



IEEE Recommended Practice for Estimating the Uncertainty in Error Vector Magnitude of Measured Digitally Modulated Signals for Wireless Communications

IEEE Microwave Theory and Techniques Society

Developed by the
Standards Committee

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STANDARDS

IEEE Recommended Practice for Estimating the Uncertainty in Error Vector Magnitude of Measured Digitally Modulated Signals for Wireless Communications

Developed by the

Standards Committee
of the
IEEE Microwave Theory and Techniques Society

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Abstract: Recommended practices for the evaluation of receiver measurements of error vector magnitude of a digitally modulated wireless communication signal and the evaluation of the associated uncertainty are provided in this recommended practice.

Keywords: digitally modulated communication signal, error vector magnitude (EVM), IEEE 1765™, measurement uncertainty, wireless telecommunications

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Introduction

This introduction is not part of IEEE Std 1765-2022, IEEE Recommended Practice for Estimating the Uncertainty in Error Vector Magnitude of Measured Digitally Modulated Signals for Wireless Communications.

Many wireless telecommunication organizations and standards bodies require the calculation of system-level distortion metrics to evaluate the quality of wireless circuits and systems when they are excited by digitally modulated signals. One such distortion metric is error vector magnitude (EVM). The EVM of a signal is generally estimated from measurement. Knowledge of the uncertainty in the estimate of the EVM of the signal thus aids in the accurate evaluation of the quality of the measured signal.

The recommended practices described here provide guidance on the use of receivers for modulated-signal measurements in the calculation of EVM. This is accomplished through agreed-upon recommended practices for estimating EVM from the measured data and the evaluation of associated uncertainties. This evaluation allows insight into the impact that the receiver has on the estimate of EVM. Knowledge of receiver impact on EVM will help to enable common design criteria and practices for wireless system design, test, and measurement.

Acknowledgments

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IEEE Recommended Practice for Estimating the Uncertainty in Error Vector Magnitude of Measured Digitally Modulated Signals for Wireless Communications

1. Overview

1.1 Scope

This standard provides recommended practices for the determination of uncertainty in the estimation of error vector magnitude (EVM) of a measured digitally modulated wireless communication signal. Such practices include several methods for validating a user's measurement of a specific reference waveform by comparison to a reference measurement. The methods differ based on the level of rigor desired by the user and the accessibility to timing and waveform recording capabilities of the available hardware. Methods for evaluating measurement uncertainty in EVM are also presented. Some of the methods described here focus on measurements and uncertainties related to the use of laboratory-based measurement equipment such as vector receivers, real-time and equivalent-time sampling oscilloscopes and other types of waveform recorders that have access to the measured waveform. This allows time-alignment and gain normalization of measured waveforms prior to the calculation of EVM. Other methods focus on specialized receivers that report symbols directly. As part of the assessment of the measurement hardware and associated uncertainty analyses, this practice includes a mathematically rigorous method for the determination of EVM.

1.2 Purpose

The purpose of this recommended practice is to provide a standardized approach to assess the impact of the receiver hardware performance on a measurement-based estimate of the EVM of a distorted signal. This is done by comparing a user's measurement to a reference measurement of a specific waveform. The reference measurement is intended to provide a well-characterized estimate of the EVM, to which the user's measurement and associated uncertainty are compared. In addition to the IEEE 1765™ baseline approach to estimating EVM, various example approaches to validating receiver measurements of EVM are provided in this recommended practice.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6,7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

JCGM 100:2008, Evaluation of Measurement Data—Guide to the Expression of Uncertainty in Measurement.⁸

Joost, M., “Theory of Root-Raised-Cosine Filter,” <https://michael-joost.de/rrcfilter.pdf>.

Humphreys, D. A., and J. Miall, “Traceable measurement of source and receiver EVM using a real-time oscilloscope,” *IEEE Transactions on Instrumentation and Measurement*, vol. 62, no. 6, pp. 1413–1416, Jun. 2013.^{9,10}

Remley, K. A., D. F. Williams, P. D. Hale, C.-M. Wang, J. Jargon and Y. Park, “Millimeter-Wave Modulated-Signal and Error-Vector-Magnitude Measurement with Uncertainty,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 63, no. 5, pp. 1710–1720, May 2015.

Silva, C., J. Sombrin, P. Manurkar, M. Hudlicka, N. Meyne, and P. Roblin, “1765 Open Source Project. <https://opensource.ieee.org/1765/1765/-/archive/main/1765-main.zip> (supplement to <https://opensource.ieee.org/1765/1765/>).

⁶ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.

⁷ The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.

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3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹¹

Baseline Error Vector Magnitude (EVM) Algorithm: A standardized, data-aided algorithm, developed within IEEE 1765™, that utilizes a known input waveform to estimate EVM of a measured waveform without removing impairments in the signal itself. The algorithm employs the minimum set of corrections necessary to compute EVM: estimation of the intended waveform sampling times, correction for the unknown local oscillator (LO) phase of the transmitter upconverter (if applicable), symbol sampling and gain normalization of the measured signal. As a consequence, the algorithm can be used to verify the level of uncertainty associated with the receiver hardware used to produce the measured waveform.

Baseline Residual Error Vector Magnitude (EVM): The EVM derived from comparing the measurement of a physical signal to a reference-lab measurement of the same signal. Baseline Residual EVM is calculated using the IEEE 1765™ data-aided algorithm as for the Baseline Signal EVM, but replacing the ideal waveform and symbols by the reference-lab-derived waveform and symbols.

Baseline Signal Error Vector Magnitude (EVM): The EVM derived from comparing the measurement of a physical signal to the corresponding ideal signal. Baseline Signal EVM is calculated using the IEEE 1765™ data-aided algorithm, which includes time alignment of the measured waveform to the ideal waveform, followed by complex gain alignment of the symbol-sampled, measured waveform to the symbol-sampled ideal waveform prior to calculation of EVM.

distorted signal: The modulated signal after distortion introduced by various electronic and environmental effects. The IEEE 1765™ Reference Waveforms simulate various types of distortion, including deterministic linear and nonlinear effects, in phase/quadrature (I/Q) imbalance, and sample delay. In some reference waveforms, “deterministic noise” is introduced by using the same seed in an additive white Gaussian noise (AWGN) generator so that it will be repeatable as a waveform.

ideal symbols: Symbols of the ideal constellation used for reference waveform generation.

ideal waveform: A waveform generated without pulse shaping, noise or distortion (can be different from reference waveforms that have been intentionally distorted or have noise added).

IEEE 1765™ measurement verification approaches: A set of comparison-based approaches for assessing measurement-derived EVM. In these approaches, reference and user labs perform measurements of a specific predistorted IEEE 1765™ Reference Waveform emanating from the same signal generator. Data-aided EVM is computed with the Baseline EVM Algorithm, which includes time alignment of the measured waveform to the reference waveform, followed by complex gain alignment of the symbol-sampled, measured waveform to the symbol-sampled reference waveform prior to calculation of EVM. The user EVM measurement, with user-derived uncertainties, is compared to the reference EVM, which, if derived from measurement, has its own uncertainty analysis. Several comparison approaches having various levels of complexity and accuracy are provided in IEEE 1765™.

matched filter: A filter that is used in a receiver to maximize the signal-to-noise ratio (SNR) at optimum symbol sampling times for the received symbols. In an additive white Gaussian noise (AWGN) channel, the frequency response of the matched filter is the complex conjugate of the frequency response of the pulse-shaping filter. Its impulse response is equal to the time-reversed impulse response of the pulse-shaping filter.

measured waveform: The representation (or estimate) of the distorted signal that is provided by the acquisition instrument, typically after calibration for hardware non-idealities.

