Application Note

HINTS FOR IEEE 802.11BE EVM MEASUREMENTS

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M. Breinbauer | 1EF114 | Version 0e | 08.2022

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Contents

1 Overview

IEEE 802.11be *Extremely High Throughput* (EHT), also known as Wi-Fi 7, is the latest amendment of the IEEE 802.11 standard and is still under development. This amendment focuses mainly on improved throughput. To do so, the most notable changes currently implemented are:

- New modulation scheme: 4096-QAM (4K-QAM)
- Larger bandwidth: 320 MHz
- Support for 16x16 MU-MIMO
- Enhanced resource allocation in OFDMA

This document provides some technical background and guidance on how to optimize the measurement of one of the key performance parameters of WLAN transmitters - the Error Vector Magnitude (EVM).

2 Introduction to 11be

The content of this chapter 2 is to a large extent an excerpt from [1]**, a Rohde & Schwarz Technology Introduction on 802.11be - with some additions mainly in chapter 2.4.1.3.**

IEEE 802.11 is the IEEE working group that develops the Wireless Local Area Network (WLAN) specifications that are behind the Wi-Fi technology. In the beginning, IEEE 802 created 11a/b/g that enabled wireless communication for everyone. The working group continues to enhance the 802.11 MAC and PHY layer to, for example, improve user experience, increase throughput, utilize resources more efficiently and/or support new use cases. These enhancements are written as amendments to the base 802.11 standard and many have been published in the last 20+ years.

The 802.11 working group is currently developing the next generation of Wi-Fi, 802.11be (Wi-Fi 7). 802.11be is also known as EHT (Extremely High Throughput). The high-level goals of EHT are defined in the 802.11be PAR (Project Authorization Request) and include enabling at least one operation mode that can support at least 30 Gbps and at least one operation mode to improve latency and jitter to better support time sensitive networks. EHT is supported in the unlicensed bands between 1 and 7.125 GHz.

EHT re-uses many of the concepts and techniques used at the HE PHY layer but makes enhancements such as assigning multiple resource units to a single user, increasing bandwidth support to 320 MHz, supporting up to 16 spatial streams and adding support for 4096 QAM modulation. At the MAC layer, EHT introduces several significant features to 802.11 such as Multi-Link Operation (MLO).

The current two 802.11be “Core” Documents are the 802.11be draft amendment version 1.0 and the 802.11be Specification Framework Document (SFD) version 23.

2.1 IEEE 802.11be Goals and Feature Summary

	802.11n (HT)	802.11ac (VHT)	802.11ax (HE)	802.11be (EHT)
Supported bands	2.4, 5 GHz	5 GHz	2.4, 5, 6 GHz	2.4, 5, 6 GHz
Channel Bandwidth (MHz)	20, 40	20, 40, 80, 80+80, 160	20, 40, 80, 80+80, 160	20, 40, 80, 160, 320
Subcarrier Spacing (kHz)	312.5	312.5	78.125	78.125
Symbol Time (us)	3.2	3.2	12.8	12.8
Cyclic Prefix (us)	0.8	0.8, 0.4	0.8, 1.6, 3.2	0.8, 1.6, 3.2
MU-MIMO	No	Downlink	Uplink & Downlink	Uplink & Downlink
Modulation	OFDM	OFDM	OFDM, OFDMA	OFDM, OFDMA
Data Subcarrier Modulation	BPSK, QPSK, 16-QAM, 64-QAM	BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM	BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM, 1024- QAM	BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM, 1024-QAM, 4096-QAM
Coding	BCC (Mandatory) LDPC (Optional)	BCC (Mandatory) LDPC (Optional)	BCC (Mandatory) LDPC (Mandatory)	BCC (Mandatory) LDPC (Mandatory)

PHY parameter values for 11n, 11ac, 11ax and 11be

802.11be aims to specify MAC and PHY features that will meet the high throughput and low latency requirements for applications like video conferencing, remote working, gaming and cloud computing. The 11be PHY is in general very similar to the PHY defined in the highly successful 11ax standard.

Further, 11be has an eye towards future compatibility. 802.11 PHY always consider backwards compatibility with legacy 802.11 generations, but 11be introduces concepts to make forward compatibility achievable. For example, 11be introduces a new preamble field called the universal SIG (U-SIG) that will be used in 802.11be and all future 802.11 generations as well as more precise terms/rules for reserved bits.

The 11be MAC layer introduces significant changes and new features such as multi-link operation, multi AP (Access Point) support, restricted target wait time (TWT) and 1024 bit block acknowledgement (1K BA) to meet the targeted low latency applications.

2.2 Achieve Extremely High Throughput and More

In order to achieve the targeted extremely high throughput, the EHT physical layer supports wider bandwidth, more spatial streams and a higher modulation scheme. MLO (Multi Link Operation) provides the possibility to increase throughput by using several physical links in parallel.

2.2.1 Up to 320 MHz Channel Bandwidth

The IEEE 802.11be standard amendment 8 (EHT) covers carrier frequency operation between 1 and 7.250 GHz ensuring backward compatibility and coexistence with legacy IEEE 802.11 devices operating at 2.4 GHz, 5 GHz and 6 GHz bands. The channel allocation is defined in the following documents:

– 2.4 GHz Band, 802.11-2016, chapter 19.3.15.2*:*
  Channel center frequency = 2407 + 5 x n_{ch} *(MHz),* n_{ch} *= 1, 2, …13*
– 5 GHz Band, 802.11-2016, chapter 19.3.15.3:
  Channel center frequency = Channel starting frequency + 5 x n_{ch} *(MHz),* n_{ch} *= 1, … 200*
  Channel starting frequency is defined as *dot11ChannelStartingFactor* x 500kHz or is set to 5GHz where *dot11ChannelStartingFactor* is false.
– 6 GHz Band, 802.1ax, 27.3.23.2:
  Channel center frequency = Channel starting frequency + 5 × n_{ch} *(MHz),* n_{ch} *= 1, ⋯, 233*
  Channel starting frequency is defined as *dot11ChannelStartingFactor* x 500kHz. For example, a channel center frequency of 5.955 GHz is indicated by *dot11ChannelStartingFactor* = 11900 and n_{ch} = 1. A channel center frequency of 5.935 GHz is indicated by *dot11ChannelStartingFactor* = 11850 and n_{ch} = 2.

The channel starting frequencies depending on the operating classes are defined in the Annex E of these documents.

The 802.11be amendment extends the previously existing standards. EHT supports 20, 40, 80, 160 and 320 MHz channel bandwidths. 320 MHz bandwidth is new in 802.11be and is made possible due to updated regulatory rules in many countries that now allow unlicensed device operation (subject to regional restrictions) in the 6 GHz band. In some regions like US and Canada full spectrum from 5925 to 7125 MHz is available while in other regions like Europe only the lower part from 5945 to 6425 MHz is available. In general, three device categories are considered in the spectrum regulations:

► low power indoor (LPI) devices with a power (EIRP) limit of around 250 mW
► very low power devices (VLP) with a power (EIRP) limit of around 25 mW
► standard power devices for indoor and outdoor with an AP applying automatic frequency coordination (AFC)

The Wi-Fi Alliance provides a global spectrum tracker of current status for unlicensed usage in the 6GHz band via its 'Countries Enabling Wi-Fi 6E' page: https://www.wi-fi.org/countries-enabling-wi-fi-6e

Because 802.11 wants to use this newly allocated spectrum to its fullest, EHT seeks to encourage high throughput and low latency applications in the 6 GHz band. Therefore, for example, EHT does not allow 20 MHz only devices to operate in the 6 GHz band. Additional EHT device bandwidth requirements for the 3 operating bands are listed below:

- An 11be AP must support:
  - 160 MHz operating channel width in the 6 GHz band
  - 80 MHz operating channel width in the 5 GHz band
  - 20 MHz operating channel width in the 2.4 GHz band
- 11be non-AP STA must support 80 MHz channel in 5 / 6 GHz (unless it is a 20 MHz only device)
- A 20 MHz only device may only operate in the 2.4 and 5 GHz band

The figure below shows the example channelization based on the FCC regulations in the US. Because there are an odd number of 160 MHz channels, EHT defines a set of overlapping 320 MHz channels. This provides a way to efficiently use the spectrum since each 160 MHz can be part of a 320 MHz channel.

The center frequencies are determined using the equation from the 802.11 standard:

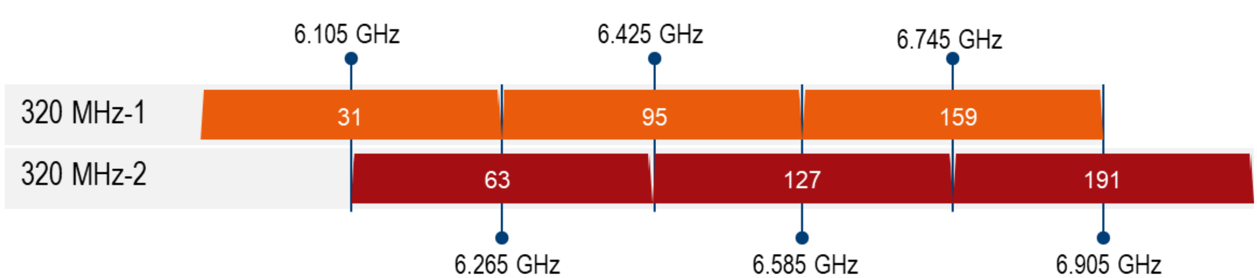
channel center frequency = channel starting frequency + 5 × n_{ch} (MHz)

where

n_{ch} = channel center frequency number
31, 95, and 159 for 320 MHz-1 or
63, 127, and 191 for 320 MHz-2 channels

channel starting frequency = 5.950 GHz

To make it easier for signaling and for a STA (Station) to identify which of the overlapping 320 MHz channels it is hearing, 11be defines two types of 320 MHz channelization to identify two non-overlapping channel sets: 320 MHz-1 and 320 MHz-2



320 MHz channel allocation based on FCC in the 6 GHz band

802.11be non-contiguous (e.g. 80+80 MHz) operation is not used because, in part, it was found that the 80+80 MHz non-contiguous channelization defined in 802.11ax is not commonly used. In addition, the 802.11be MLO MAC feature can be used to achieve the same result as the non-contiguous channels in the PHY.

To achieve extremely high throughput, 802.11be will also support up to 16 spatial streams across all scheduled stations for DL/UL MU-MIMO and SU-MIMO. For EHT MU-MIMO transmissions the maximum number of spatial streams per STA is 4 to maximum eight users.

2.2.2 Multi-Link Operation (MLO)

A new MAC feature called MLO is introduced in EHT. A device capable of MLO (called an MLD or Multi-Link Device) can establish multiple links on different channels with another MLD.

2.2.3 Restricted Target Wake Time

The target wake time (TWT) feature was introduced in 802.11ah to support low power IoT applications by allowing STAs - after negotiation with the AP - to go into the sleep mode outside the wake time period. It also allows the AP to distribute the wake period of different STAs over time in order to minimize contention. 802.11be extends the TWT capability to give the AP mechanisms to provide more predictable latency to support time sensitive application requirements.

2.2.4 Multi-AP Operation

In 802.11be also a couple of features are under discussion to improve efficiency of operation of adjacent access points. By this means spectrum resources can be used more efficiently and the throughput can be further improved.

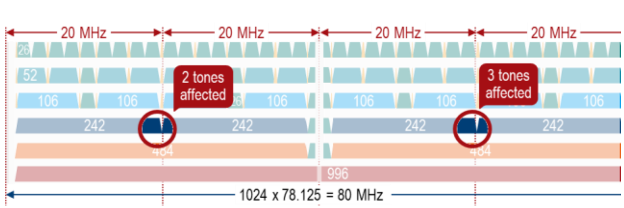
2.3 IEEE 802.11be Physical Layer

2.3.1 New RU and Tone Plans

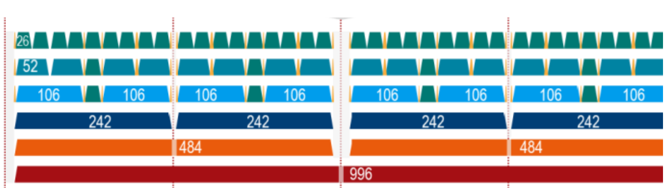
802.11ax (HE) introduced OFDMA to 802.11 and users were allocated RU (Resource Units) that were 26, 52, 106, 242, 484 or 996 tones in size.

The EHT tone plan and resource unit (RU) locations for a 20 and 40 MHz PPDU (Physical Layer Protocol Data Unit) are the same as for the 802.11ax 20 and 40 MHz PPDU. The EHT 80 MHz PPDU RU and tone locations, however, are slightly different from HE. When HE developed the tone plan, the focus was to use the spectrum as efficiently as possible. Therefore, they used as many subcarriers as possible to transmit data. For example, a middle RU was defined that straddled DC and no null carrier was used between two 242-tone RUs.

One consequence of this design is that the 242-tone RU do not align with a 20 MHz subchannel boundary and the middle 26-tone RU falls into two 20 MHz sub-bands. This causes problems in case of preamble puncturing, for example, where a punctured 20 MHz subchannel punctures tones from an adjacent RU, causing some degradation to the adjacent channel RU. The following figure shows the misalignment of the 20 MHz boundaries and the 242-tone RU.



HE 80MHz tone plan showing 2 examples where a punctured 20 MHz subchannel impacts subcarriers of adjacent resource units



EHT 80 MHz tone plan solving the misalignment

The EHT 80 MHz plan solves this issue with a minimal change to the HE 80 MHz plan. This small change means that the same RU sizes can be used in EHT as was used in HE, but it eliminates the middle 26-tone RU and aligns the 242-tone RU with 20 MHz channel boundaries.

2.3.2 Multiple Resource Units per User

While much of the 802.11be PHY is the same or very similar to 11ax, a key differentiator for 802.11be is the capability to allocate more than one resource unit to a single user. Assigning multiple RUs per user provides scheduling flexibility to take advantage of frequency diversity and to allocate resources efficiently within the spectrum. The drawback of this additional flexibility is the potential need to increase overhead to describe all of the possible RU combinations. EHT circumvents this by defining rules to limit which RUs may be combined, focusing on those combinations that provide the most benefit. The basis of the rules is the EHT classification of the RU as a small or a large size RU. Small size RUs are less than 20 MHz, i.e. 26, 52, 106 tone RUs. A large size RU is 20 MHz or larger, i.e. 242-tone (20 MHz), 484-tone (40 MHz), 996-tone (80 MHz) RUs. A small size RU and a large size RU are not used together in MRU. That is, MRUs either contain only 2 small size RU or 2 large size RU.

