Reference Measurements of Error Vector Magnitude

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***Abstract*—We demonstrate the applicability of the IEEE P1765 Reference Waveforms in ascertaining EVM and associated uncertainties by performing traceable measurements on a calibrated equivalent-time sampling oscilloscope at 44 GHz. With this knowledge, a user can employ the IEEE P1765 measurement-comparison approach using these reference waveforms in their laboratory to estimate the impact of their receiver on EVM and its associated uncertainties.**

***Keywords*—Wireless communication, digitally modulated signals, quadrature amplitude modulation, error vector magnitude, measurement uncertainty, uncertainty analysis.**

I. Introduction

Error vector magnitude (EVM) is one of the distortion metrics used to evaluate the quality of wireless communication systems that utilize digitally modulated signals. To estimate the EVM of a distorted signal, symbol values determined from recorded samples of the received signal are compared to ideal symbol values by use of an EVM algorithm. In many scenarios, where the ideal symbol value is not known, a "recovered symbol" is used. The recovered symbol location is geometrically closest to the measured symbol in the constellation diagram, giving the lowest EVM value. In some "data-aided" cases, the symbol pattern is known *a priori*. For the data-aided case described here, obtaining the lowest EVM is not the goal, but rather assessing the contribution to EVM from the measurement hardware is desired.

Many standards describe approaches for determining uncertainty in EVM [1]–[7]. We have previously shown [8], [9] that uncertainty associated with EVM can be traceably computed from measurements of periodic waveforms, thereby providing an accurate evaluation of the distortion introduced by the instrumentation. Recently, researchers from industry, government and academia have proposed recommended practices to provide a standardized IEEE P1765 approach to understand the receiver impact on EVM [10]. The method is based on estimating EVM from measurements of periodic waveforms along with the associated uncertainties in a data-aided manner. In this paper, we demonstrate the applicability of reference measurements to implement the IEEE P1765 approach using the carefully designed IEEE P1765 Reference Waveforms.

II. IEEE P1765 Approach

The IEEE P1765 Recommended Practice for EVM Measurement and Uncertainty Evaluation is depicted in Fig. 1. The user estimates EVM and the associated measurement uncertainty and compares it to a similar estimate made by a reference receiver, which is typically calibrated by a National Metrology Institute (NMI). The NMI's calibration also offers traceability to the primary standards. To evaluate the impact of only the user's receiver hardware on the estimate, all other variables are kept constant. Therefore, the IEEE P1765 approach utilizes standardized reference waveforms uploaded to a single arbitrary waveform generator (AWG) and a common "baseline" EVM estimation algorithm that provides no error correction. In addition, guidelines are provided on making these measurements.

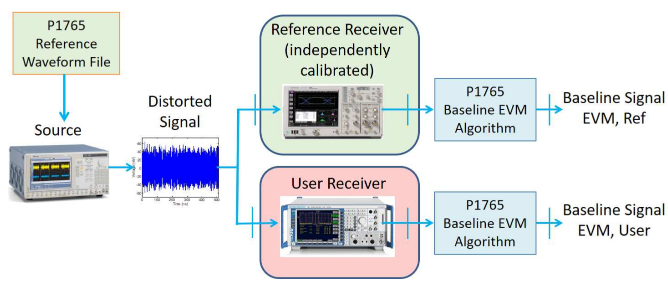

Fig. 1. IEEE P1765 approach to estimate the impact of the user's receiver on the estimate of EVM and uncertainty.

The measurement comparison is performed using one of the P1765 Reference Waveforms. These waveforms simulate different EVM scenarios by adding various deterministic effects to an ideal signal. These include effects such as fixed additive white Gaussian noise (AWGN), phase distortion (offset or delay), I/Q distortion (amplitude imbalance or phase imbalance or skew), linear distortion, and nonlinear distortions such as AM/AM and AM/PM distortion.

The selected waveform is uploaded to an AWG and the signal is measured at the source's output. Since the source itself adds nonidealities to the ideal signal, an iterative predistortion process is carried out to produce a measured signal that closely resembles the ideal Reference Waveform. Such a predistortion process has been explained in detail in [11].

The final predistorted signal is uploaded to the AWG and a measurement is performed on the Reference Receiver. The EVM of the measured signal is calculated using the IEEE P1765 Baseline EVM Algorithm. This is the Reference Measurement to which the user's measurement is compared. Because the predistortion process compensates for impairments introduced by both the source and the Reference Receiver, the nominal EVM under-reports the actual EVM of the source. The uncertainties associated with the Reference Receiver measurement are included in the analysis to account for this artificially low EVM value.

Table 1. Basic communication parameters used for producing the IEEE P1765 Reference Waveforms.