¹¹*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

measurement validation: Verification, where the specified requirements are adequate for an intended use as documented in JCGM 101:2008 [B31]¹². In the context of IEEE 1765™, measurement validation refers to the process of validating a user's measurement by comparison to a reference measurement.

national metrology institute (NMI): A laboratory, often representing a specific country, that provides metrological traceability to the International System of Units (SI Units).

non-baseline error vector magnitude (EVM): Normalized root mean square (rms) difference between measured, sampled symbols and either ideal (data-aided) symbols or those estimated from a non-data-aided algorithm. The algorithm may apply a number of corrections to the receiver such as in-phase/quadrature (I/Q) offset corrections, frequency offset corrections, etc. The algorithm may or may not be time aligned to other measurements of the same signal. Examples of such algorithms include the minimum-EVM algorithm and proprietary, vendor-specific algorithms (that may or may not include features such as “dc offset removal” or “carrier drift removal” or “I/Q offset removal”).

normalized mean square error (NMSE): A scalar measure of the relative error between two continuous or time sampled real or complex waveforms, wherein the waveforms have been power normalized, time aligned and phase shifted to reduce this error. In the most common and practical time sampled waveform case, NMSE is explicitly given by

$$NMSE = \frac{\sum_{i=1}^K |y_i - x_i|^2}{\sum_{i=1}^K |x_i|^2} = \frac{\sum_{k=1}^K |Y_k - X_k|^2}{\sum_{k=1}^K |X_k|^2}$$

where $x(t_i) =: x_i$ and $y(t_i) =: y_i$, $i = 1, \dots, K$, are the two sampled waveforms of length K , $y(t_i)$ has been optimized with respect to $x(t_i)$ to reflect the aforementioned error minimization, and X_k and Y_k , $k = 1, \dots, K$, represent the discrete Fourier transforms (DFTs) of $x(t_i)$ and $y(t_i)$, respectively. NMSE thus corresponds to the ratio of the error power between the two waveforms normalized by the power in one of the waveforms. It can be expressed as a percentage or in dB, where -10 dB NMSE is equivalent to 10% NMSE. In the theoretical continuous waveform case, the sums become integrals over the time duration T_s with the same power ratio interpretation.

normalized mean-square error (NMSE), baseline: The NMSE calculated after IEEE 1765™ time and complex-gain alignment. In IEEE 1765, the two waveforms could both be measured or one could be measured and one ideal (see 7.5).

Nyquist filtering: The combination of the pulse-shaping filter and the matched filter result in zero inter-symbol interference (ISI) if the combination of filters obey the Nyquist criterion that is expressed either in the frequency domain (the sum of aliased copies of the frequency response is equal to 1) or in the time domain (the response at one symbol sampling time is 1 and is 0 at all other symbol sampling times). Examples of such shaping and matched filters are square-root-raised-cosine and rectangular filters.

oversampling (OS): After mapping the symbols to the complex plane, the waveform is obtained by OS at an integer number of samples per symbol, and then applying the pulse-shaping filter. The over sampling is at least 2, in general 2 to 4 in hardware, and higher for the reference waveforms. This term can also be used to mean that a given time-domain waveform of finite bandwidth is being sampled beyond the classical Nyquist rate (twice the highest non-zero frequency component of the waveform).

pulse-shaping filter: The pulse-shaping or shaping filter transforms a time sequence of Dirac pulses at the symbol frequency, each bearing symbol information, into a continuous (or an oversampled digital) waveform for transmission in a channel. The chosen filter response depends on the channel characteristics such as frequency and bandwidth.

reference lab: The group or person performing the reference measurement that generates the test waveform to be compared to the user measurement for the IEEE 1765™ measurement verification approaches.

reference measurement: The measurement of the distorted signal that is performed by the reference lab, typically after calibration of the acquisition instrument (reference receiver) for hardware non-idealities.

¹² The numbers in brackets correspond to those of the bibliography in Annex G.

reference receiver: An electronic instrument that records a distorted signal to be used as a reference for the IEEE 1765™ measurement verification approaches. The reference receiver has an error analysis associated with its measurements. Examples include an acquisition instrument such as an equivalent-time sampling oscilloscope triggered by the source or a vector signal analyzer (VSA).

reference waveform: The representation of a pulse-shaped modulated signal having various intentionally introduced impairments. The IEEE 1765™ Reference Waveforms are described in 6.1. Among other uses, these waveforms a) facilitate the comparison of EVM algorithms to each other, b) may be used as target waveforms for the experimental determination of EVM, such as in an interlaboratory comparison, and c) may aid in verification of the user's receiver calibration and uncertainty analysis.

signal impairment sets (SISs): The set of IEEE 1765™ Reference Waveforms made available to users of this recommended practice.

signal source: The electronic equipment that produces the modulated electrical signal to be measured, converting a specified waveform to a transmitted signal. This equipment often consists of an arbitrary waveform generator (AWG) and an upconverter, filters, and amplifiers, among other components.

symbol-sampling time: After matched filtering and time alignment of the reference and measured waveforms, the measured waveform is sampled at the symbol clock frequency to retrieve the measured symbols. The time interval between these samples is thus equal to the symbol period.

system-level calibration: Application of calibration coefficients to a measurement of a modulated signal, where the calibration coefficients were determined from prior measurement of external standards such as power through a power-meter measurement and relative phase through a calibrated sampling-oscilloscope measurement.

test waveform: The true, but unknown waveform produced in a given signal-generation test setup intended to realize an IEEE 1765™ Reference Waveform. This physical waveform, even if predistorted, is not identical to the IEEE 1765 Reference Waveforms because it was created with non-ideal signal generation, amplification, and frequency conversion, etc. Thus, the test waveform is the true waveform that is measured by both the reference and user labs in the IEEE 1765 measurement verification approaches.

traceable reference receiver: A characterized reference receiver in which the error analysis provides traceability to fundamental physical quantities.

user lab: The group or person performing the user measurement of the test waveform in the IEEE 1765™ measurement verification approaches.

user receiver: An electronic receiver under test that records a distorted signal for the IEEE 1765™ measurement verification approaches. The user receiver may or may not have an error analysis associated with its measurements.

waveform-sampling time: The sampling time of the analog IF/RF waveform utilized by an acquisition instrument. For IEEE 1765™, the waveform sampling time yields an oversampled waveform.