2.3.3 Preamble / Subchannel Puncturing

802.11 operates in unlicensed bands that can be utilized by other networks and technologies. In addition, incumbent users are present in the newly allocated 6 GHz. It is important that 802.11 networks limit any interference into already occupied channels. At the same time, however, it is important to utilize spectrum as efficiently as possible and make use of the wider channel bandwidths defined for 802.11be (and 802.11ax). 802.11be (and ax) therefore can utilize a wide bandwidth channel (for example 160 MHz) for transmission but ‘puncture’, or not transmit, in a subchannel that is already in use. This is called preamble puncturing.

2.3.4 PPDU Formats

In 802.11 data is transmitted over the wireless medium using PHY frames which are also called PPDU (PHY layer Protocol Data Unit). The PPDU contain the data to be transmitted along with a preamble prepended to the data. The preamble consists of several fields which are used to aid reception (e.g. automatic gain control and timing synchronization) and provide information that the receiver will need to know to demodulate the packet. The field names are listed in the following table.

Field	Description	Field	Description
L-STF	Legacy Short Training Field	**EHT-SIG**	EHT Signal Field
L-LTF	Legacy Long Training Field	**EHT-STF**	EHT Short Training Field
L-SIG	Legacy Signal Field	**EHT-LTF**	EHT Long Training Field
RL-SIG	Repeated Legacy Signal Field	**Data**	Data
U-SIG	Universal Signal Field	**PE**	Packet Extension Field

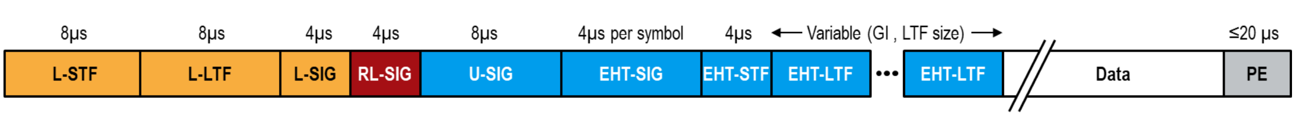
PPDU Field Descriptions

Two PPDU formats are defined in EHT:

► Multi User PHY Protocol Data Unit (EHT MU PPDU)

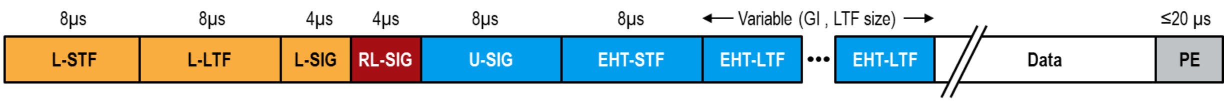
► Trigger Based PHY Protocol Data Unit (EHT TB PPDU).

The EHT MU PPDU can be sent to a single user or to multiple users. The related EHT-SIG field, along with the U-SIG, provides RU/MRU allocations and other information the STA(s) need to know in order to understand the EHT MU Packet. When the MU PPDU is sent to multiple users, the transmission can be OFDMA or MU-MIMO. Further, an RU that is 242 tones or larger in an OFDMA transmission may use MU-MIMO to send the RU to up to 8 users.



EHT Multi User PDDU Format

An AP uses a control frame called a trigger frame to assign resources and solicit a response from one or more STAs. The STA(s) use the EHT TB PPDU to respond to the trigger from the AP. The EHT TB frame format is very similar to the EHT MU PPDU. However, the TB PPDU does not contain the EHT-SIG preamble field. In addition, the EHT-STF field is two times longer than in the EHT MU PDDU in order to improve performance and reliability for the uplink transmissions.

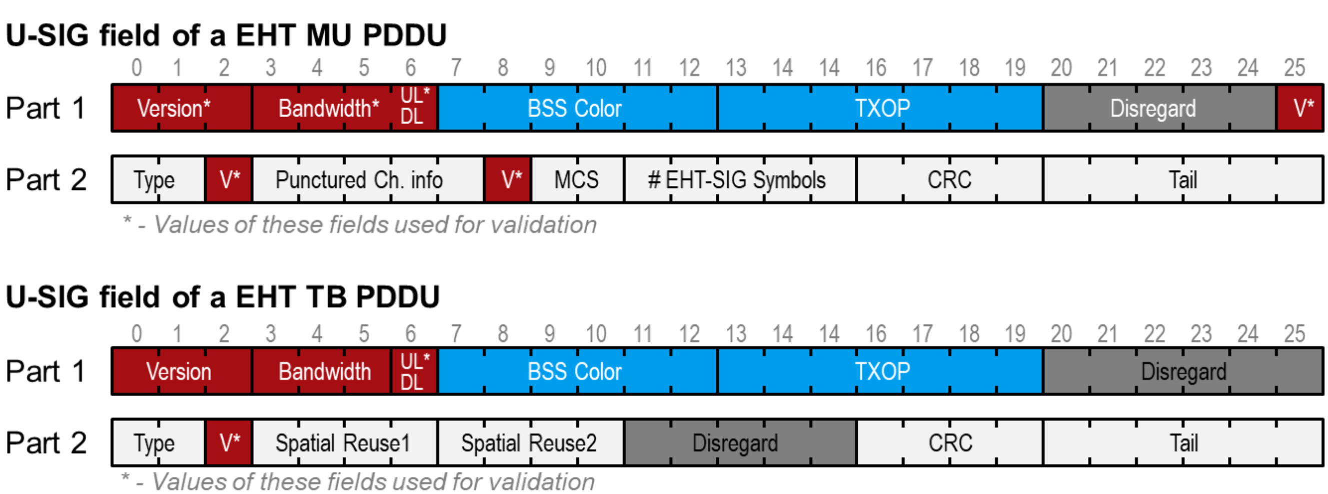


EHT Trigger Based PDDU Format

2.3.5 EHT Preamble: Designed for the Future

The preamble is an important part of the design. It is used to provide information such as MCS (Modulation and Coding Scheme) that is needed for the receiver to decode the transmitted data. It is also used to provide backwards compatibility with previous PHY versions. However, the preamble never directly conveyed the PHY version of the packet. Instead auto detection / spoofing mechanisms were defined for the receiver to determine the PHY version implicitly. As the number of PHYs has increased, the auto detection algorithms have become more complex.

EHT will solve this problem by introducing the universal sig (U-SIG) field. The U-SIG comes right after the RL-SIG and is 2 OFDM symbols in length. The U-SIG will be present in EHT and all future 802.11 PHYs and contains version independent and version dependent bits. The version independent bits are the first 20 bits of the U-SIG and will have the same location and definition for EHT and all future PHYs. The first 3 bits (bits 0 to 2) of the U-SIG are used to identify the PHY version which will greatly simplify auto detection for EHT and future 802.11 generations. The next 3 bits indicate the spectrum occupancy of the PPDU (e.g. 80 MHz BW). The 7th bit signals the link direction (i.e. uplink or downlink). The next 6 bits identify the BSS (Basic Service Set) in use via the BSS color and the 7 TXOP bits provides information on how the long the PPDU uses the medium. The remainder of the U-SIG bits/fields (not described in the table) will depend on the PHY version and PPDU type.



U-SIG filed content for EHT MU PDDU and EHT TB PDDU

To provide flexibility and prepare for possible new capabilities, EHT classifies the reserved bits in the EHT preamble as 'disregard' or 'validate'. This classification helps a receiver determine the appropriate action if it comes across a bit value that is not used in a PHY it supports. Disregard means it doesn't matter/ignore this bit and continue reception. Validate means the device should check if the bit matches a known value and if it does not, the device should terminate reception.

2.4 PHY Layer Test Requirements

2.4.1 Transmitter Requirements

2.4.1.1 Transmit Spectral Mask

The spectrum mask requirements for the 11be 20/40/80/160 MHz bandwidth transmissions are the same as in 11ax. The spectrum mask for the 11be 320 MHz bandwidth is a scaled version of the 11ax mask. Measurements are made using RBW=100 KHz and VBW=7.5 KHz. No other analyzer settings are specified.

2.4.1.1.1 Spectrum Mask for a PPDU with Punctured Channel(s)

Punctured subchannels are used in EHT (and HE) to avoid transmitting on subchannels that are not available or are occupied by other/incumbent users. To limit the leakage from the occupied subchannel(s) into the punctured subchannel(s), EHT applies an additional mask so that an overall spectrum mask for a PPDU containing punctured channel(s) is formed by combining the transmit spectral mask defined in the previous section with a puncture mask. The puncture masks are based on the puncture masks defined in the ETSI BRAN (Broadband Radio Access Networks) EN 301 893 standard.

2.4.1.2 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 subcarriers energy in that range deviates by more than the value specified. EHT spectral flatness requirements for 20, 40, and 80 MHz non-punctured PPDU are the same as in HE.

2.4.1.3 Transmitter Modulation Accuracy

2.4.1.3.1 Transmit Center Frequency 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 false trigger on the signal.

2.4.1.3.2 Transmitter Constellation Error

The transmitter constellation error - also called EVM (Error Vector Magnitude) - is an important figure of merit for a transmitter in a digital modulation system. It provides a way to measure how close to an ideal constellation point the device is able to transmit.

The EVM requirements depend on the specific transmission parameters used by a WLAN device. These are adapted according to the current quality of the RF environment. All the allowed combinations of e.g. modulation and coding rate are listed in the *Modulation on Coding Scheme (MCS)* tables under a unique MCS index.

MCS	Modulation	Coding	EVM of EHT MU PDDU	EVM of EHT TB PDDU transmit power larger than MCS 7 maximum power	EVM of EHT TB PDDU transmit power equal or less than MCS7 max power
0	BPSK	1/2	- 5 dB	-13 dB	-27 dB
1	QPSK	1/2	- 10 dB	-13 dB	-27 dB
2		3/4	-13 dB	-13 dB	-27 dB
3	16-QAM	1/2	-16 dB	-16 dB	-27 dB
4		3/4	-19 dB	-19 dB	-27 dB
5	64-QAM	2/3	-22 dB	-22 dB	-27 dB
6		3/4	-25 dB	-25 dB	-27 dB
7		5/6	-27 dB	-27 dB	-27 dB
8	256-QAM	3/4	-30 dB	-30 dB	-30 dB
9		5/6	-32 dB	-32 dB	-32 dB
10	1024-QAM	3/4	-35 dB	-35 dB	-35 dB
11		5/6	-35 dB	-35 dB	-35 dB
12	**4096-QAM**	**3/4**	**-38 dB**	**-38 dB**	**-38 dB**
13		**5/6**	**-38 dB**	**-38 dB**	**-38 dB**
14	BPSK-DCM-DUP	1/2	-5 dB	N/A	N/A
15	BPSK-DCM	1/2	-5 dB	-13 dB	-27 dB

ETH transmitter constellation error specification

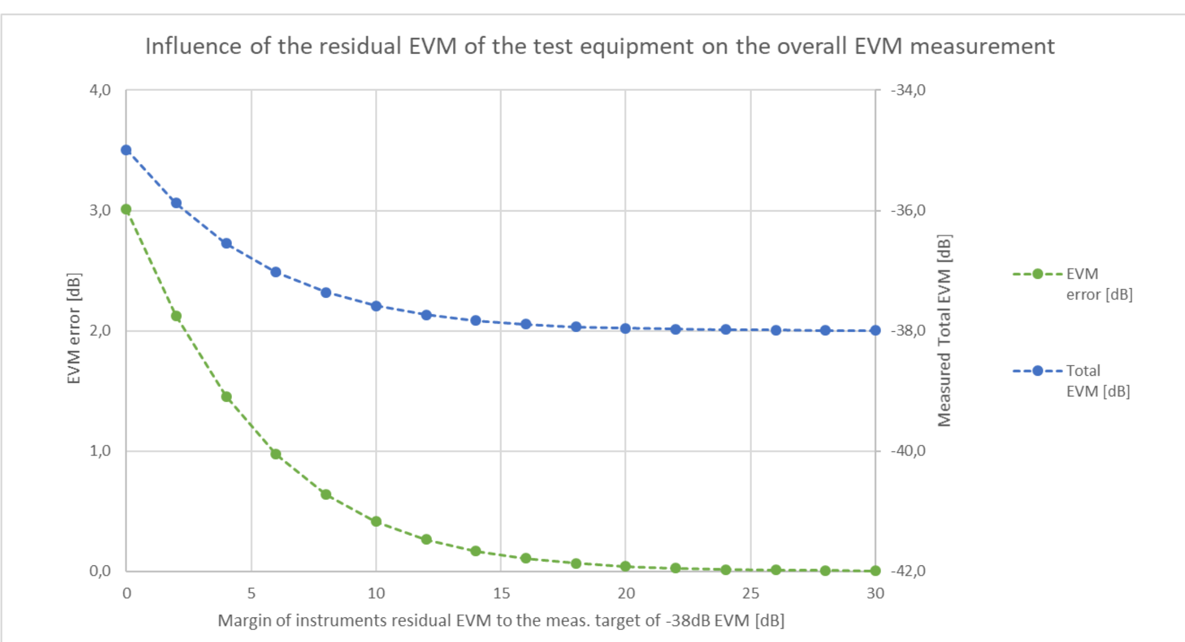
As stated in chapter 36.3.19.4.1 of the 802.11be draft amendment (also see table above), transmitters need to fulfill the -38 dB EVM requirement for 4096-QAM (practically required additional margin is not considered here). This means the measurement equipment must be able to accurately measure EVM values around and below -38 dB.

A signal analyzer cannot be assumed to be an ideal measurement equipment by itself, but it also contributes to the measured EVM. There are in principle two different types of EVM contributions: on the one extreme there are coherent contributions. These sum up well-defined depending on their specifics in a way either increasing the overall EVM or possibly even lower the measured EVM. On the other side there are incoherent, noise-like contributions. These random contributions always increase the overall measured EVM according to the rooted sum of squared EVM contributions (RSS).

The sources for residual EVM of signal analyzers are mainly not coherent to the signal which should be measured and thus the influence on the measured EVM value can be calculated according to the RSS formula. If the signal analyzers residual EVM shows a 10dB margin to the targeted EVM value of -38 dB ("it is able to measure down to -48 dB EVM"), the error in the measured EVM value due to the signal analyzers contribution is around 0.41 dB or 0.06% - as shown in the following table.

