPDU is transmitted in the 80 MHz channel (Figure 16).

The center frequency leakage is measured using a 312.5 KHz RBW (Resolution Bandwidth).

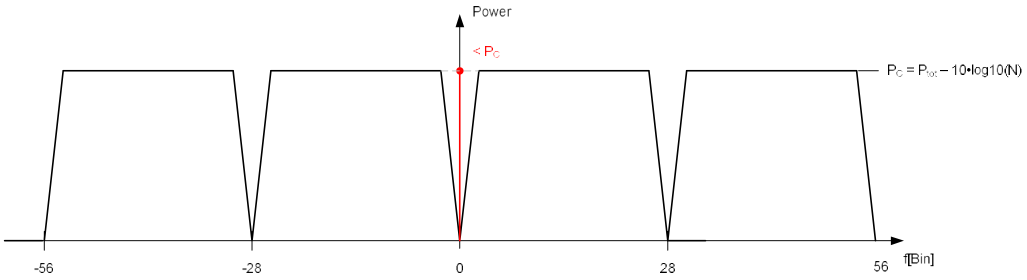


Figure 14: Center Frequency Leakage when RF LO falls in center of 80 MHz transmission bandwidth

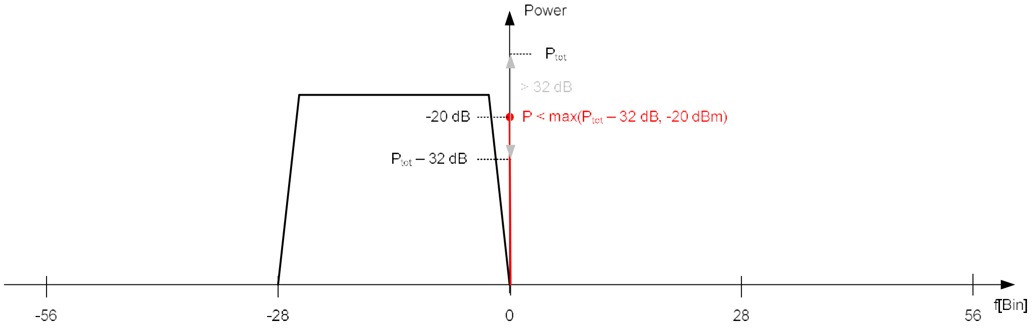


Figure 15: Center Frequency Leakage when RF LO is not in center of transmission bandwidth; in this example only 20 MHz transmission is sent in the 80 MHz channel

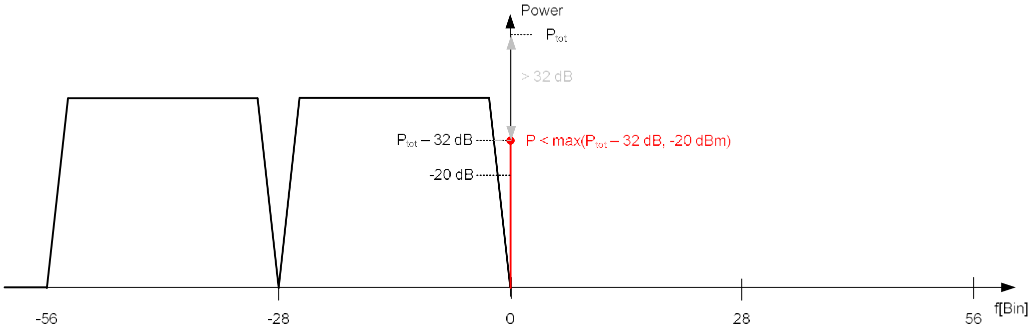


Figure 16: Center Frequency Leakage when RF LO is not in center of transmission bandwidth; in this example only 40 MHz transmission is sent in the 80 MHz channel

4.5.4.2 Transmitter Constellation Error

Relative constellation error (RCE) requirements are given in Table 10. Note that this requirement is the same regardless of the signal bandwidth. For the test, the number of spatial streams is required to be equal to the number of transmit antennas, with the RCE being measured for each transmit port. The transmitted signal should be more than 19 frames with at least 16 symbols per frame and should contain random data.