3.2 Acronyms and abbreviations

ADC	analog-to-digital converter
AM	amplitude modulation
AWG	arbitrary waveform generator
AWGN	additive white Gaussian noise
CCDF	complementary cumulative distribution function
DFT	discrete Fourier transform

DNL	differential nonlinearity
DUT	device under test
ENOB	effective number of bits
EOS	electro-optic sampling
EVM	error vector magnitude
FBMC	filter bank multicarrier
IBO	input back off
ICI	inter-carrier interference
IDFT	inverse discrete Fourier transform
INL	integral nonlinearity
I/Q	in-phase/quadrature
ISI	inter-symbol interference
LNA	low noise amplifier
LO	local oscillator
NMI	national metrology institute
NMSE	normalized mean square error
NPR	noise power ratio
NRZ	non-return to zero
OBO	output back off
OFD	official frequency domain
OFDM	orthogonal frequency division multiplex
OS	oversampling
PAPR	peak-to-average power ratio
PDD	photodiode detector
PDF	probability distribution function
PM	phase modulation
PRN9	pseudo-random noise of length $2^9 - 1 = 511$ bits
QAM	quadrature amplitude modulation

RF	radio frequency
rms	root mean square
RRC	root raised cosine
RX	receiver
S&H	sample and hold
SI	The International System of Units
SINAD	signal-to-noise and distortion
SIS	signal impairment set
SNR	signal-to-noise ratio
TAA	time-alignment algorithm
TBD	time-base distortion
TDMA	time division multiple access
TWTA	traveling wave tube amplifier
TX	transmitter
UMTS	Universal Mobile Telecommunications Service
VNA	vector network analyzer
VSA	vector signal analyzer
VSWR	voltage standing wave ratio

3.3 Table of symbols

Table 1—Table of symbols

Symbol	Description
B	Spectral angular frequency bandwidth of signal ($B = 2\pi/\Delta t$)
$\Delta\omega = 2\pi/T_s, \Delta f = 1/T_s$	Discrete spectrum angular and regular frequency spacing of waveform
$\Delta t, R_s$	Waveform-sampling time interval, waveform-sampling rate ($R_s = 1/\Delta t$)
$e_n = e(nT)$	Error between measured symbol and reference symbol for data-aided case
$e_{\text{rec}}(nT)$	Error between measured symbol and reference symbol for non-data-aided case (see Figure 1)
$f, f_k = (k-1)\Delta f$	Continuous and discrete regular frequency variables
G_0	Optimum gain for EVM time-alignment computation (multiplies user measurement)
$G_{\text{OPT}}, s_n = G_{\text{OPT}} r_n + e_n$	Optimum gain for symbol-sampled EVM time-alignment computation (multiplies received symbols)
$h^{\text{RX}}(t_i) = h_i^{\text{RX}}, H^{\text{RX}}(\omega_k) = H_k^{\text{RX}}$	Matched filter impulse response and frequency response (discrete)
$h^{\text{TX}}(t_i) = h_i^{\text{TX}}, H^{\text{TX}}(\omega_k) = H_k^{\text{TX}}$	Pulse-shaping filter impulse response and frequency response (discrete)
i	Index for samples in the signal
k	Index for samples in the spectrum
K	Number of samples in the signal and spectrum
L	Number of repetitions of periodic sequence
m	Number of bits in the symbol
M	Number of points in the constellation ($M = 2^m$)
n	Index for the symbols
N	Number of symbols in periodic sequence
N_{OS}	Number of samples per symbol (OS ratio) $N_{\text{OS}} = K/LN$
$\omega, \omega_k = (k-1)\Delta\omega$	Continuous and discrete angular frequency variables
$r_n = r(nT); R(\omega), R(\omega_k) = R_k$	Received symbols, symbol-sampled waveform and spectrum (continuous, discrete)*
R	Symbol-sampling rate ($R = 1/T$) (Note: in 1765-2022, 1 sample per symbol is used for computation of EVM)
$s_n = s(nT)$	Ideal symbols for data-aided case
$s_{\text{rec}}(nT)$	Ideal symbols recovered from constellation diagram in non-data-aided case (see Figure 1)
$s(t), s(t_i); S(\omega), S(\omega_k) = S_k$	Ideal signal and spectrum before the matched filter (continuous, discrete)
$t, t_i = (i-1)\Delta t$	Continuous and discrete time variables

Symbol	Description
T	Duration of the symbol
T_s	Duration of signal (e.g., the duration of the envelope, NLT)
τ_0	Optimum delay for waveform time alignment
$u(t), u(t_i) = u_i; U(\omega), U(\omega_k) = U_k$	Fine time aligned waveform and spectrum (continuous, discrete)
$x(t), x(t_i); X(\omega), X(\omega_k) = X_k$	Ideal signal and spectrum after the matched filter (continuous, discrete)
$x^{\text{PreD}}(t), x^{\text{PreD}}(t_i) = x_i^{\text{PreD}};$ $X^{\text{PreD}}(\omega), X^{\text{PreD}}(\omega_k) = X_k^{\text{PreD}}$	Predistorted waveform and spectrum (continuous, discrete)
$x^{\text{Ref}}(t), x^{\text{Ref}}(t_i) = x_i^{\text{Ref}};$ $X^{\text{Ref}}(\omega), X^{\text{Ref}}(\omega_k) = X_k^{\text{Ref}}$	Reference waveform and spectrum (continuous, discrete)
$x^{\text{TX}}(t), x^{\text{TX}}(t_i) = x_i^{\text{TX}};$ $X^{\text{TX}}(\omega), X^{\text{TX}}(\omega_k) = X_k^{\text{TX}}$	Transmitted waveform and spectrum (continuous, discrete)
$y(t), y(t_i) = y_i; Y(\omega), Y(\omega_k) = Y_k$	Measured waveform and spectrum before matched filter (continuous, discrete)
$z(t), z(t_i) = z_i; Z(\omega), Z(\omega_k) = Z_k$	Measured waveform and spectrum after matched filter (continuous, discrete)

*The symbols in time are discrete, at the symbol-sampling time. The spectrum is continuous if the sequence of symbols is not periodic and the spectrum is discrete if the sequence of symbols is periodic.

4. Overview of the IEEE 1765 approach for evaluating EVM and associated uncertainty from receiver measurements.

4.1 Background

The recommended practices described here provide a standardized approach for the estimation of EVM from measurement and facilitate the evaluation of uncertainty related to the receiver hardware in the estimate of the EVM by comparison to a reference measurement of a standardized IEEE 1765 Reference Waveform. This approach provides insight into the impact that distortion introduced by the receiver hardware has on the estimate of EVM. A standardized Baseline EVM Algorithm allows isolation of receiver hardware effects on reported EVM by eliminating algorithmic corrections of the signal that can reduce EVM. To achieve this, the Baseline EVM Algorithm includes only the minimum set of steps needed to calculate EVM.

The comparison approach provided in this recommended practice provides user labs with confidence in both the accuracy of their measurements and the ensuing evaluation of the uncertainties of the measurement. Baseline EVM Algorithms with additional corrections are provided as a tool to explore further the differences between the two compared measurements, the instruments that made those measurements, and the algorithms employed by those instruments. The IEEE 1765 Reference Waveforms and Baseline EVM Algorithm are provided as part of this recommended practice, as are example methods for the evaluation of uncertainty in EVM measured by receivers. In one of these methods, components of uncertainty can be correlated, while in the other, the components of uncertainty are assumed to be noise-like and uncorrelated. The methods presented here are only intended to serve as examples.

4.2 Determining EVM from measurement

EVM is a metric that is used to assess distortion that is introduced into a measured digitally modulated communication signal after it has passed through a physical system such as an electronic component or a

channel. The EVM of a measured radio frequency (RF) signal is calculated from demodulated symbols, minimally after frequency downconversion (if applicable), filtering, symbol extraction (sampling) and normalization. To estimate the EVM of a distorted signal, the symbol values determined from the recorded samples of the received signal are compared to ideal symbol values by use of an EVM algorithm. Problems related to traceable determination of EVM have been outlined in, for example, Hudlíčka [B17].

In this recommended practice, the EVM associated with each measured symbol, $r(nT)$, is calculated with respect to the corresponding ideal symbol, $s(nT)$. The EVM for this symbol is defined as $|e(nT)|/|\gamma|$, where γ is a complex normalizing factor, containing both amplitude scaling and phase correction terms. $|\gamma|$ is conventionally set to the root-mean-square of the magnitudes of the entire reference symbol sequence. Because the features and sampling times of the waveform to be measured are also known in advance, this is referred to as a “data-aided” scenario. The data-aided scenario, which is commonly used in a controlled laboratory environment and for high values of EVM, is employed in IEEE 1765 in order to study the effects of noise and distortion in the measurement hardware and/or from a user’s EVM algorithm.