EVM to measure [dB]	EVM to measure [%]	Assumed SA EVM Margin [dB]	SA EVM contribut. [dB]	SA EVM contribut. [%]	Total EVM [%]	EVM error [%]	Total EVM [dB]	EVM error [dB]
-38	1,259	0	-38	1,259	1,780	0,521	-34,990	3,010
-38	1,259	2	-40	1,000	1,608	0,349	-35,876	2,124
-38	1,259	4	-42	0,794	1,489	0,230	-36,545	1,455
-38	1,259	6	-44	0,631	1,408	0,149	-37,027	0,973
-38	1,259	8	-46	0,501	1,355	0,096	-37,361	0,639
-38	**1,259**	**10**	**-48**	**0,398**	**1,320**	**0,061**	**-37,586**	**0,414**
-38	1,259	12	-50	0,316	1,298	0,039	-37,734	0,266
-38	1,259	14	-52	0,251	1,284	0,025	-37,830	0,170
-38	1,259	16	-54	0,200	1,275	0,016	-37,892	0,108
-38	1,259	18	-56	0,158	1,269	0,010	-37,932	0,068
-38	1,259	20	-58	0,126	1,265	0,006	-37,957	0,043
-38	1,259	22	-60	0,100	1,263	0,004	-37,973	0,027
-38	1,259	24	-62	0,079	1,261	0,003	-37,983	0,017
-38	1,259	26	-64	0,063	1,261	0,002	-37,989	0,011
-38	1,259	28	-66	0,050	1,260	0,001	-37,993	0,007
-38	1,259	30	-68	0,040	1,260	0,001	-37,996	0,004

Influence of the signal analyzers residual EVM margin on the measurement result, fixed target EVM



Influence of the signal analyzers residual EVM margin on the measurement result, target EVM -38 dB

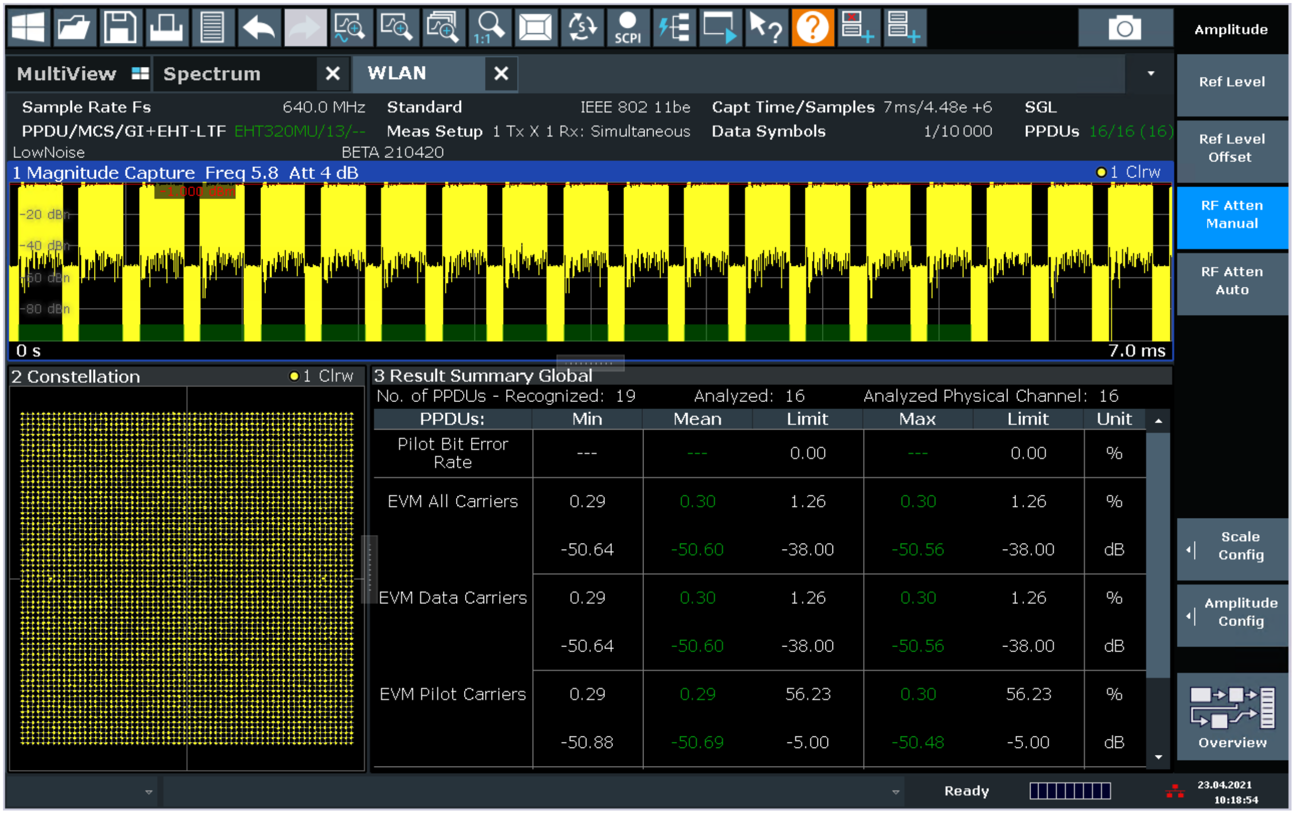
If a fixed margin of 10 dB for the instruments residual EVM is assumed, the EVM contributions at different target EVM values calculate as follows:

Target EVM [dB]	Real EVM [%]	SA EVM Margin [dB]	SA EVM contr. [dB]	SA EVM contr. [%]	Total EVM [%]	EVM error [%]	Total EVM [dB]	EVM error [dB]
-30	3,162	10	-40	1,000	3,317	0,154	-29,586	0,414
-32	2,512	10	-42	0,794	2,634	0,123	-31,586	0,414
-34	1,995	10	-44	0,631	2,093	0,097	-33,586	0,414
-36	1,585	10	-46	0,501	1,662	0,077	-35,586	0,414
-38	**1,259**	**10**	**-48**	**0,398**	**1,320**	**0,061**	**-37,586**	**0,414**
-40	1,000	10	-50	0,316	1,049	0,049	-39,586	0,414
-42	0,794	10	-52	0,251	0,833	0,039	-41,586	0,414
-44	0,631	10	-54	0,200	0,662	0,031	-43,586	0,414
-46	0,501	10	-56	0,158	0,526	0,024	-45,586	0,414
-48	0,398	10	-58	0,126	0,418	0,019	-47,586	0,414
-50	0,316	10	-60	0,100	0,332	0,015	-49,586	0,414
-52	0,251	10	-62	0,079	0,263	0,012	-51,586	0,414
-54	0,200	10	-64	0,063	0,209	0,010	-53,586	0,414
-56	0,158	10	-66	0,050	0,166	0,008	-55,586	0,414
-58	0,126	10	-68	0,040	0,132	0,006	-57,586	0,414
-60	0,100	10	-70	0,032	0,105	0,005	-59,586	0,414

Influence of the signal analyzers residual EVM margin on the measurement result, fixed EVM margin

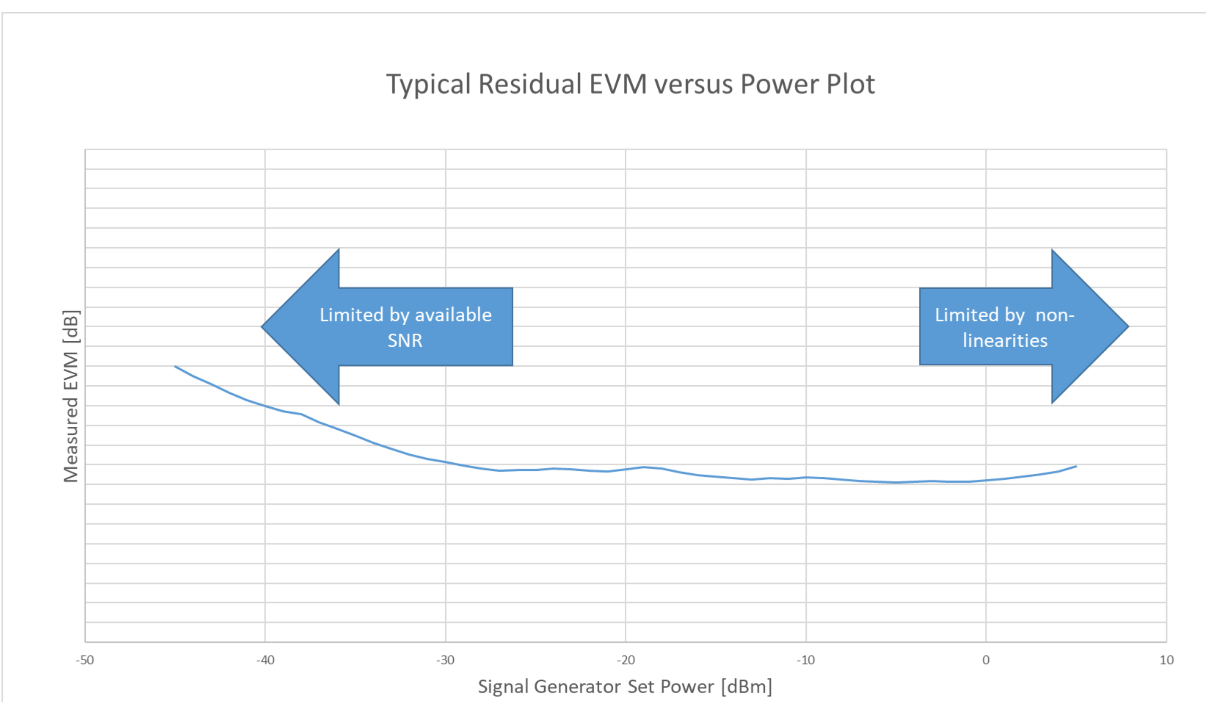
The procedure for calculating EVM is very similar to IEEE802.11ax. The test is performed using a minimum of 20 PPDUs with at least 32 data symbols containing random data if the occupied RU has 26 tones. If the occupied RU has more than 26 tones, then the PPDUs shall be at least 16 data symbols long. EVM calculation is done using compensation of both estimated frequency offset and sampling offset drift. The result is determined by averaging over the subcarriers, frequency segments, EHT PPDUs and spatial streams.

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 -48 dB for the 4096 QAM case. The following figure shows a screenshot from the R&S®FSW Signal and Spectrum Analyzer achieving -50 dB EVM for an EHT PPDU using 4096 QAM modulation in a 320 MHz channel.



4096QAM WLAN constellation on 320 MHz channel and EVM

The residual EVM of a signal analyzer is usually evaluated by directly connecting it to a high-end signal generator. Then the EVM is measured for the frequency and signal of interest over different power levels. The result is a typical bathtub curve *EVM vs. Power*. This curve is dominated by noise on the low-power side and non-linearities on the high-power side.



Typical bathtub curve measuring EVM versus signal power

To minimize the EVM measurement uncertainty from test system contributions over a wide range of power levels, the RF front-end of both instruments needs to be adapted continuously - ideally using an automatic levelling algorithm. These algorithms generally have to do a trade-off between best possible performance and the required time to achieve this optimal levelling.

Both instruments - the generator and the analyzer - contribute to the measured residual EVM.

2.4.1.3.3 Unused Tone Error

For EHT 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 a 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, an EHT TB PPDU must also meet an EVM requirement for unused tones to measure if the STA is causing interference to adjacent RUs.

2.4.2 EHT Receiver Requirements

The 802.11be receiver testing requirements and limits are similar to those defined in the 802.11ax specification and cover the following test items:

- Receiver minimum input sensitivity
- Adjacent and nonadjacent channel rejection
- Receiver maximum input level
- Trigger based PPDU precorrection specifications
- Transmit power accuracy and RSSI measurement
- Carrier frequency offset (CFO) error and timing drift

3 Instrument Selection

To optimally cover all the very different markets and applications for signal analyzers and signal generators, these instruments can be configured with a whole lot of different options to best suit the customer requirements. The chosen configuration can strongly influence the performance parameters of the setup. Comparing the performance of instruments with respect to certain parameter is only feasible, if the possibly different optioning of the instruments is kept in mind.

3.1 Signal Analyzer:

When selecting the best signal analyzer for a test setup to ensure lowest possible residual EVM contribution, the following points have to be considered.

The R&S®FSW Signal and Spectrum Analyzer is called FSW in the following.

Lowest frequency option possible (8/26GHz)

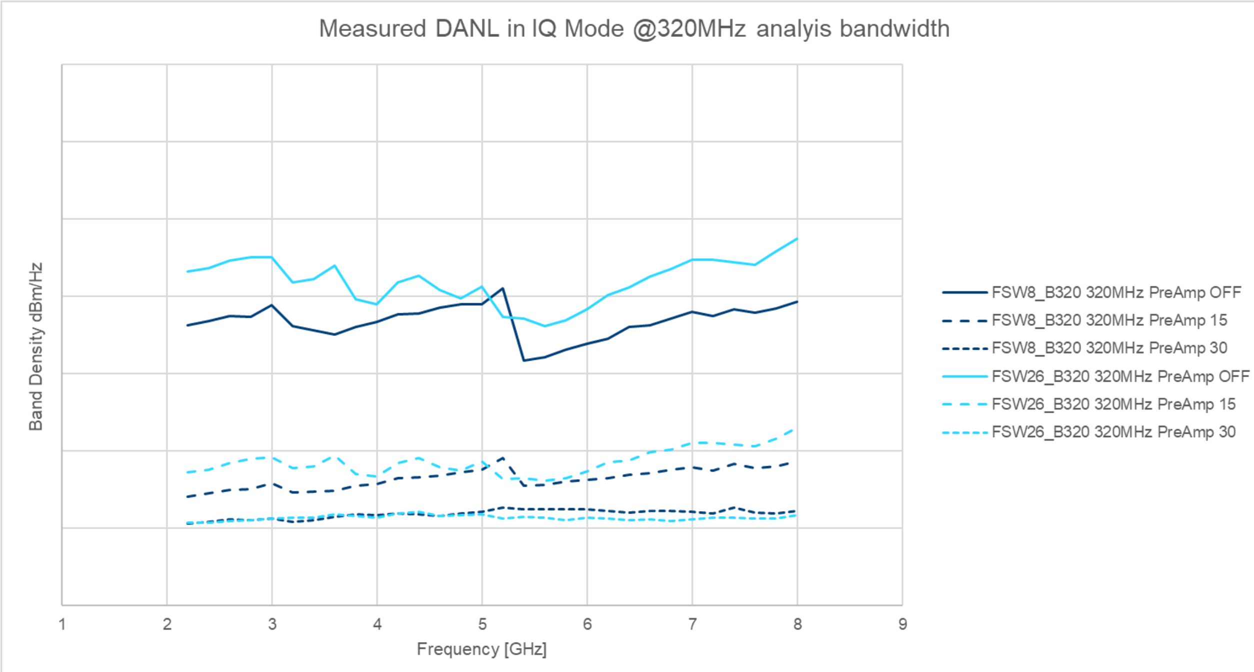
A higher maximum input frequency is always associated with a more complex RF front-end of the instrument. Typically, some switching is required to provide best performance over the wider frequency range. This adds some loss to the signal path. Additionally, the elements of the front end must be designed to handle wider frequency spans. This in general increases the challenges for the design.