Table 10: RCE specification

MCS	Modulation	Coding Rate	RCE (dB)
0	BPSK	1/2	-5
1	QPSK	1/2	-10
2	QPSK	3/4	-13
3	16-QAM	1/2	-16
4	16-QAM	3/4	-19
5	64-QAM	2/3	-22
6	64-QAM	3/4	-25
7	64-QAM	5/6	-27
8	256-QAM	3/4	-30
9	256-QAM	5/6	-32

4.6 802.11ac Receiver Specification

4.6.1 Receiver Minimum Input Sensitivity

The minimum input sensitivity test verifies that a receiver is able to successfully demodulate a signal at a given minimum imput level. Successful demodulation is determined by a packet error rate (PER) of less than 10%. For 802.11ac the minimum input level depends on the modulation, coding rate and bandwidth as shown in Table 11. The 11ac packets used for this test should be 4096 bytes in length, use a long GI (800 ns guard interval), BCC, and a non-STBC.

Table 11: Receiver Minimum Sensitivity Specification

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

4.6.2 Adjacent and Nonadjacent Channel Rejection

The adjacent channel rejection test measures the ability of an 802.11ac receiver to detect and demodulate a signal in the presence of a stronger signal in a nearby channel. Figure 17 illustrates the concept. The receiver is demodulating the wanted 802.11ac signal at f_0 with a bandwidth of W MHz (W=20, 40, 80, or 160) and power set 3dB higher than the value of the minimum sensitivity level given in Table 11. An interfering OFDM signal with a duty cycle (on/off ratio) greater than 50% and the same bandwidth as the wanted signal is centered W MHz from the wanted signal (f_0+W 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 12. (In the case that a 160 MHz receiver is being tested but the regulatory domain does not allow an adjacent 160 MHz channel, the adjacent channel rejection test can be skipped.)

The non-adjacent channel rejection is similar, but the interfering signal is 2W MHz from the wanted signal as shown in Figure 18.