In many applications, such as test instruments where the ideal symbol value is not known, a “recovered symbol,” $s_{rec}(nT)$, is used. The recovered symbol location is geometrically closest to the measured symbol, giving the lowest EVM value. EVM_{rec} is defined as $|e_{rec}(nT)|/|\gamma|$. This case is often referred to as a “non-data-aided” scenario. Non-data-aided EVM algorithms are commonly used in realistic test and operational scenarios in which communications receivers first demodulate signals into information symbols.

The relationship between ideal, measured and recovered symbols is geometrically defined in Figure 1(a) as a constellation diagram. The difference between EVM calculated from ideal symbols and recovered symbols for the 16-quadrature amplitude modulation (QAM) signal shown in Figure 1(a) is plotted in Figure 1(b).

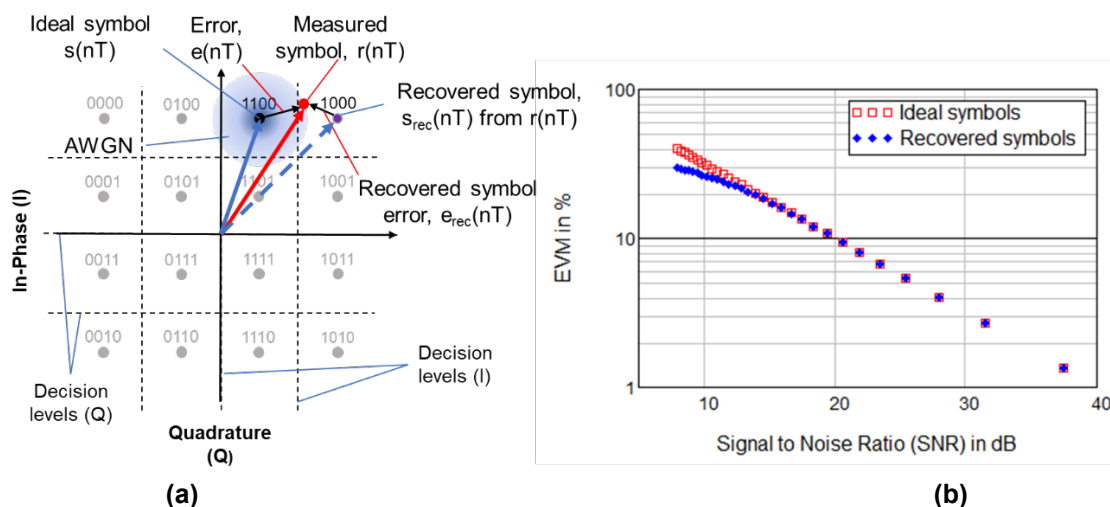


Figure 1—(a) Ideal symbol, measured symbol, recovered symbol and error vectors for a 16-QAM signal. (b) The difference between EVM calculated from ideal symbols and recovered symbols as a function of SNR for the same 16-QAM signal shown in (a).

Figure 2 illustrates a scenario from which the EVM of a measured RF signal can be derived. As illustrated in Figure 2, the EVM of the Distorted Signal is derived from measurement in post processing by use of an EVM Algorithm that performs signal processing, sampling, normalization, and computes the EVM. Contributors to EVM consist of distortion introduced by both the signal generation components as well as

the device under test (DUT) or channel. Distortion can also be introduced into the measured signal by the receiver hardware and/or by the algorithm used to calculate EVM. When not corrected through, for example, receiver calibration, this distortion contributes to the uncertainty in the estimate of EVM. Goals of IEEE 1765 include separately identifying the distortion caused by the receiver and the EVM algorithm, as well as estimating the uncertainty in an estimate of EVM based on residual errors in measurements made with imperfect hardware.

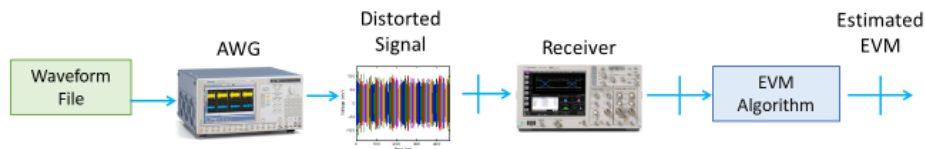


Figure 2—Estimation of EVM from a receiver measurement of a distorted signal and EVM algorithm

4.3 Overview of the standardized IEEE 1765 approach

Many textbooks and standards present methods for estimating EVM that arises from distortion introduced by a DUT or channel. However, there are very few publications that describe methods to check the validity of the EVM obtained from a given lab's measurement and/or post-processing procedures. Such validation, along with determination of the related measurement uncertainty, is the goal of the IEEE 1765 approach. This recommended practice document provides several methods to assess the contribution of a user's receiver hardware and a user's EVM algorithm to the estimate of EVM by comparison to EVM from a reference system. These methods require that the user first correct receiver impairments in a calibration step and then assign uncertainties to account for remaining receiver errors that could not be corrected in the calibration and measurement process. Comparing nominal (computed) values of EVM and associated uncertainties allows the user lab to validate its measurements and uncertainty analyses with respect to those made by a reference lab.

Such measurement comparisons for validation of a measurement-derived quantity such as EVM are well accepted as best-practice approaches. For example, note 6.5.3 part (b) from ISO/IEC 17025:2017 [B27]:

When metrological traceability to the SI units is not technically possible, the laboratory shall demonstrate metrological traceability to an appropriate reference, e.g.: a) certified values of certified reference materials provided by a competent producer; b) results of reference measurement procedures, specified methods or consensus standards that are clearly described and accepted as providing measurement results fit for their intended use and ensured by suitable comparison.

To evaluate the quality of the user's estimate and associated uncertainty, the IEEE 1765 approach compares the user's derived EVM to that derived from a reference system for the same signal. The reference measurement and post processing is, ideally, performed by a national metrology institute (NMI) or other reference laboratory. The reference lab receiver to be used in the measurement comparison is calibrated in magnitude, phase, and impedance, often through the use of transfer standards that are traceable to the International System of Units (SI). This is typically done independently from the IEEE 1765 comparison. For this comparison, the data-aided Baseline EVM Algorithm is applied to both measured signals.

It is essential to hold as many variables in the measurement process constant as possible. Thus, the user and reference laboratories perform calibrated measurements of the same test waveform emanating from the same physical signal generator. One approach for this is illustrated in Figure 3. Because EVM values for both labs are calculated with the standardized Baseline EVM Algorithm, the only significant difference between measurements corresponds to differences in the receiver hardware.

Key to this measurement comparison approach is the Baseline EVM Algorithm. The purpose of the Baseline EVM Algorithm is to estimate the EVM of the physical signal that was incident on the receiver's reference plane, *without correcting for non-idealities in that signal*. Thus, the Baseline EVM Algorithm is deliberately designed not to correct for, and thereby obscure, impairments in the measured signal such as in phase/quadrature (I/Q) offset and frequency drift. This distinguishes it from many commercial EVM algorithms, which are designed to correct for numerous impairments in both the signal and receiver hardware simultaneously with the goal of minimizing EVM and best determining the transmitted bit stream.