The displayed average noise level (DANL) from the datasheet can be used as an indicator for good EVM measurement performance:

Frequency [GHz]	DANL R&S FSW8 [dBm]	DANL R&S FSW13/26 [dBm]	DANL R&S FSW43 [dBm]	DANL R&S FSW50 [dBm]	DANL R&S FSW67 [dBm]
1 GHz	-150/-154	-149/-154	-149/-154	-149/-	-149/-
<3 GHz	-152/-156	-151/-156	-150/-155	-150/-	-150/-
>3 GHz	-152/-156	-151/-156	-150/-155	-150/-	-150/-
8 GHz	-152/-156	-149/-154	-148/-152	-148/-	-144/-

DANL, nominal/typ. values, preamplifier off, instrument without R&S®FSW-B13, noise cancellation off, RF attenuation = 0 dB, termination = 50 Ω, normalized to 1 Hz RBW, see datasheet

The values in the above table are valid for the spectrum mode. The values for the IQ-mode can differ but are not listed separately in the datasheet. The figure below shows an example measurement of the DANL in IQ-mode for two specific R&S®FSW models with R&S®FSW-B320 option.



DANL in IQ mode for 320MHz measurement bandwidth; different R&S®FSW models with pre-amplifier off, 15dB and 30dB gain

Therefore - as a rule of thumb - instrument models with a frequency range "just enough" for the measurement task should be preferred.

In addition, it has to be noticed that the auto-levelling routine of the WLAN-11be application is optimized for the most relevant models R&S®FSW8/13/26 so far. The optimization for the models R&S®FSW43/50/67 might follow, even though we do not recommend these models for WLAN applications. The optimal levelling of the RF frontend (preamplifier gain, attenuation, reference-level) is absolutely crucial for the residual EVM measurement. Manual optimization of the levelling is always possible.

Preamplifier option

The signal analyzer should be equipped with the R&S®FSW-B24 preamplifier option. The switchable preamplifier helps to optimally level the signal in a wider power range. Multi-stage preamplifiers provide an even more precise levelling compared with single-stage preamplifiers.

As stated in the previous section, R&S®FSW8 or R&S®FSW26 are recommended for 802.11be measurements.
If models with higher frequency range are used, it should be kept in mind that a new, redesigned and optimized preamplifier model with an enhanced microwave frontend is available for the R&S®FSW43, R&S®FSW50 and R&S®FSW67. New instruments starting with the following serial numbers are equipped with this enhanced frontend by default (if R&S®FSW-B24 is ordered):

Type	From Serial Number
R&S®FSW43	102199
R&S®FSW50	101672
R&S®FSW67	101701

Serial numbers for FSW with new preamplifier option by default

With the latest firmware, the new enhanced R&S®FSW-B24 option will show *B24U* in the option list to clearly identify the new hardware. Upgrade kits are available for instruments with material number 1331.5003.XX, which already have a previous version R&S®FSW-B24 installed.

Option R&S®FSW-B25

If this option is installed (electronic attenuator), the specified DANL of the datasheet is degraded by typ. 1dB. Option R&S®B25 should only be chosen, if a heavy use of the mechanical attenuator is expected (e.g. in automated test systems). It can then help to reduce the number of switching cycles of the mechanical attenuator which extends the lifetime of the mechanical relays.

Smallest bandwidth option possible

Instruments equipped with wider instantaneous bandwidth options, are generally also more susceptible to noise in the receive path. If the R&S®FSW-B1200/-B2001/-B800R/-B4001/-B6001/-B8001 option is installed, the specified DANL in the datasheet has to be corrected by typ. +2dB.

Comparison of EVM versus Power measurements with different bandwidth options

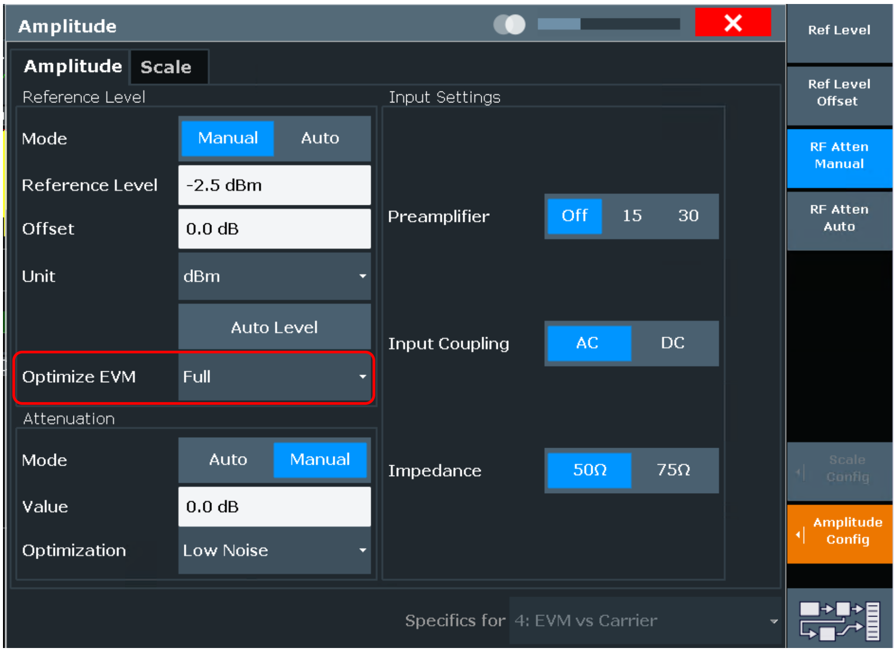
Therefore, the R&S®FSW-B320 and R&S®FSW-B512 are the recommended bandwidth options for 11be measurements. Instruments equipped with R&S®FSW-B1200 show slightly higher residual EVM values as expected based on the DANL specification.

In addition, it has to be noticed that the auto-levelling routine of the WLAN-11be application is optimized for the most relevant options B160/320/512 so far. The optimization for the B1200 option will follow. The optimal levelling of the RF frontend (preamplifier gain, attenuation, reference-level) is absolutely crucial for the residual EVM measurement. Manual optimization of the levelling is always possible.

Latest Firmware with "Optimize EVM" function

The *R&SFSW-K91BE IEEE 802.11be Measurements* option was first available in the firmware version 4.90 and enhanced in the firmware version 5.00.

The firmware release 5.10 introduces the new auto-levelling feature *Optimize EVM* in combination with the bandwidth options R&S®FSW-B320 and R&S®FSW-B512. This extends the optimization of the RF frontend settings by an iterative search for the minimum residual EVM. If activated, this helps to find the best instrument settings with respect to the signal conditioning in a fast, repeatable and automatic manner.



Optimize EVM drop down menu

3.2 Signal Generator

For a measurement of the residual EVM of a signal analyzer, a high-quality signal source is required to create the test signal. Same as the signal analyzer, also the R&S®SMW200A Vector Signal Generator can be adopted to the customer requirements with a lot of different hardware options. To achieve the best possible signal fidelity for 11be measurements, the following points should be considered.

The R&S®SMW200A Vector Signal Generator is called SMW in the following.

Latest RF hardware

Since its introduction, the SMW has been established as the leading high-end vector signal generator in the market. Rohde & Schwarz continuously improves the instrument to keep it state of the art. One of these upgrades relates to the RF frequency options. To distinguish older from the latest hardware, the new frequency options use the following new nomenclature:

RF path A: SMW-B10xx
RF path B: SMW-B20xx

In contrast to that, the older frequency options had 3-digit option numbers.

To achieve best EVM performance, instruments with the new RF options should be used.

Low noise options

The SMW with the new RF hardware can be equipped with different types of low phase noise options, providing different levels of phase noise performance.

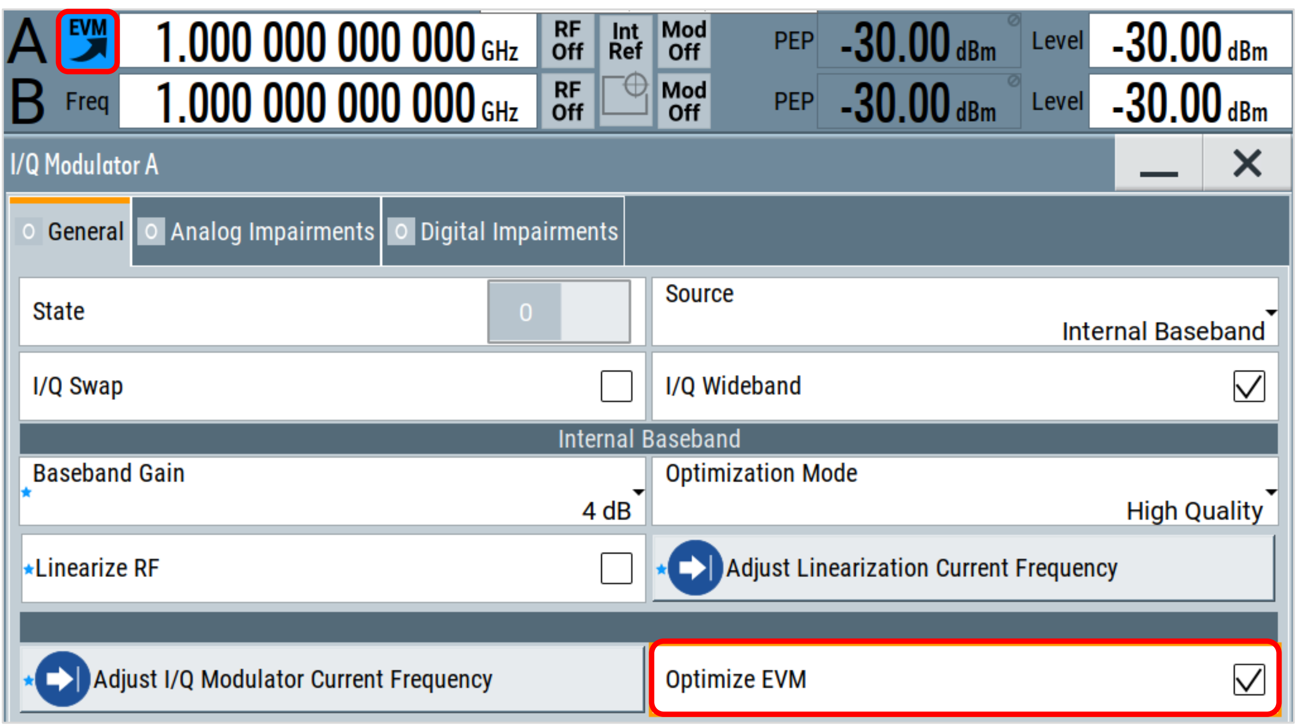
Phase noise performance level	Required options for RF path A	Required options for RF path B
Standard performance	R&S®SMW-B10xx frequency option	R&S®SMW-B20xx frequency option
Low phase noise	R&S®SMW-B10xx frequency option and R&S®SMW-B709	R&S®SMW-B20xx frequency option and R&S®SMW-B719
Improved close-in phase noise performance	R&S®SMW-B10xx frequency option and R&S®SMW-B710	R&S®SMW-B20xx frequency option and R&S®SMW-B720
Ultra-low phase noise	R&S®SMW-B10xx frequency option and R&S®SMW-B711	R&S®SMW-B20xx frequency option and R&S®SMW-B721

Possible option combinations for an SMW with two RF paths

As phase noise in the signal also directly affect the residual EVM of a test set up, ideally, the signal generator should be equipped with the *Ultra-low phase noise* option.

Latest Firmware with "Optimize EVM" function

From release firmware 5.00 and higher, the optimization of the preexisting excellent EVM performance of the SMW is simplified by the addition of a one-button-click automated procedure.



Optimize EVM button in the I/Q Modulator menu of the signal generator

This procedure includes the previously existing *Adjust I/Q Modulator Current Frequency* and *Optimize for current settings* functions plus some other adjustments to deliver best EVM by a mouse-click or automatically after any change of the signal, frequency or power. If activated, a small icon is shown next to the frequency field on the top of the instrument.
These optimizations do require some extra steps which add-up to the settling time of the generator.

4 Factors Influencing the EVM Measurement

In addition to the selected instrument hardware and firmware (see chapter above), also specific settings in the measurement application and the signal parameters do affect the measured EVM values.

4.1 Measurement Settings

The following table gives an overview of standard-conform and EVM-optimized settings for channel estimation and tracking in the WLAN measurement application. If non-standard EVM corrections are activated during a test, the EVM result might be artificially improved and thus not usable to check compliance against the standard.

Setting	Standard conform setting 802.11be, 36.3.19.4.4.	Setting for best EVM	Comment
CHANNEL ESTIMATION			
Channel Estimation Range	Preamble	Payload	
Interpolation	Wiener / None	Wiener	
Wiener Relative Delay Spread	ON/OFF, tuned manually	ON, tuned manually	The optimum value depends on the channel properties. Lower values increase smoothing.
TRACKING			
Preamble Channel Estimation	n.a. for 11be	n.a. for 11be	Only available for 802.11ac and n
Phase	ON	ON	
Timing	ON	ON	
Level	OFF	ON	802.11ax places different target EVM values for amplitude drift compensation on and off and 1024QAM; not applicable for 11be
I/Q Mismatch Compensation	OFF	ON	
Pilots for Tracking	According to standard	According to standard / Detected	If the pilot generation algorithms of the DUT has a problem, mode "Detected" might allow synchronization
EHT-LTF Symbol Duration	6.4 µsec, 12.8 µsec	12.8 µsec	Setting of waveform / signal generator

Important settings for standard conform EVM measurements

The 802.11 standard allows to "…Estimate the complex channel response coefficient for each of the subcarriers…" for the EVM measurement. The channel estimation is done in frequency domain based on known pilots in the Long Training Field in the preamble and missing subcarrier estimations are obtained by interpolation.

The physical layer for EHT (802.11be) provides support for 6.4µs (2xLTF), and 12.8µs (4xLTF) LTF symbol durations. This can be configured in the R&S®SMW200A 802.11 WLAN option, while the R&S®FSW WLAN option automatically detects the LTF duration. Longer LTF durations allow for better equalizer training e.g. by averaging the measurement values for the repeated LTFs.

The channel estimation interpolation setting is only available for 802.11ax and be. It applies filtering to the channel, which reduces signal noise and influences the interpolation of gaps in the signal due to unused subcarriers and thus the smoothing of the equalizer function during channel estimation.

The channel estimation is done on a per-subcarrier basis. Assuming independent noise on each subcarrier, some averaging can reduce the noise in the frequency response calculation. This can reduce the EVM value - except under low-noise conditions or when the real frequency response is unusually rough, which would require a very "un-smooth" correction also.

The filter for the Wiener interpolation is defined by the *Wiener Relative Delay Spread*. By default, the filter is determined automatically. Decrease this setting to finetune the EVM result if there is negligible delay spread - for example for a wired connection.