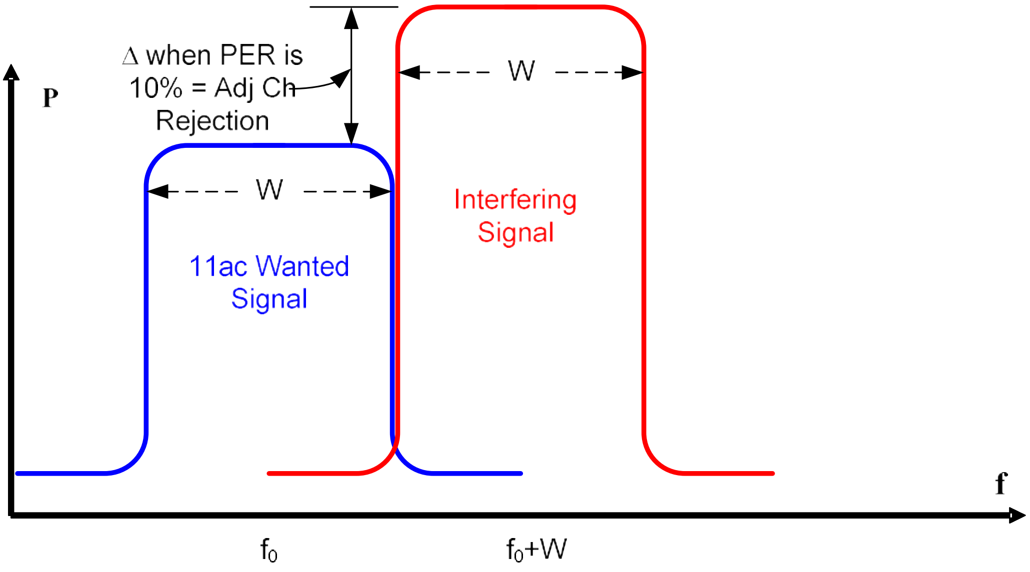


Figure 17: Adjacent Channel Rejection

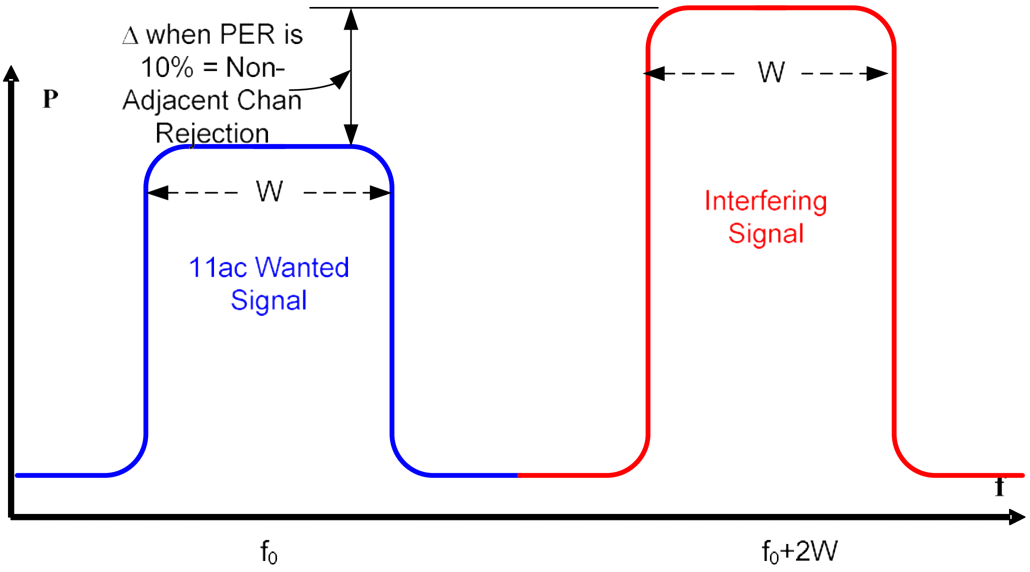


Figure 18: Nonadjacent Channel Rejection

Table 12: Minimum Adjacent and Nonadjacent Channel Rejection Requirements

Modulation	Rate (R)	Adjacent channel rejection (dB)		Nonadjacent channel rejection (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
16-QAM	1/2	8	5	24	21
16-QAM	3/4	4	1	20	17
64-QAM	2/3	0	-3	16	13
64-QAM	3/4	-1	-4	15	12
64-QAM	5/6	-2	-5	14	11
256-QAM	3/4	-7	-10	9	6
256-QAM	5/6	-9	-12	7	4

4.6.3 Receiver Maximum Input Level

Receiver Maximum Input Level tests the ability of the receiver to demodulate an 11ac signal with an input level of -30dB. At each antenna, a -30dBm signal is applied and the PER is measured and must be below 10%.

4.6.4 Clear Channel Assessment (CCA)

The clear channel assessment tests the ability of the 11ac device to determine if a channel is free or occupied. If occupied, the 802.11 PHY indicates this by setting a CCA indication signal field to ‘busy’.

In the primary channel, the device is required to detect whether the channel is busy within 4us with a probability greater than 90%. In the secondary channel, the device is required to detect whether the channel is busy within 25us with a probability greater than 90%. The power level of the occupying signal is dependent on the bandwidth of the signal and whether it is a VHT or a non-VHT signal. (See [3] for information on CCA test for non-VHT signals in the primary 20MHz channel.)

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6 Abbreviations/Acronyms/Initialisms

Abbreviations/Acronyms/Initialisms	
BCC	Binary Convolutional Coding
BPSK	Binary Phase Shift Keying
BW	Bandwidth
CCA	Clear Channel Assessment
CRC	Cyclic Redundancy Check
EVM	Error Vector Magnitude
GI	Guard Interval
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
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
RCE	Relative Constellation Error
STBC	Space Time Block Coding
STF	Short Training Field
SU	Single User

TG	Task Group
TXOP	Transmission Opportunity
VHT	Very High Throughput
WLAN	Wireless Local Area Network

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