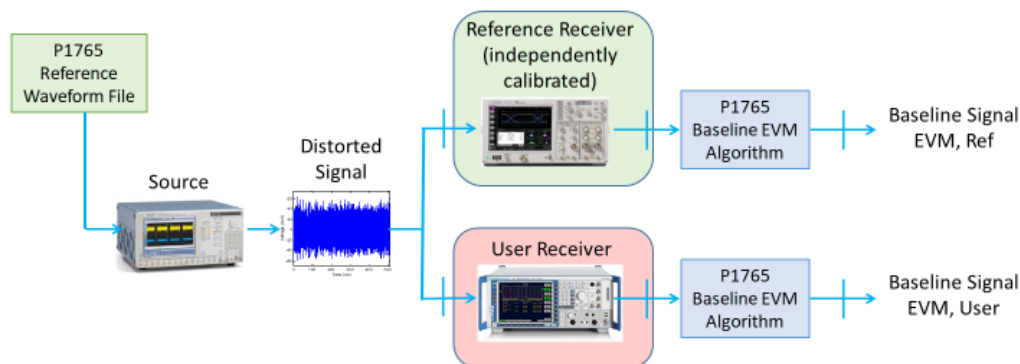


Figure 3—General approach used in IEEE 1765 to identify contributions of receiver hardware and EVM algorithm to uncertainty in a user's estimate of EVM in a distorted signal. In practice, the signal emanating from the source is often predistorted by the reference lab to compensate for imperfections introduced by the source hardware. The reference and user receivers then measure the same predistorted test waveform.

Note that the Baseline EVM Algorithm does not necessarily provide the minimum EVM that may be obtained from measurement. For a calculation performed on the same signal, the EVM value from the Baseline EVM Algorithm is often similar to, but never less than, the minimum EVM value.

The Baseline EVM Algorithm is described in detail in Clause 5, with 5.1 devoted to single-carrier modulation and 5.2 to orthogonal frequency division multiplex (OFDM) waveforms that utilize multiple subcarriers. Every lab that applies the Baseline EVM Algorithm should obtain the same EVM (to within machine precision, which represents the smallest difference between two numerical values that can be identified) when inputting the same waveform file. To this end, a set of standardized IEEE 1765 Reference Waveforms have been created that are available for download (see Annex A), and the code for implementing the Baseline EVM Algorithm and the OFDM Baseline EVM Algorithm is made available as part of this document (see the IEEE 1765 Open Source Project¹³).

The IEEE 1765 Reference Waveforms and predistortion of these waveforms that is often required when they are generated in hardware are described in Clause 6. The IEEE 1765 Reference Waveforms are a central component of the IEEE 1765 approach for assessing both the reference and user receiver measurements and EVM estimates. The reference waveforms are also used in the comparison of EVM algorithms and to explore differences between various IEEE 1765 EVM algorithms and individual, lab- or company-specific EVM algorithms. The predistortion process is often required when generating the reference waveforms using a physical signal generator and frequency conversion hardware. The reference laboratory iteratively measures and modifies the waveform file until the electrical signal emanating from the signal generator matches the desired waveform to within a specified tolerance (or as limited by the uncertainty of the reference receiver).

¹³ Information on references can be found in Clause 2.

The measurement comparison process is described in Clause 7 for several different scenarios. Which scenario to choose depends on a number of factors, including whether or not the user has access to the waveform data from the receiver and whether or not a user wishes to compare measurements with a reference lab or to a reference waveform, where the former can provide additional insight into the distortion introduced by the receiver hardware.

As mentioned above, both the estimate of EVM, derived from calibrated receiver measurements by use of the Baseline EVM Algorithm, and an associated uncertainty analysis are required for the validation procedure. Clause 8 provides two methods for determining the uncertainty in the resulting EVM in which correlations may exist within or between components of uncertainty (Method 1) or for cases where the components of uncertainty can be considered as noise-like and uncorrelated (Method 2). Calibration approaches are discussed in informative annexes.

The IEEE 1765 methodology also accommodates extensions to its Baseline EVM Algorithm that include additional corrections not performed by the Baseline EVM Algorithm. For example, frequency drift and I/Q offset corrections are often employed in commercial implementations to correct for impairments in either the transmitted or received signal. A Baseline EVM Algorithm extended to correct for I/Q offset would be called “The Baseline EVM Algorithm with I/Q Offset Correction” under the naming convention described in Clause 5 to distinguish it from the Baseline EVM Algorithm. These additional algorithms, described in Clause 9, can help users identify sources of impairments in their transmitters and provide a library of known approaches for correcting various impairments.

5. The Baseline EVM Algorithms

The goal of the Baseline EVM Algorithm approach is to compute the EVM between two symbol sequences, where at least one of these sequences is derived from measurement. The result is an evaluation of the acquisition performance of the receiver’s hardware, as opposed to an evaluation of its ability to best decode the data carried by the signal. Thus, the Baseline EVM Algorithm compares the two symbol sequences at the intended constellation points and specified symbol-sampling times and does not attempt to correct for other impairments that can be present in the measured signal, such as frequency offset or I/Q imbalance. This allows an assessment of the “raw” hardware performance of a receiver before other impairments are corrected for by signal-processing techniques.

The Baseline EVM Algorithm and the OFDM Baseline EVM Algorithm determine EVM from two sets of symbols, where, as in most EVM calculations, one set of symbols serves as a reference to which the other is compared. In IEEE 1765, reference symbols are derived directly from an IEEE 1765 Reference Waveform or derived from a measured waveform. The second set of symbols is derived from a measurement performed by either a Reference or a user laboratory. The appropriate Baseline EVM Algorithm is then used to obtain EVM for the reference lab or user lab measurement. Providing a standardized EVM calculation algorithm facilitates comparison of EVM from various instruments. When two instruments measure the same waveform, the Baseline EVM Algorithm should be used to compare EVM or find Baseline Residual EVM (defined in Clause 3) using one of the several techniques described in Clause 7.

To facilitate the identification of receiver hardware errors, the Baseline EVM Algorithms do not correct for impairments in the signal itself. Thus, the Baseline EVM Algorithm only employs the minimum set of corrections necessary to compute EVM. For the single-carrier case, this consists of estimation of the intended waveform-sampling times, time alignment (which also corrects for the unknown LO phase of the transmitter upconverter), symbol sampling and normalization of the measured signal. For the OFDM case, the process additionally includes removal of cyclic prefixes, guard interval and shaping, followed by an N-point discrete Fourier transform (DFT), parallel-to-serial conversion, and pilot tone removal. The Baseline EVM Algorithms are data-aided to allow them to best estimate the EVM of the measured signal without correcting for receiver impairments. The algorithm was implemented in a simple but rigorous way using commonly available mathematical methods. We start by describing the single-carrier version of the

Baseline EVM Algorithm, and then describe the additional elements necessary to implement the OFDM Baseline EVM Algorithm.

5.1 The Baseline EVM Algorithm for single-carrier modulation formats

We refer to the single-carrier implementation as simply the Baseline EVM Algorithm. Its extension to the multi-carrier OFDM modulation format is described in 5.2. As illustrated in Figure 4, the Baseline EVM Algorithm provides an estimate of the EVM of a measured, repetitive, baseband, oversampled, filtered signal $z(t)$ with discrete spectrum $Z(\omega)$, given a finite-duration, filtered input signal $x(t)$ with discrete spectrum $X(\omega)$. If the input signal is generated by a physical signal source, it is often predistorted to correct for internal hardware impairments in the source and, hence, is termed $x^{\text{PreD}}(t)$. Generation and, if necessary, predistortion of the input signal are discussed in Clause 6. Three preprocessing steps that may be required prior to the application of the Baseline EVM Algorithm to the measured signal $y(t)$ are to convert $y(t)$ to the frequency domain $Y(\omega)$ (5.1.1.1), to down convert RF signals to baseband (5.1.1.2), and to resample the measured signal (5.1.1.3). These steps are discussed below. The Baseline EVM Algorithm steps are then: optimally time-align the signals; sample the symbols; align their LO phases and gains; and calculate the EVM of the signal. This procedure is illustrated in Figure 4 and Figure 5.