The 802.11be standard provides the following additional specifics about the EVM measurement:

"… Local oscillator leakage that can potentially show up at the center frequency of the EHT PPDU tone plan and within ±3 neighboring subcarriers shall be excluded from the computation of the transmitter modulation accuracy test…"

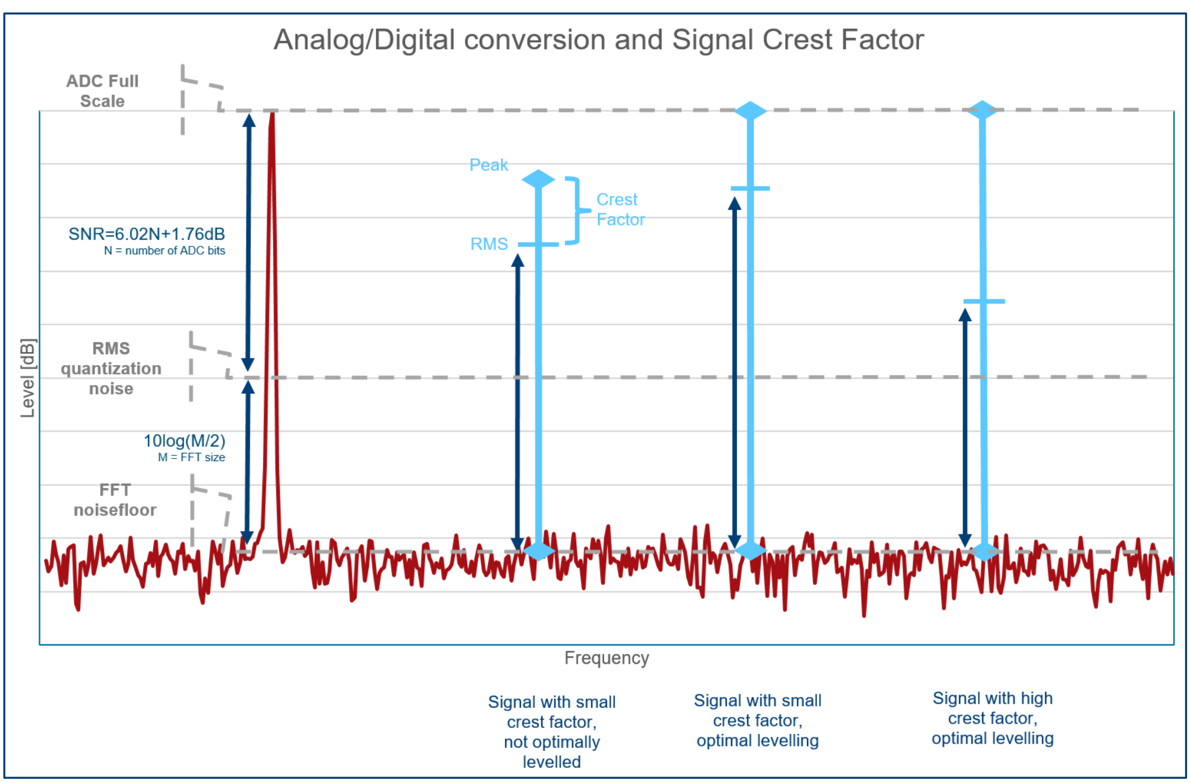
"…The test shall be performed over at least 20 PPDUs … If the occupied RU has 26 tones, the PPDUs under test shall be at least 32 data OFDM symbols long. For occupied RUs that have more than 26 tones, the PPDUs under test shall be at least 16 data OFDM symbols long. Random data shall be used for the symbols…"

While the 802.11b/g DSSS standards distinguish between Peak Error Vector and PPDU EVM, this is not the case for 802.11be and the other OFDM based WLAN versions.

4.2 Crest Factor of the Test Signal

Like other communication standards, WLAN utilizes high order modulation and multiple carrier techniques. The complexity of these signals can lead to high crest factors (peak voltage to average voltage ratio). High crest factors in turn are associated with two problems in the signal conditioning chain:

- High peak voltages challenge the linearity of power amplifiers (compression) and thus can cause intermodulation effects.
- Since the whole RF chain - including the D/A and A/D converters - has to be configured to handle the peak voltages, the average voltages are converted with relatively low resolution. This leads to higher quantization noise and thus reduced SNR.



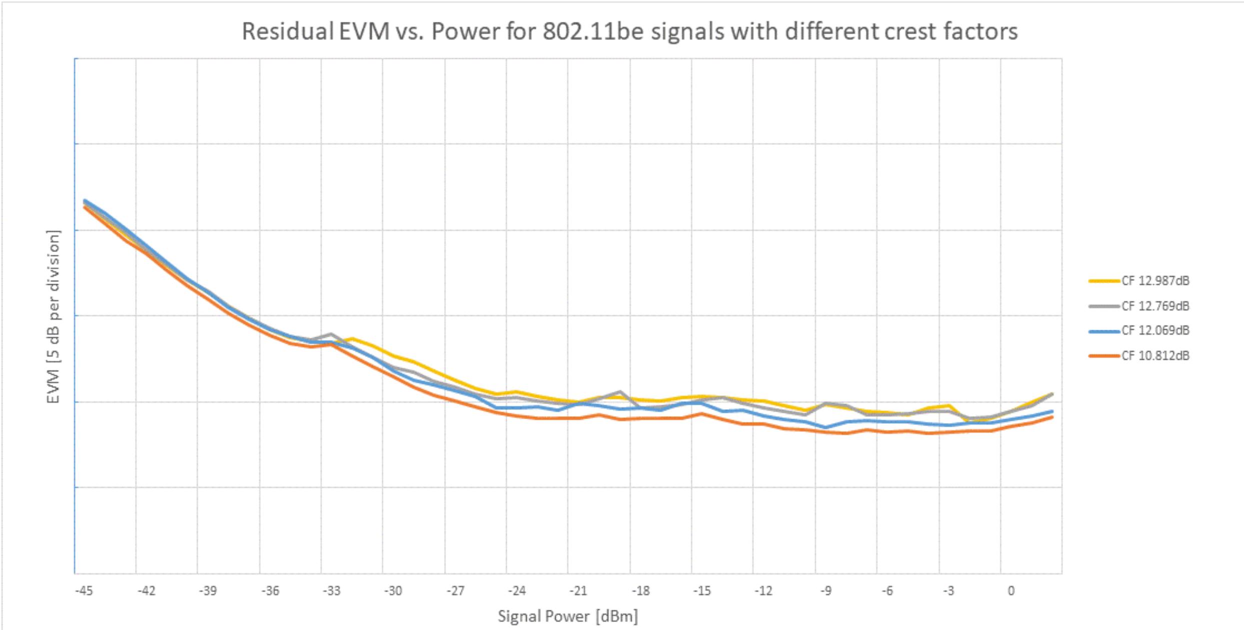
Principal relationships of AD-converter and waveform parameters in a schematic spectrum-analyzer plot

Therefore, the crest factor is - together with the signal bandwidth - the main signal parameter which influences the achievable residual EVM value. Performance comparisons always need to be based on waveforms with similar characteristics regarding these two parameters.

The *Overload* indication of signal analyzers reacts on the peak in the measured signal. For 802.11ax and 11be signals, this peak is typically located in the preamble area:

Screenshot of the WLAN application showing an IF-Overload warning

In addition, the crest factor of a specific 11be waveform can also depend quite significantly on settings like the *Scrambler Init* value which was set on the signal generator. The following figure shows EVM vs. Power results for similar 11be waveforms mainly differing in the crest-factor value:

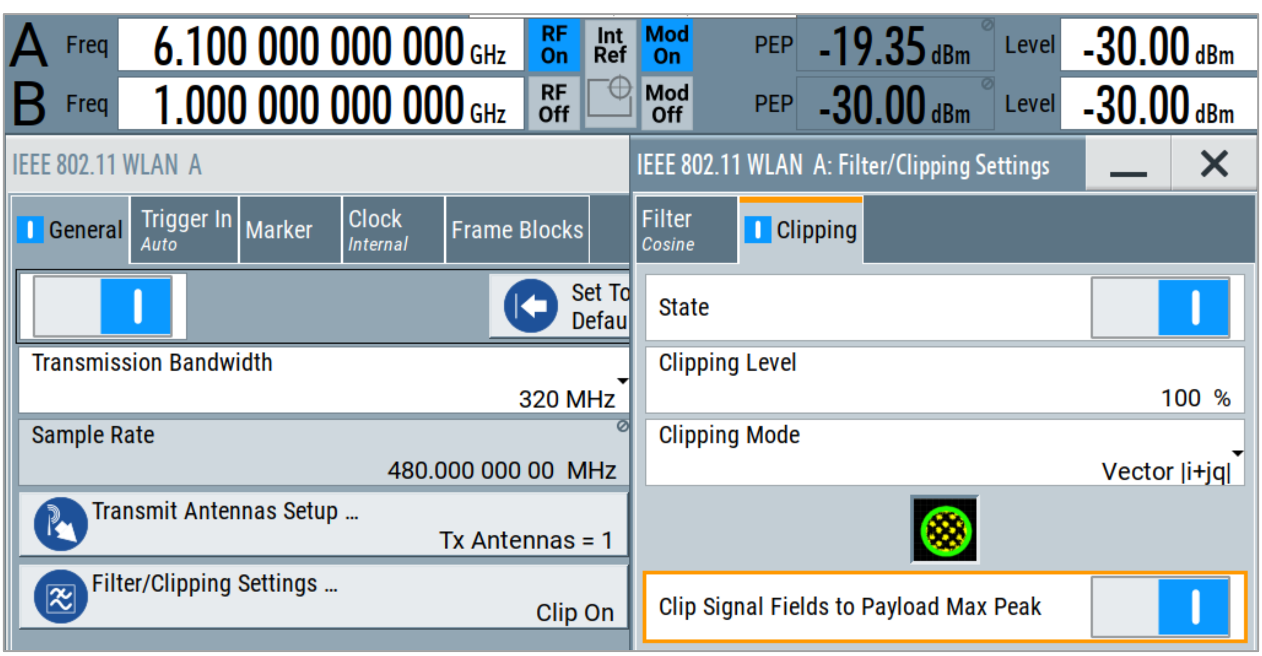


EVM versus Power measurements for signals with different crest-factors

The preamble part of the WLAN signal, which is responsible for the increased crest factor in the above example, does not affect the EVM measurements. EVM is defined to only evaluate the payload of the transmission. Furthermore, robust modulation schemes are used in the preamble part. These modulations schemes can be demodulated correctly even if they are clipped slightly.

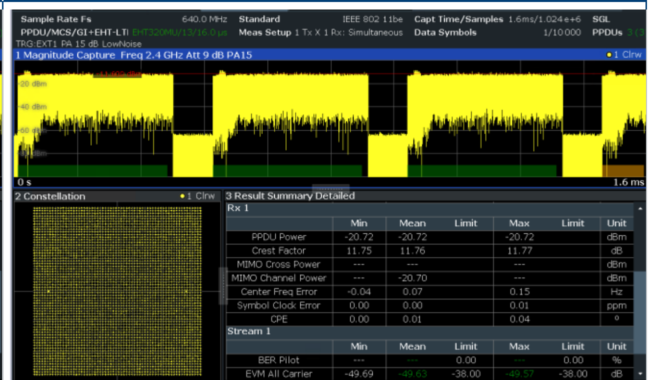
A clipping feature is implemented directly in the R&S®SMW-K147 IEEE 802.11be option of the signal generator. This feature aims to clip all preamble parts exceeding the payload max peak and can be found in the 11be as well as in the 11ax implementation. It harmonizes the crest factor between preamble and payload.

Navigate to the *General* tab of the WLAN option, open the *Filter/Clipping Settings* menu, select the *Clipping* tab and finally activate the *Clip Signal Fields to Payload Max Peak* option.



Clipping settings in the IEE802.11 WLAN menu of the signal generator

This immediately reduces the crest factor of the signal. At the same time, the achievable SNR for the signal increases by approximately the same amount. The resulting improved EVM performance can be observed on the signal analyzer.

Clip Signal Fields to Payload Max Peak OFF	Clip Signal Fields to Payload Max Peak ON
	
Crest Factor 13.01dB EVM All -49.02dB	Crest Factor 11.76dB EVM All -49.63dB

Signal without and with "Clip Signal Fields to Payload Max Peak" activated

Since the crest factor is dependent on many different parameters of the signal, the EVM gain achievable by this option is different for every signal.

To ensure valid measurements, it is generally recommended to absolutely avoid overload conditions on the signal analyzer (indicated by the red OVLD status display). As for 11be signals the peak signal is typically located in the preamble area, while the EVM is calculated over the payload fields, a small overload can result in a better EVM value, because only some parts of the preamble are clipped slightly. But this always needs special attention and validation.

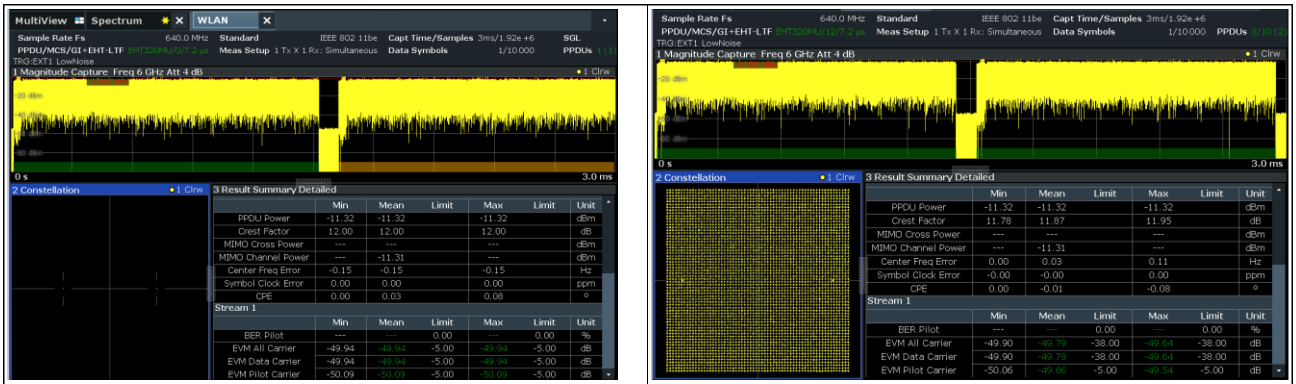
4.3 EVM Independence from Modulation Order & Burst Length

Modulation Order

OFDM systems add up a large number of individually modulated subcarriers at the transmitter. Without crest-factor-reduction these summed-up signals have power characteristics similar to additive white gaussian noise with high peak-to-average power ratios above 10dB.

The crest factor of M-QAM modulated signals does not constantly increase with growing modulation M order but saturates at sqrt(3) or 4.8dB for high modulation orders (theoretical value for quadratic constellation and equally likely constellation points).
Also, the properties of the underlaying modulation are "scrambled" by the IFFT (Inverse Fast Fourier Transformation) operation which is applied to switch from the frequency-domain to the time-domain signal. These two facts help to explains why the modulation-order of the individual subcarriers does not affect the final crest factor of the time-domain signal much.