NOTE—For the “Align” operations, the upper input signal is time shifted or amplitude normalized to the lower input signal.¹⁴

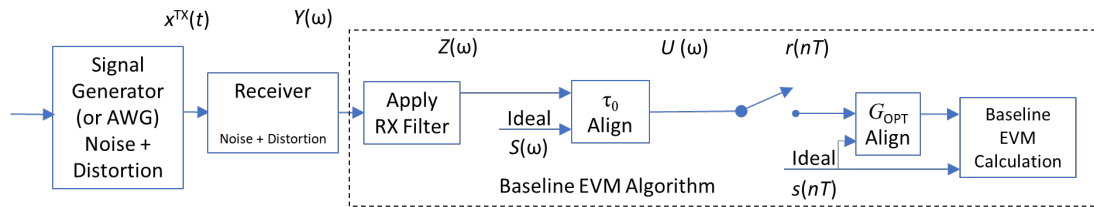


Figure 4—Block diagram illustrating the calculation of Baseline EVM for a user or reference lab where (see Table 1) $Y(\omega)$ is the spectrum of the oversampled received signal, $Z(\omega)$ is its match-filtered spectrum, $S(\omega)$ is the spectrum of the ideal signal without RX or TX match filtering, $U(\omega)$ is the spectrum of the fine-time-aligned signal, $r(nT)$ is one symbol from the symbol-sampled waveform, and $s(nT)$ is the corresponding ideal symbol from the symbol-sampled ideal signal. Symbol sampling is indicated by the switch.

¹⁴ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

$$\text{EVM} = \sqrt{\frac{\sum_{n=1}^N |y_n - x_n|^2}{\sum_{n=1}^N |x_n|^2}} = \sqrt{\frac{\sum_{k=1}^N |Y_k - X_k|^2}{\sum_{k=1}^N |X_k|^2}}$$

Baseline EVM Calculation

N = number of symbols

Figure 5—Baseline EVM Calculation, where y_n and x_n are two symbol sequences that can be ideal or derived from IEEE 1765 Reference Waveform files, measured waveforms, or other sources.

The steps required for determination of EVM with the data-aided Baseline EVM Algorithm are somewhat different than those for the classical non-data-aided case because, in the IEEE 1765 case, the ideal signal and its symbol-sampling times are already known. In the classical non-data-aided case, the symbol-sampling times are typically derived by synchronizing the nominal transmitted frequency with the symbol rate by use of a phase-locked loop. The data-aided case used here is intended to identify receiver hardware non-idealities by use of the comparison process described in Clause 7. Identifying such distortion is the focus of this recommended practice.

In the following description of the Baseline EVM, the EVM is calculated from symbols derived from two waveforms. Symbols derived from Waveform 1 provide a reference to which symbols from Waveform 2 are compared. Typically, Waveform 1 corresponds to an IEEE 1765 Reference Waveform or a waveform derived from a reference-lab measurement, as discussed in Clause 7. Preprocessing steps are described first, followed by the baseline EVM steps.

5.1.1 Preprocessing steps

5.1.1.1 Perform measurements and transform digitized temporal samples to frequency domain

The received signal $y(t)$ is the output of the receiver. In some cases, this waveform is measured by a frequency-domain instrument. However, when measured by a temporal instrument, the digitized temporal samples are first converted to the frequency domain. This is done both to simplify mismatch and instrument-response corrections and because there is a unique frequency-domain representation for the waveform (i.e., independent of the waveform sampling approach used in the signal-acquisition instrument).

In the IEEE 1765 approach, temporal measurements are oversampled at the “waveform-sampling time” (see Clause 3) and should be averaged to reduce random noise introduced as part of the measurement process (as opposed to “deterministic” noise introduced into some of the IEEE 1765 Reference Waveforms). Acquiring an integer number of samples in the RF or envelope domains can help reduce spectral leakage during the transformation to the frequency domain. An outline of the IEEE 1765 recommended measurement procedure for temporal transformation to the frequency domain is included as follows:

- a) Measurement procedure
 - 1) Sample the entire waveform. This is possible because signals are strictly repetitive and have discrete spectra.
 - 2) Acquire four or more samples per RF cycle to provide oversampling (OS) of the waveform.

- 3) If possible, measure the signal multiple times to further increase averaging and facilitate determination of the component of uncertainty due to measurement repeatability.
- b) Measurement-specific processing
 - 1) If needed, correct each measurement for time-base distortion.
 - 2) If needed, apply drift correction to each measurement before averaging repeat measurements.
 - 3) Transform to the frequency domain.

5.1.1.2 Downconvert the measured waveforms

Many commercial instruments such as vector signal analyzers (VSAs) downconvert and filter with mixers before sampling the waveform. This allows for rapid one-shot data acquisition. Frequency downconversion of a measured waveform made with a commercial instrument is typically accomplished by algorithms internal to the instrument.

To provide the reference measurement, many NMIs measure directly at RF to simplify the traceability path using instruments such as equivalent-time sampling oscilloscopes. For a direct RF measurement, there is no need to characterize the frequency converter and filter transfer functions in the traceability path. The trade-off here is that measuring directly at RF will have degradations in both analog digital converter (ADC) resolution and frequency timing compared to a low IF or baseband measurement afforded by frequency downconversion. In addition, these degradations only increase with frequency.

If either the user-lab- or reference-lab-measured waveform is an RF signal, the discrete components of the signal that fall within the signal's intended bandwidth are down converted numerically to baseband. This is usually only required when performing oversampled temporal measurements of an RF signal directly with calibrated sampling oscilloscopes or other such measurement instruments. To perform the RF-to-baseband translation, the user would identify the RF Fourier coefficients within the bandwidth of the matched filter and subtract the carrier frequency. This effectively filters out-of-band components with a rectangular filter.

5.1.1.3 Resample the measured signal

Measured waveforms are typically oversampled as mentioned in 5.1.1.1 in the measurement procedure. Numerically generated waveforms may have other sampling rates. To compute EVM using most numerical software packages, the two waveforms need to be sampled at the same rate, or, in other words, the two waveform vectors need to be of the same length. Therefore, the waveforms should be resampled before employing the Baseline EVM Algorithm.

5.1.2 Step-by-step description of the Baseline EVM Algorithm

5.1.2.1 Filter the baseband signals

Many modern digital modulations use a (square) root-raised-cosine filter (see, for example, Section 8.9 of Jeruchim, Balaban, and Shanmugan [B29]) for generating and receiving modulated signals. If the sampled symbols are represented by Dirac pulses having complex amplitude (the message) at the appropriate symbol-sampling intervals (and 0 between the pulses), the application of an RX filter that matches the TX filter produces a power-limited signal that can be used to modulate an RF carrier. The RX filter frequency response should be the conjugate of the frequency response of the filter applied to the transmitted signal for optimum extraction of the received signal from white additive noise. When the product of both frequency responses obeys the Nyquist conditions, there is no inter-symbol interference (ISI) between the recovered symbols.

The baseband signal whose EVM value is to be computed has a discrete spectrum $Y(\omega)$. This signal is filtered in the frequency domain with the matched filter intended for the modulation type being used to obtain the filtered spectrum $Z(\omega)$.