This is shown exemplarily in the following table, where a 320MHz wide 11be waveform with different modulation schemes for the data stream was analyzed. *Clip Signal Fields to Payload Max Peak* is enabled on the generator to measure independent of the specifics of the signaling fields:



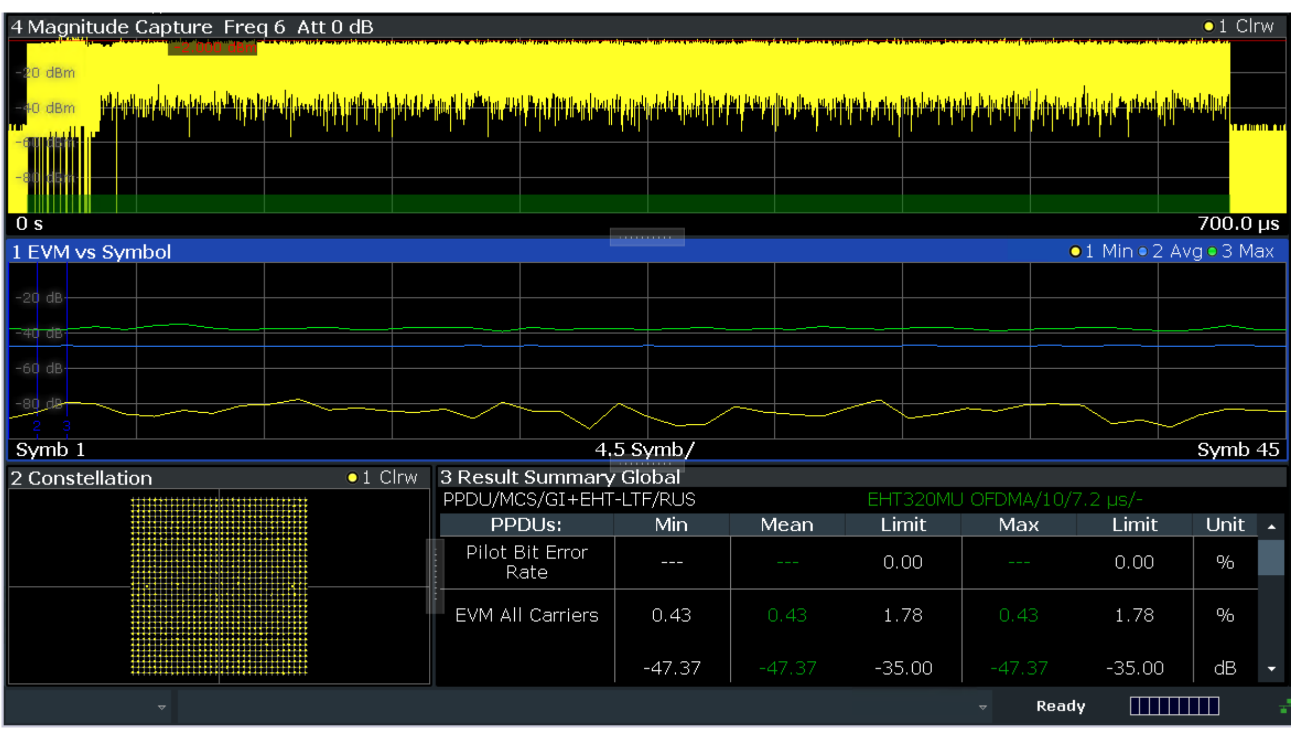
Modulation	Measured CF [dB]	Measured EVM All @-10dBm set power [dB]
QPSK	11.62	-49.7
16 QAM	11.79	-49.8
64 QAM	11.65	-49.7
256 QAM	11.63	-49.6
1024 QAM	11.96	-49.8
4096 QAM	11.88	-49.7

EVM results for an 11be 320MHz signal using different subcarrier modulations at a fixed power level; *Optimize EVM* activated on signal generator and signal analyzer; >~ 100 symbols; *Clipping Signal Fields to Payload Max Peak* set on generator;

A high signal length of around 100 symbols was chosen to increase the probability of high instantaneous signal amplitudes in the captured signal.

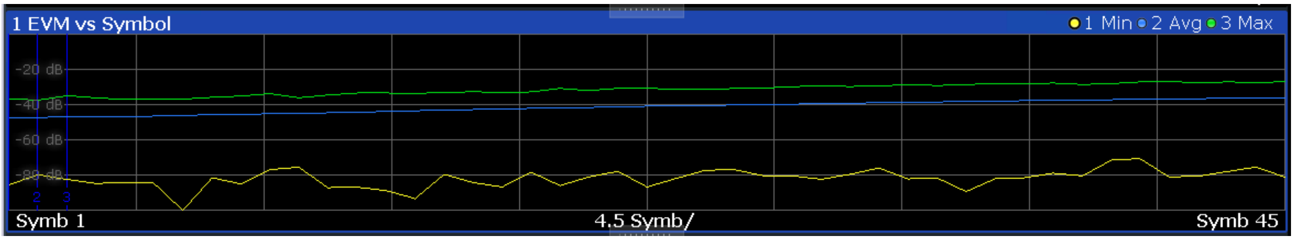
Burst Length

The number of symbols in a PPDU does not affect the average EVM, as the EVM vs. Symbol result should not drift over time (i.e. versus the symbol number).



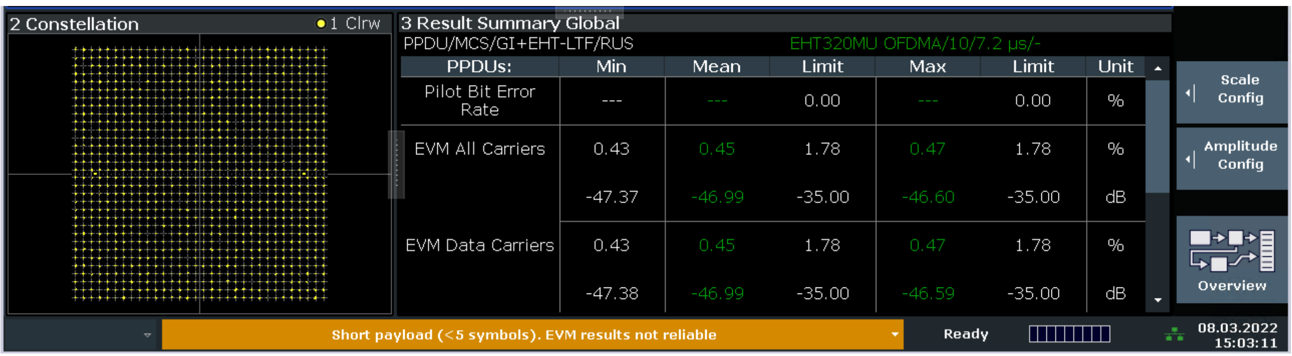
EVM versus Symbol plot showing no drift over time

As the timing synchronization is based on the preamble symbols, one could expect a sampling point drift for very long burst length. But as time tracking is required for a standard conform EVM measurement, a possible drift would be compensated. Disabling the time tracking in the above measurement directly results in a visible drift - if the reference clocks of the instruments are not coupled.



EVM versus Symbol plot: drift over time due to disabled time tracking and uncoupled reference clocks

The standard demands a minimum of 16 symbols. If less than 5 symbols are found in the payload, a warning is displayed on the signal analyzer:



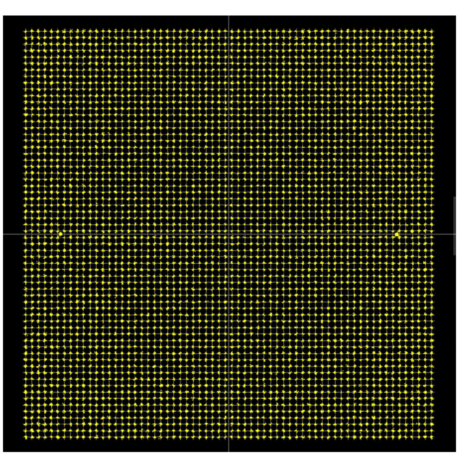
Short Payload warning for signals with less than 5 symbols

For such short payload lengths, the compensation of certain error terms (frequency/phase offsets) and the phase training become less accurate.

4.4 4096-QAM EVM Limitation for Low-SNR Conditions

To increase the maximum possible throughput, 802.11be introduced the 4096 QAM modulation of the subcarriers. Up to 802.11ax, 1024 QAM was the maximum applied modulation order.

With the increasing number of constellation points, these points get closer and closer in the constellation diagram.



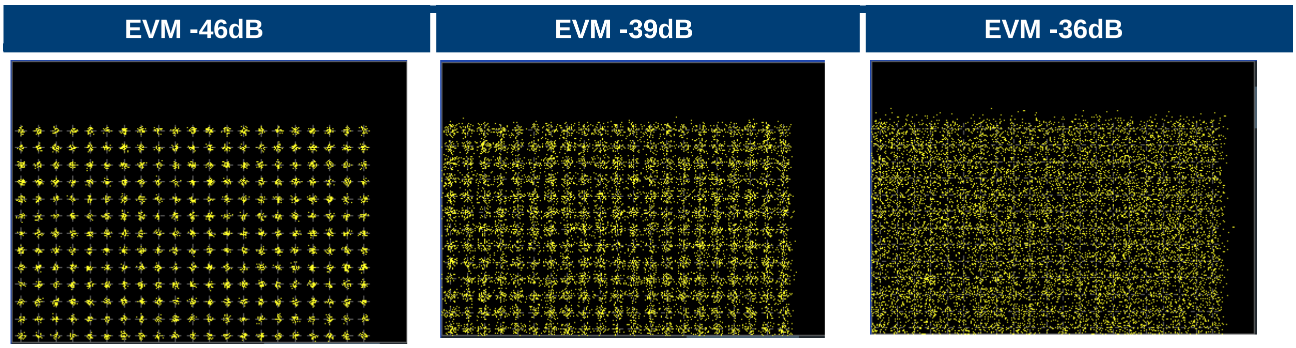
Typical 4096 QAM constellation

To calculate the EVM value, each sampled point has to be assigned to an ideal constellation point. Based on the "distance" to this ideal point, the EVM is calculated.

As the option R&S®FSW-K91 does not have additional information about the measured signal, this decision can only be based on the vicinity of the sampling point to a constellation point. The closest "neighbor" constellation point will be selected for the EVM calculation.

The deviation of the sampling points from the ideal constellation points can be caused e.g. by non-linearity of an amplifier, spurious interferers, IQ gain imbalance or by noise added to the intended signal. These effects can create different types of deformations of the constellation.

Assuming only wideband, uncorrelated noise as a source of increased EVM for the following, the "spread" of the sampled points increases with decreasing signal-to-noise ratio and might be in the range or even bigger than the "distance" of the constellation points:

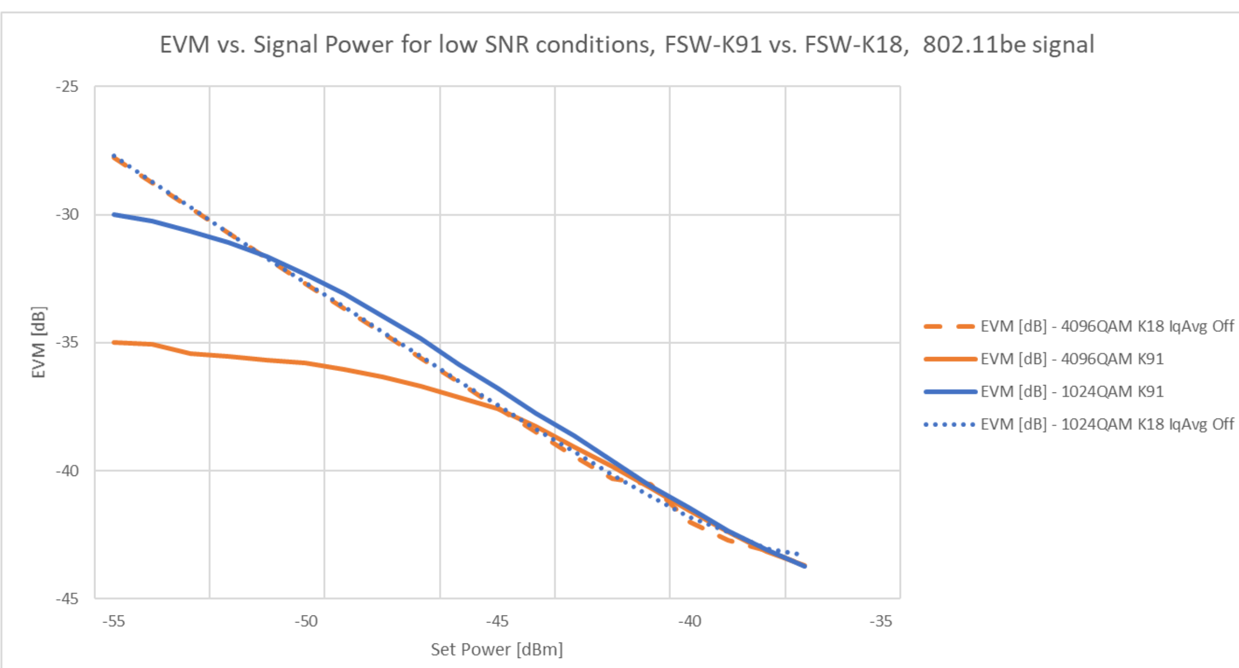


Top-right segment of a typical 4096 QAM constellation with decreasing signal to noise ratio

With decreasing SNR, this approach leads to more and more wrong assignments of the sampled data to simply the closest constellation point instead of the correct one. Therefore, the measured EVM value will be unrealistically good under low SNR conditions and saturate at some point.

In opposite to the R&S®FSW-K91 WLAN option (nearest constellation point decision), the R&S®FSW-K18 Amplifier option calculates the EVM based on the known reference waveform. This means, that in this option the calculation of the EVM is based on the knowledge of the sent signal. Therefore, no wrong decisions are taken also under bad signal to noise conditions and the EVM value does not saturate at some point.

Comparing both approaches clearly shows the difference in the low signal power region:



EVM versus Power plot: nearest-constellation-point EVM calculation (FSW-K91) versus known-reference EVM calculation (FSW-K18)

COARSE ESTIMATION OF THE LIMITATIONS FOR NEAREST-POINT EVM CALCULATION

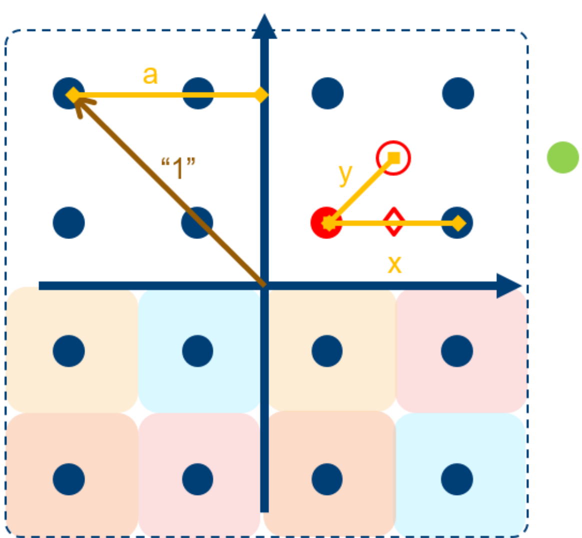
The following applies for EVM calculations based on a nearest-constellation-point-decision for QAM modulated signals, assuming only fully quadratic constellations.

From a certain distance of a real sampling point from the ideal constellation point (let's assume the red dot in the figure below should be the correct constellation point), the sampling point will be wrongly assigned to a neighbor constellation point if no further information about the real waveform is available.

Sampling points with a distance x/2 like the red diamond, will be assigned to a wrong constellation point if the angle is 0, 90,180 or 270 degrees relative to the red dot.
Sampling points with a distance bigger than the red circle will always be assigned to a wrong constellation point, independent of their angle.

This is valid only for sampling points "inside" the constellation. If the sampling point lies outside the constellation area (like the green dot), bigger distances are possible without a wrong decision, as fewer neighbor points exist. This affects modulations with lower order in the following estimation more than high-order modulations - assuming a more or less equal distribution of sampling points across all the possible constellation points.

16 QAM Example



EVM closest-point decision for different sampling point locations

◇ Distances bigger than this can lead to wrong decisions, depending on the angle

○ Distances bigger than this lead to 100% wrong nearest-point decisions

$$x = \frac{2a}{N} = \frac{\sqrt{2}}{N}$$

$$N = \sqrt{Modulation\ Order} - 1$$

$$a^2 + a^2 = 1 \rightarrow a = \sqrt{\frac{1}{2}}$$

$$y^2 = \left(\frac{1}{2}x\right)^2 + \left(\frac{1}{2}x\right)^2$$

$$y = \sqrt{\frac{1}{2}x^2}$$

From the above sketch, the following numbers can be derived for the estimated worst case EVM:

QAM Order	x [linear]	X/2 [dB] Possibly wrong decision	y [linear]	y [dB] 100% wrong decision	Worst case EVM [dB] measured while increasing AWGN level on generator
16	0.4714	-12.5	0.3	-9.5	-12
256	0.0943	-26.5	0.066	-23.5	-21
1024	0.0456	-32.8	0.0323	-29.8	-29
4096	0.0224	-39.0	0.0159	-36	-35

Estimation of worst case EVM boundaries for closest-point-decision based EVM; only considering points inside the constellation

These number can only be used to give a rough idea of the possible EVM range for different QAM modulations. A true signal always has a certain amplitude distribution. Also, other effects like the type of distortion might affect the EVM measurement.
In the last column, numbers of real EVM measurements are provided for comparison. To simulate low SNR scenarios, the signal was charged with an increasing level of *Additive White Gaussian Noise.* The highest EVM reading, that was obtained under increasing noise level, is given in the table.

5 How to Set Up for Best EVM Performance

So far, the following important topics for accurate EVM measurements were discussed in this document:

- Instrument selection (model, option, firmware version)
- Signal/waveform selection (crest factor)
- Correct measurement parameters

In this chapter some additional points will be highlighted, especially with respect to the optimal hardware settings of the signal generator and signal analyzer.

To cover a wide range of frequencies, bandwidths, standards and applications, the generator as well as the analyzer comprise complex hardware for optimal signal conditioning under changing circumstances and requirements. This hardware has to be configured appropriately to achieve the best possible performance.

5.1 Signal Generator

5.1.1 Digital Attenuation

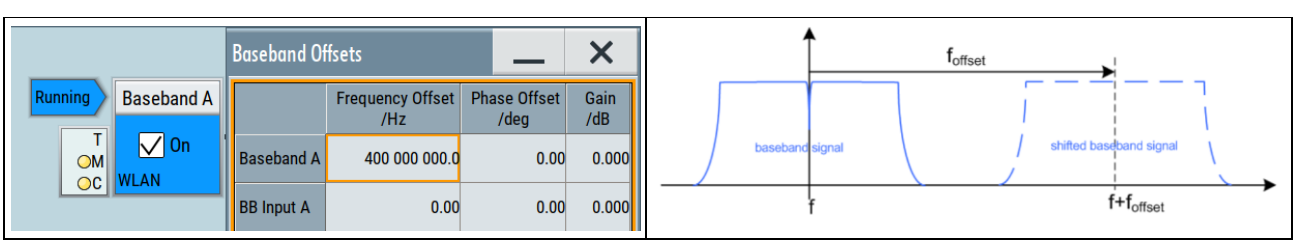
The generator offers the option to add a negative digital attenuation to the baseband. This amplification in the digital domain can be used to trade-in a bit of linearity versus an improved SNR. Similar to the effect discussed in chapter 4.2, this may lead to an overall better EVM result while degrading signal parameters which are less important for this specific measurement.

With wider bandwidths, also the noise in the signal path is increasing in general. This leads to a certain bandwidth dependency of the optimal setting. It can be advantageous to increase the baseband signal level for wider bandwidths while decreasing it for low-bandwidth signals.

5.1.2 Baseband Offset

Every mixer-based hardware shows carrier leakage at the center frequency. To further optimize the signal characteristics, it can be helpful to shift the baseband signal with a user-defined baseband frequency offset to a different center frequency. To allow this, the complex I/Q bandwidth of the shifted useful signal must not exceed the total available baseband bandwidth of the signal generator.

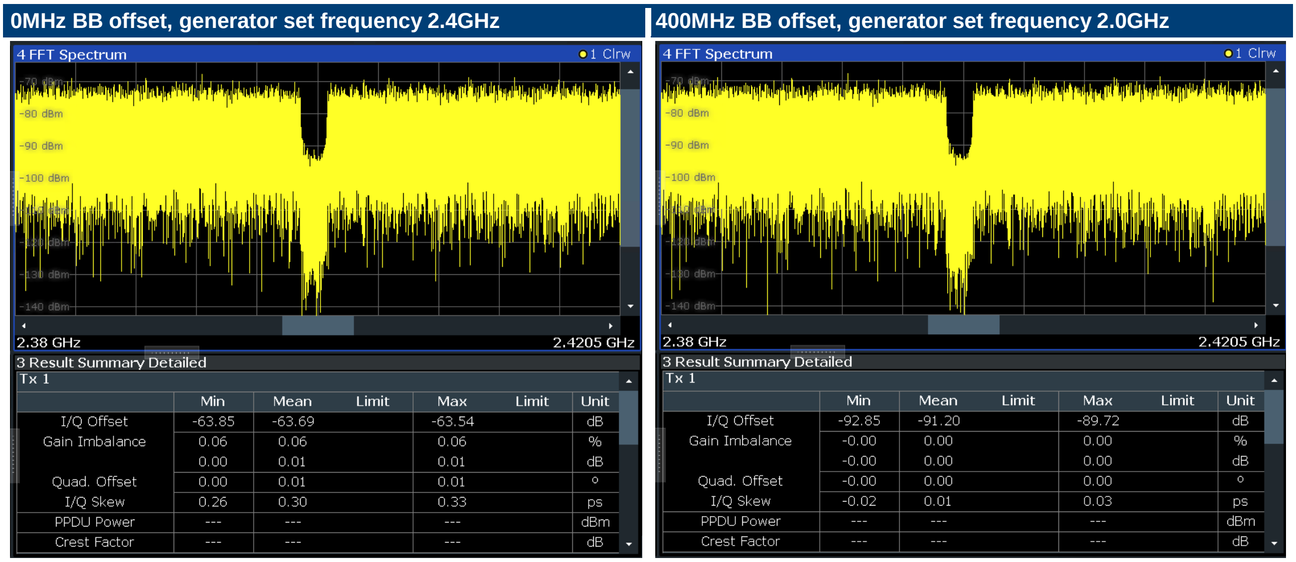
Shifting the baseband signal to a different center frequency can eliminate the carrier leakage impact.



Principle of a baseband frequency offset

When a baseband frequency offset is applied, the RF spectrum shows the wanted signal offset from the LO leakage peak and a suppressed sideband signal at the image frequency.

To shift the generated baseband signal, select Baseband > Baseband Offsets > Frequency Offset. This offset has to be taken in to account when calculating the correct receive frequency for the analyzer.



Effect of a baseband frequency offset

5.1.3 Optimize-EVM Feature

From release firmware 5.00 and higher, the optimization of the preexisting excellent EVM performance of the R&S®SMW200A Vector Signal Generator is simplified by the addition of a one-button-click automated procedure.

Please see chapter 3.2 for additional details.

5.2 Signal Analyzer

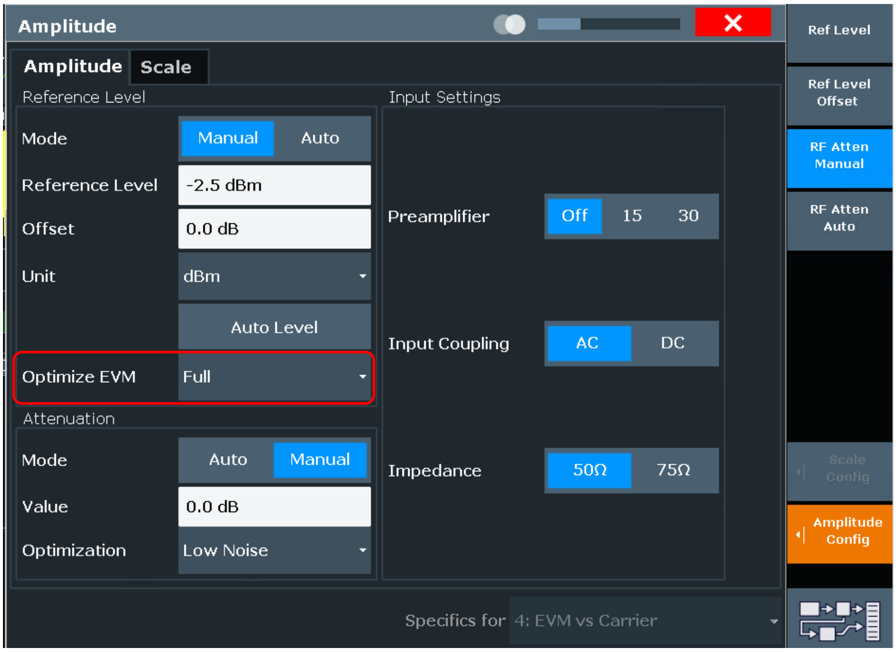
5.2.1 Auto-Level Enhancements and Optimize EVM Feature

The signal conditioning in the RF front-end of signal analyzers is crucial to achieve the best performance with respect to image-suppression, noise-floor, dynamic range and other RF-key parameters.

Precise signal levelling is especially important for complex measurements like Error-Vector-Magnitude. To minimize the measurement uncertainty from test system contributions over a wide range of different power levels, the RF front-end needs to be adapted continuously according to the signal characteristics, signal power and frequency - ideally using an automatic levelling algorithm.

The firmware release 5.00SP3 introduces an improved auto-level algorithm for the 802.11be measurement application in combination with the bandwidth options R&S®FSW-B320 and R&S®FSW-B512.

Firmware 5.10 rolls-out the additional auto-levelling feature *Optimize EVM*.



Optimize EVM drop down menu

The *Optimize EVM* drop down menu defines whether an optional, iterative search is performed to determine the required settings for minimum residual EVM with increased accuracy. If enabled, the reference level, preamplifier and, optionally, attenuation are configured:

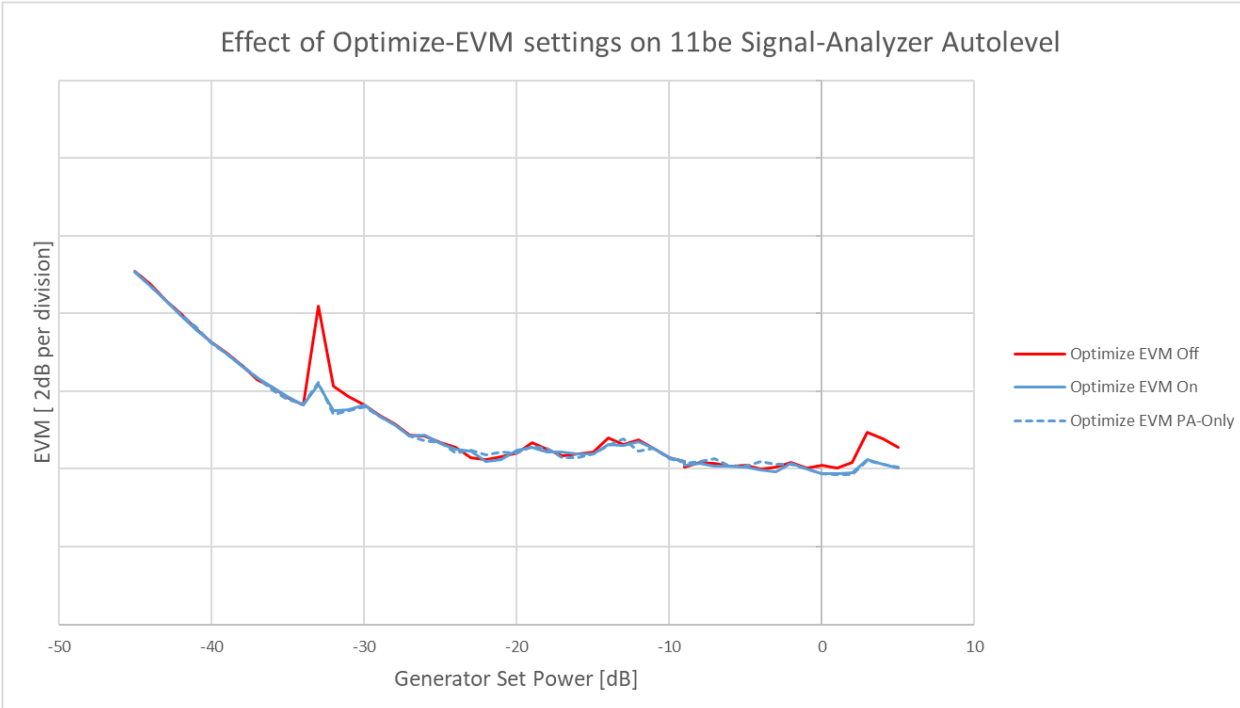
– Off: switches off the additional auto-level functionality; in this case, the default auto-levelling is NOT using data from the demodulated signal

– Full: An optional iterative search for minimum residual EVM is performed for the available preamplifier and attenuation settings using also results from several EVM measurements; therefore, the R&S®FSW-K91 has to be configured to correctly demodulate the signal for this mode;

– PA only: Only the preamplifier settings are optimized using also results from several EVM measurements with different settings; the attenuation setting is not changed; the R&S®FSW-K91 has to be configured to correctly demodulate the signal for this mode;

For signals with 160MHz or 320MHz bandwidth the *Low Noise Attenuation* optimization mode is set automatically.