5.1.2.2 Optimal time alignment of Waveform 2 to Waveform 1 and removal of constant phase offset

The optimal solution for estimating the temporal offset of the two signals to be compared by the Baseline EVM Algorithm depends on the source of the errors in the two signals and their correlations, and there is no single solution to this problem. Thus, the Baseline EVM Algorithm optimally aligns the amplitude, local-oscillator phase and time offset of two communication signals with baseband spectra Y_1 and Y_2 under the assumption that the noise in the signals is independent and identically distributed complex Gaussian. This procedure is described in detail in Annex B.

5.1.2.2.1 Coarse time alignment

Perform a coarse time alignment of the measured and reference signals to help ensure that the time-alignment algorithm finds the global minimum. The coarse time-alignment algorithm is based on a cross-correlation in time.

5.1.2.2.2 Fine time alignment

For fine time alignment, the algorithm minimizes the error function $E(G, \tau)$:

$$E(G, \tau) = \sum_{k=1}^K \left| X_k^{\text{Ideal}} - G Z_k e^{j(k-1)\Delta\omega\tau} \right|^2 \quad (1)$$

where

G	is a complex gain
τ	is the delay that best aligns the two signals X^{Ideal} and Z
K	is the number of waveform-sampled points in the finite duration signals
$\Delta\omega = \frac{2\pi}{T_s}$	is the angular frequency corresponding to the repetition rate of the modulated signals.

For the measurement comparison scenarios in Clause 7, note that:

- In Figure 11, X^{Ideal} would correspond to S (see Table 1) and Z to Z .
- In Figure 12, X^{Ideal} would again correspond to S , but Z now corresponds to Z_2 .
- In Figure 13 and Figure 14, there are two τ_0 -alignment operations. In the lower one, X^{Ideal} would correspond to S and Z to Z_2 , while in the upper one, X^{Ideal} would correspond to U_2 and Z to Z_1 .
- In Figure 16, X^{Ideal} would correspond to Y_2 and Z to Y_1 .

To minimize the error function $E(G, \tau)$, we write it as an analytic function

$$E(G, \tau) = \sum_{k=1}^K \left(X_k^{\text{Ideal}} - G Z_k e^{j(k-1)\Delta\omega\tau} \right) \left(X_k^{*\text{Ideal}} - G^* Z_k^* e^{-j(k-1)\Delta\omega\tau} \right) \quad (2)$$

and set the derivatives of E with respect to G and τ equal to 0. That is, we search for the optimum values G_0 and τ_0 satisfying

$$\frac{\partial E(G, \tau)}{\partial G} \Big|_{G_0, \tau_0} = -\sum_{k=1}^K Z_k \left(e^{j(k-1)\Delta\omega\tau_0} X_k^{*\text{Ideal}} - G_0^* Z_k^* \right) = 0 \quad (3)$$

and

$$\frac{\partial E(G, \tau)}{\partial \tau} \Big|_{G_0, \tau_0} = 2\text{Im} \left(G_0 \sum_{k=1}^K (k-1)\Delta\omega Z_k X_k^{*\text{Ideal}} e^{j(k-1)\Delta\omega\tau_0} \right) = 0 \quad (4)$$

Equation (3) allows G_0 to be written in terms of τ_0 as

$$G_0 = \frac{\sum_{k=1}^K X_k^{\text{Ideal}} Z_k^* e^{-j(k-1)\Delta\omega\tau_0}}{\sum_{k=1}^K |Z_k|^2} \quad (5)$$

and Equation (4) then yields the key result

$$\text{Im} \left[\left(\sum_{k=1}^K (k-1) (X_k^{\text{Ideal}})^* Z_k e^{j(k-1)\Delta\omega\tau_0} \right) \left(\sum_{k=1}^K X_k^{\text{Ideal}} Z_k^* e^{-j(k-1)\Delta\omega\tau_0} \right) \right] = 0, \quad (6)$$

which is solved by an iterative approach (see Annex B.2). Convergence criteria for this approach is the working numerical precision of the computer.

5.1.2.3 Symbol sampling

Now that the reference-lab and user-lab measured waveforms are time aligned, the user-lab measured waveform is symbol-sampled at the same times used to symbol-sample the test waveform. The RX filter was designed to help minimize noise at these sample times.

5.1.2.4 Determine the complex gain G_{OPT} and normalization

All EVM algorithms include magnitude and LO phase compensation of the constellation diagram, and that step is now accomplished in the Baseline EVM Algorithm by refining the estimate of the complex gain G_0 determined earlier. Now that the symbol-sampling times have been chosen in a way that best aligns them with the test waveform, the user lab determines the complex gain G_{OPT} that best captures the difference in the magnitudes and the LO phases of the two symbol-sampled signals. Using only the symbol-sampling times determined in the last step in the optimization process allows the user lab to take advantage of the reduction of noise there and to be consistent with the definition of EVM. This is accomplished by symbol-sampling the signals¹⁵, recomputing their spectra $\tilde{X}_k^{\text{Ideal}}$ and $\tilde{Z}_k$ based only on the N symbol-sampling times, and applying Equation (5) again. Thus, G_{OPT} is given by

$$G_{\text{OPT}} = \frac{\sum_{n=1}^N \tilde{X}_n^{\text{Ideal}} \tilde{Z}_n^* e^{-j(n-1)\Delta\omega\tau_0}}{\sum_{n=1}^N |\tilde{Z}_n|^2} \quad (7)$$

where

G_{OPT} is the refined value of the complex gain.

¹⁵ Determining the final LO offset and amplitude normalization is consistent with the conventional way in which EVM is calculated.

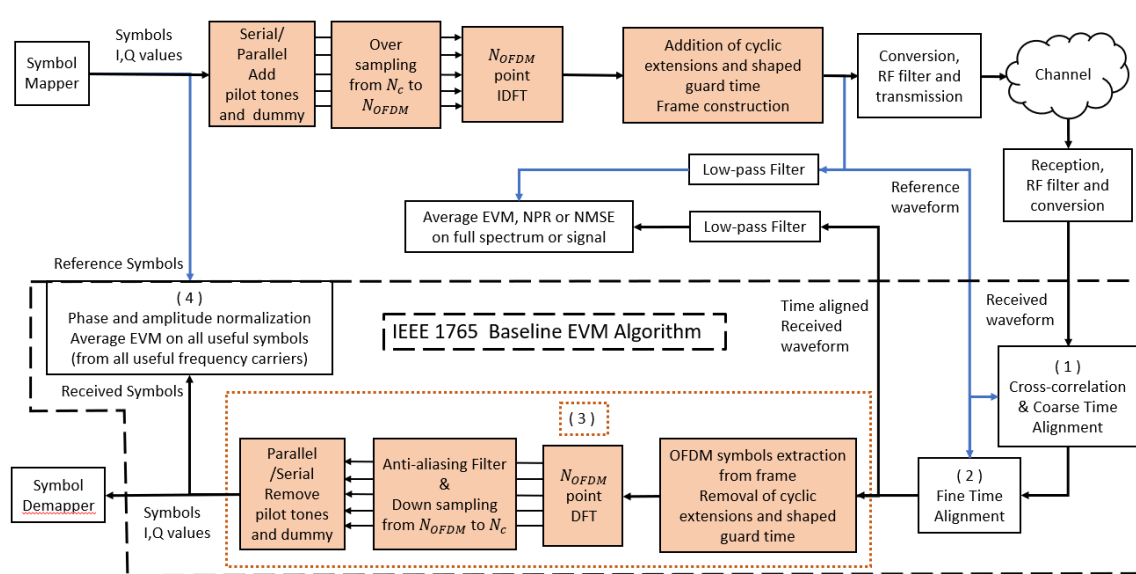
5.1.2.5 Determining the EVM of the user-lab and reference-lab measured waveforms

Now the EVM of the sampled signals should be calculated by comparing the actual values of the two signals to the intended constellation points for the signals. The full details of this algorithm and its code implementation, operation, and results are given in Annex A. The actual code is made available in the IEEE 1765 Open Source Project.