The following figure gives an example of the effect of the *Optimize-EVM* feature on an EVM vs. Power bathtub curve:



EVM versus power; random set-power sequence during measurement; 320MHz 802.11be signal; Optimize-EVM Off, On and Pa-Only

The improved auto-levelling is especially important around the preamplifier-switching points (~-32dBm in the above figure) but also helps at other power settings to achieve an optimal EVM result.

5.2.2 R&S®FSW-K18 Option with IQ Averaging

The R&S®FSW-K18 Amplifier option was introduced already in chapter 4.4 to analyze the EVM numbers for low SNR scenarios. The *IQ-Averaging* feature of this option can be utilized to further analyze and separate several contributors to the residual EVM by e.g. averaging out some of the uncorrelated noise sources.

Special attention and validation is required when IQ-averaging is applied to correctly contextualize the achieved EVM results. They might not be in accordance to the standard test requirements.

5.2.3 Modulation Measurement Optimizer Tool

The Rohde & Schwarz *Modulation Measurement Optimizer (MMO)* tool was developed to support the automatic optimization of the signal analyzer RF front-end settings to minimize the instrument contribution to the residual EVM.

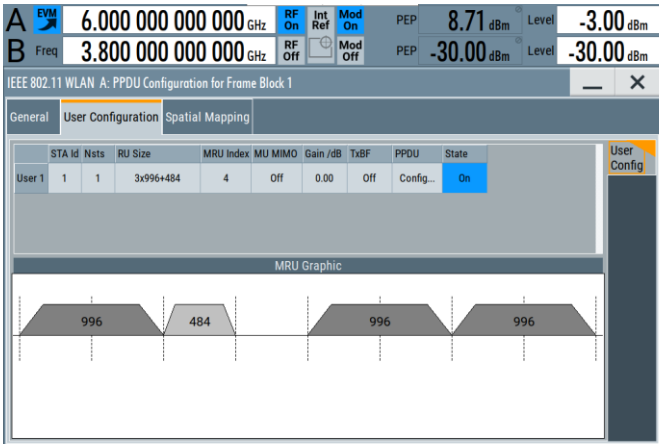
https://www.rohde-schwarz.com/de/applikationen/modulation-measurement-optimizer-application-note_56280-1168512.html

The 11be application in the latest firmware versions with optimized auto-levelling / Optimize EVM feature (see chapter 3.1) is already able to automatically determine optimized settings for the RF front end for best EVM for the recommended instruments.

The MMO tool might be useful though for hardware/firmware which is not supported by the new auto-level algorithm or to gain further insights in the challenges of auto-levelling.

6 Other 11be Transmitter Test Items

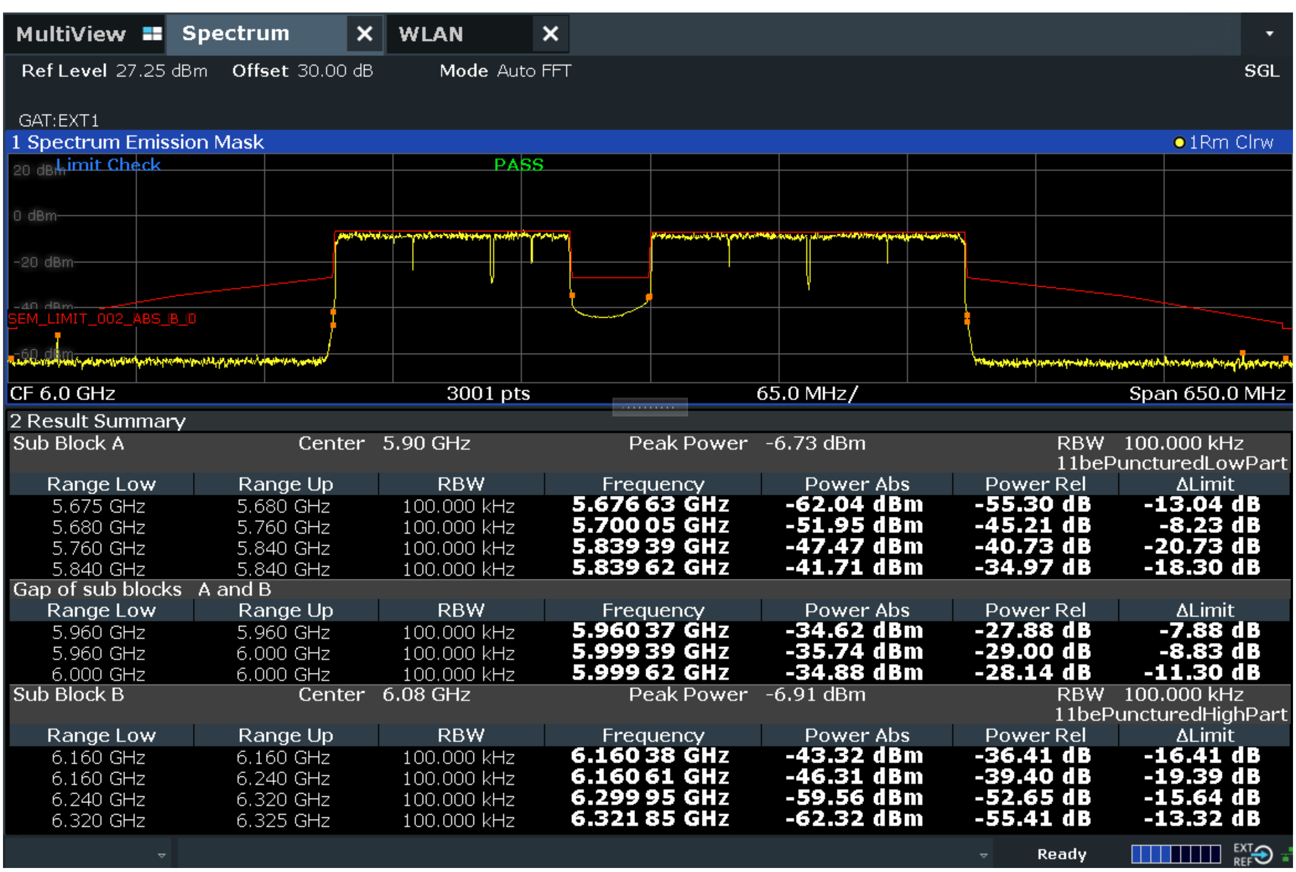
Spectrum Emission Mask (SEM) with punctured channel



Signal setup with punctured 40MHz block

If there are punctured subchannels in the signal bandwidth, the overall spectral mask is constructed by overlaying the standard mask for the unpunctured signal and the puncture masks for the specific puncture case (802.11be amendment chapter 36.3.19.2).

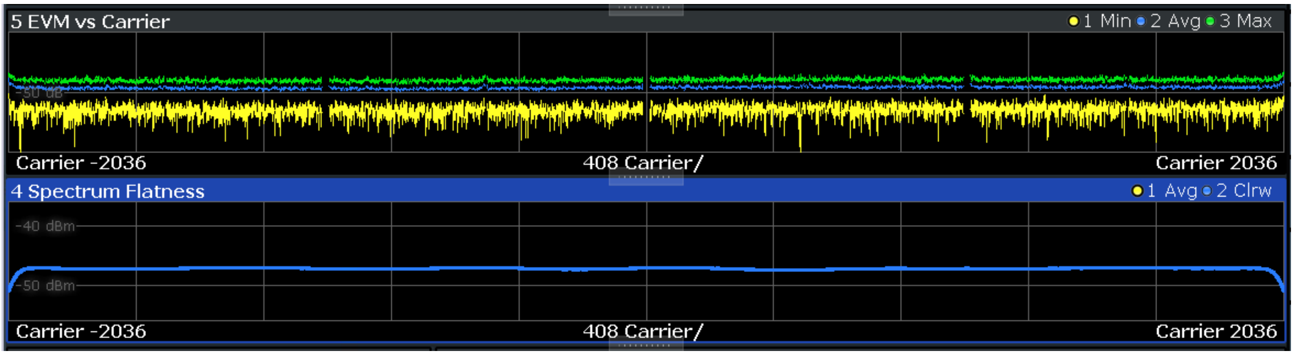
The *Multi-SEM* mode (using several Sub-Blocks for the mask definition) of the *SEM* measurement in the *Spectrum* mode can be used to create a combined mask for punctured signals:



SEM measurement: RU Size 3x994+484 MRU Index 4, 40MHz puncturing 111x1111

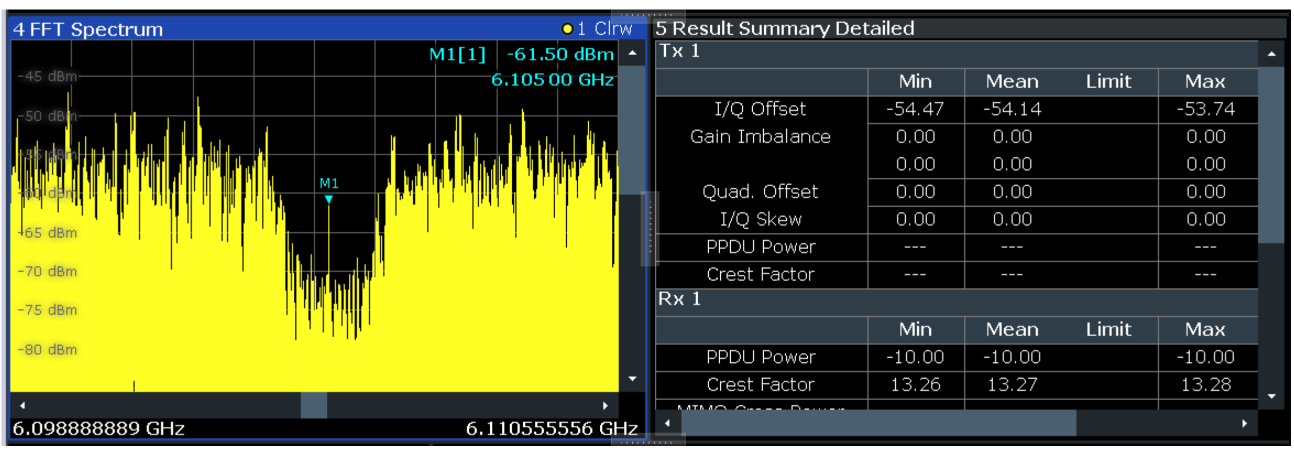
Spectral flatness

The *Spectrum Flatness* trace of the R&S®FSW-K91 WLAN option is derived from the magnitude of the estimated channel transfer function. Since this estimated channel is calculated from all payload symbols of the PPDU, it represents a carrier-wise mean gain of the channel.



Spectrum Flatness measurement

Transmit center frequency leakage



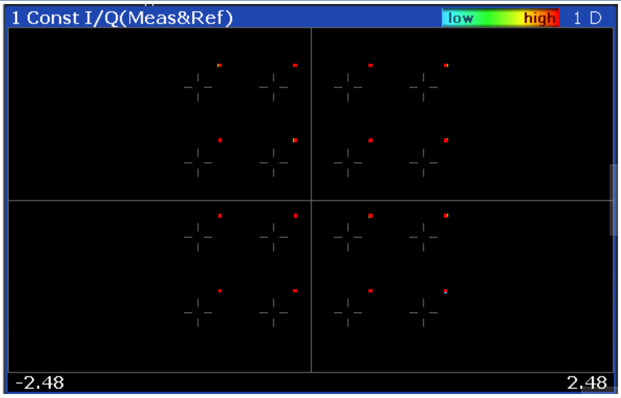
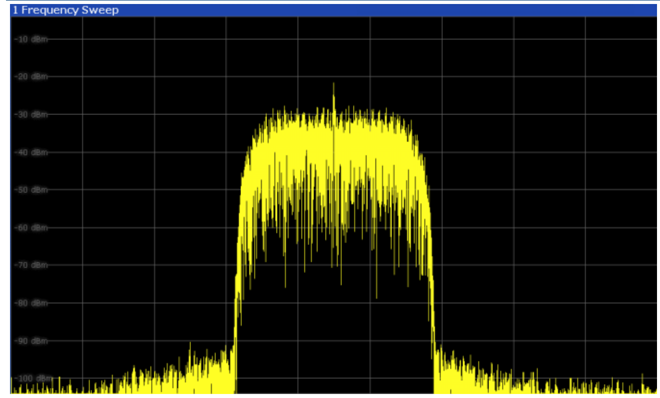
Center frequency leakage measurement

Center frequency leakage is the portion of the transmitter energy that leaks through the transmitter components. This unwanted energy appears in the modulated signal at the signal center frequency which can lead to bad demodulation performance - depending on the receiver implementation.

Often OFDM-based receiver systems utilize some way to remove the carrier leakage. IEEE mandates that the transmitter center frequency leakage does not exceed certain limits.

The center frequency leakage can be observed either directly in the FFT-spectrum or as I/Q Offset measurement in the result summary window.

IQ offsets are typically removed during demodulation in the measurement applications before the constellation diagram is plotted. The following figure illustrates the effect of IQ offsets on a 16 QAM signal using the generic R&S®FSW-K70 Vector Signal Analysis option.

Constellation without IQ offset compensation	Spectrum degraded by IQ offset
	

Example of a 16 QAM signal with 10% I and Q offset

7 Literature

[1] *IEEE 802.11be Technology Introduction,* White Paper: Rohde & Schwarz, 2022.

[2] *White paper: IEEE 802.11ax technology introduction (search for "1MA192"),* Rohde & Schwarz.

[3] Rohde & Schwarz, "Even Faster, An outline of the upcoming 802.11be WLAN standard," *NEWS,* no. 224, pp. 19-21, 2021.

8 Ordering Information

Designation	Type	Order No.
WLAN 802.11be measurements	R&S®FSW-K91BE	1350.6730.02
WLAN 802.11be measurements	R&S®FSV3-K91BE	1346.4966.02
IEEE 802.11be measurements	R&S®VSE-K91BE	1345.1428.06
IEEE 802.11be	R&S®SMW-K147	1413.6677.02
IEEE 802.11be (WinIQSIM2™)	R&S®SMW-K447	1413.6683.02

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1EF114 | Version 0e | 08.2022
Application Note | Hints for IEEE 802.11be EVM Measurements
Data without tolerance limits is not binding | Subject to change