5.2 The Baseline EVM Algorithm for multi-carrier OFDM transmission formats

This section describes the extension of the Baseline EVM Algorithm to waveforms that utilize the multi-carrier, OFDM transmission format. There are additional processing steps required for the OFDM case prior to the calculation of EVM. These include removal of the cyclic prefix, guard interval and shaping prior to symbol sampling; application of an N-point DFT that performs both the matched filtering and the symbol sampling; parallel-to-serial conversion and pilot tone removal of the data. In order to maintain the IEEE 1765 measurement validation approach in which the same algorithm is applied to all measured data, several of these steps require a standardized implementation. The IEEE 1765 implementation of these steps is described below, and the standardized algorithm is available on the IEEE 1765 Open Source Project.

Figure 6 illustrates the generation and Baseline EVM Algorithm implementation for the IEEE 1765 OFDM reference waveforms. The “Channel” consists of one of the Signal Impairment Sets described in Annex A. The shaded boxes illustrate processing steps that are different from the single-carrier case.



NOTE 1—IEEE 1765 coarse time alignment (time domain)

NOTE 2—IEEE 1765 fine time alignment (frequency domain)

NOTE 3—Orange shading: requires implementation of standardized algorithm. The N_{OFDM} -point DFT is equivalent to IEEE 1765 matched filter and symbol sampling.

NOTE 4—IEEE 1765 phase and amplitude normalization and computation of EVM.

Figure 6—Schematic of signal transmission, distortion, reception, and the OFDM Baseline EVM Algorithm

The IEEE 1765 OFDM implementation uses the same 64 QAM modulation on all channels. The average EVM on all information-bearing channels is obtained after removing dummy carriers and pilot tones and after parallel-to-serial conversion. Note that for the IEEE 1765 measurement verification procedure, all subcarriers are bearing information (there are no dummy channels) and pilot tones are not used. Only the average EVM is computed, as illustrated in Part (4) of Figure 6.

5.2.1 Step-by-Step Description of the OFDM Baseline EVM Algorithm

5.2.1.1 Down Convert the measured waveforms

The procedure here is identical to that provided in 5.1.1.2.

5.2.1.2 Optimal time alignment of Waveform 2 to Waveform 1

The procedures for both coarse and fine time alignment of the waveforms are identical to those provided in 5.1.2.2.

5.2.1.3 Low-pass filtering

Low-pass filtering is used only for the computation of normalized mean square error (NMSE) on the full signal or spectrum. The low-pass filter is slightly larger than the OFDM spectrum. A larger filter accepts more out-of-band noise. A more selective filter introduces linear distortion by removing some out-of-band OFDM signal that exists in the reference waveform. An optimum selectivity depending on the noise and distortion of the received filter gives the lowest value for NMSE. It corresponds to a rectangular filter having a cut-off frequency corresponding to the OFDM multiplex plus a guard band of four frequency intervals between carriers on each side, either for 51 carriers or 601 carriers.

In the OFDM Baseline EVM Algorithm, identical low-pass filters are used on both signals. Thus, the identical distortion on both signals has no effect on the NMSE. For this case, the optimum bandwidth for the filters is the OFDM multiplex plus a guard band of 1 frequency interval between carriers on each side.

5.2.1.4 Determination of symbol values

The symbols are determined in Part (3) of Figure 6 (shaded boxes). These functions are the reverse of the shaded functions in the transmission path.

Inter-symbol guard intervals, which are usually populated with cyclic prefixes consisting of a copy of the end of the symbol, are often added to OFDM signals to reduce ISI such as multipath with delays smaller than the guard interval duration.

The receiver truncates the oversampled signal in successive segments with length equal to the oversampled OFDM symbol with cyclic prefix and guard interval.

The receiver removes the guard interval, resulting in a symbol duration that is equal to the inverse of the carrier frequency separation $T = 1/DF$. The length of this oversampled symbol is $N_{OFDM} = N_c \times OS_{OFDM}$, where N_c is the number of carriers in the OFDM multiplex and OS_{OFDM} is the OFDM OS coefficient.

The receiver then integrates over this T duration when it performs OFDM demodulation with the DFT. This integration over T , which is an integer number of sinusoid cycles of each of the multicarrier signals, suppresses inter-carrier interference and is the basis for the orthogonality of the carriers in OFDM.

As explained in Annex C (The OFDM Baseline EVM Algorithm), the guard intervals and their associated cyclic prefixes, if any, are added to IEEE 1765 OFDM reference waveforms by inserting an integer number of samples, which are copied from the end of the symbol, in front of the symbol. In keeping with the functioning of most OFDM receivers, the guard intervals are removed by the OFDM Baseline EVM

Algorithm by removing the same integer number of samples from the front of the symbol during the demodulation process before the DFT is performed.

The spectrum of the oversampled symbol is computed by an N_{OFDM} -point DFT.

The DFT mathematical formula is equivalent to:

- Applying to each of the OFDM carriers a frequency shift depending on the carrier frequency to bring back each one to dc frequency
- An integration of the signal during a symbol duration equivalent to the OFDM matched filter square impulse response in the time domain
- An optimum sampling of the signal at the end of this integration

The anti-aliasing filter and down-sampling is implemented in the frequency domain by removing from this symbol spectrum all samples corresponding to frequencies higher than half of the resulting sampling frequency.

An anti-aliasing low-pass filter is necessary in a receiver before down-sampling to help ensure that no aliasing occurs during the down-sampling of the OFDM symbol. This filter would set to 0 or nearly 0 all samples at frequencies higher than half the resulting sampling frequency. Its frequency response is rectangular with a cut-off just over the maximum frequency of the OFDM multiplex (half the down-sampling frequency). This filter is not the matched filter that is implemented by the DFT.

When the down-sampling is implemented in the frequency domain, all these high frequency samples are removed from the spectrum so it is not necessary to set them to 0 first.

The down-sampled spectrum of the OFDM symbol is composed of N_c modulation symbols.

The N_c symbols are then converted from parallel to serial, after removing pilot tones and dummy carriers if any have been added at transmission (not used in the simulation code).

This is done for all successive groups of samples in the waveform and results in a sequence of I/Q symbols that should be compared to the transmitted sequence of symbols.

5.2.1.5 Determine the EVM of the user-lab and reference-lab measured waveforms

The procedure for this is identical to that provided in 5.1.2.5.

6. Generating and predistorting the reference waveform

The reference waveforms have several uses. Their primary use within this recommended practice is for comparison of the user measurement, including calibration and uncertainty analysis, to that obtained by an NMI or other reference lab. This requires that a single-signal generator outputs one of the reference waveforms, which is subsequently measured by both the user receiver and a calibrated reference receiver, typically supplied by an NMI. This verification method, which provides a high degree of confidence in measurement-based EVM, is described in 7.4.

In addition, these waveforms facilitate the comparison of EVM algorithms to each other. They can also be used to help verify that the EVM algorithms discussed in this recommended practice document have been coded correctly and to explore differences between IEEE 1765 EVM algorithms and individual, lab- or company-specific EVM algorithms.