Parameter	Value
Modulation	64 QAM
Number of symbols (*N*)	511 (using PRN9 algorithm, gray coded from 0 to 63)
IF carrier frequency	4 GHz
Symbol rate	1 GSymbols/s
Sample rate	20 GSamples/s
No. of samples in the waveform	10,220
Time duration	511 ns

Table 1 lists the basic communication parameters of the single-carrier Reference Waveforms. To generate the waveform from the periodic sequence of symbols, the latter are mapped to a complex signal constellation plane. The symbols are then oversampled to produce an ideal time-domain complex waveform. A root raised cosine (RRC) filter [12], along with any applicable deterministic effects and distortions, are applied to produce the baseband waveform, which is ideally upconverted to an intermediate frequency (IF) of 4 GHz. The resulting waveform is uploaded to the AWG.

EVM is calculated between two symbol sequences using a standardized algorithm developed within IEEE P1765, named the Baseline EVM Algorithm. For an EVM calculation from a receiver measurement, the received baseband signal $y(t)$ or equivalently $Y(\omega)$ is compared with ideal baseband signal $x(t)$ or $X(\omega)$ with a few added steps. The received signal is first filtered using the previously applied RRC filter. The filtered received signal is then optimally time-aligned with the ideal signal. Next, the symbols are sampled and optimally phase and gain aligned, followed by the EVM computation using (1) as follows

$$EVM = \sqrt{\frac{\sum_{i=1}^{N}|y_i - x_i|^2}{\sum_{i=1}^{N}|x_i|^2}} = \sqrt{\frac{\sum_{k=1}^{N}|Y_k - X_k|^2}{\sum_{k=1}^{N}|X_k|^2}}, \qquad (1)$$

where $\{x_i\}$ and $\{y_i\}$, $i = 1,\ldots, N$, are the two symbol sequences. The details of the Baseline EVM Algorithm and its implementation is available on the IEEE's open-source website [10].

III. Measurements and Uncertainty Analysis

To demonstrate the Reference Measurement process, we measured seven of the 17 different P1765 Reference Waveforms. The first waveform has no added distortion, thereby having a theoretical EVM of ~0%. In the subsequent waveforms, individual effects or their various combinations are added as described in Table 2. These effects were chosen because they are often encountered in experimental setups.

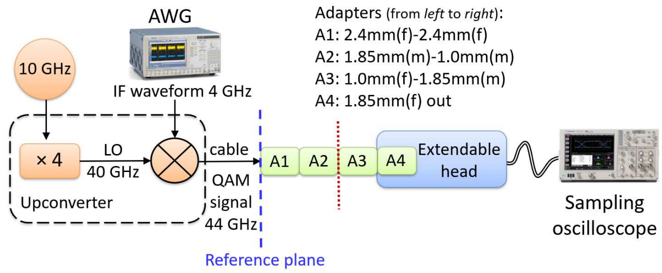

Fig. 2. Simplified schematic of the modulated-signal source at 44 GHz. The calibrated equivalent-time sampling oscilloscope is the Reference Receiver in the context of Fig. 1.

Fig. 2 shows a simple schematic of the modulated-signal source at 44 GHz used to perform reference measurements on the equivalent-time sampling oscilloscope. A detailed schematic can be found in our previous publications [8], [9]. The AWG generates the IF waveform, which is mixed with an LO at 40 GHz to generate the QAM signal at 44 GHz. The 44-GHz signal is band-pass filtered, passed through an attenuator and isolator, and measured on a calibrated sampling oscilloscope, which provides the traceability to the primary standards [13]–[15]. In the context of Fig. 1, this oscilloscope is the Reference Receiver which has been independently phase calibrated using a photodiode calibrated with the NIST electrooptic sampling system [14] [15]. The oscilloscope mismatch and response were measured at the red dotted line. However, we de-embedded the two adapters, A1 and A2, to predistort the QAM signal to the blue dashed line. The source mismatch was also measured here. The goal was to obtain a predistorted QAM signal at this reference plane which can be used in several other experiments.

Table 2. Distortions added to create some of the P1765 Reference Waveforms used for measurements in this work (AWGN: additive white Gaussian noise, ^low AWGN, *medium AWGN).

Reference Waveform	AWGN	I/Q Amplitude Imbalance	I/Q Phase Imbalance	I/Q Skew	Phase Offset	Sample Delay
1						
2		✓	✓			
3	✓^	✓	✓		✓	✓
4	✓^	✓	✓	✓	✓	✓
5	✓*					
6	✓*	✓	✓		✓	✓
7	✓*	✓	✓	✓	✓	✓

For each Reference Waveform measurement, we predistorted the designed signal in four iterations. The final predistorted signal was uploaded to the AWG at 4 GHz and we performed 10 repeats, which were complex averaged to reduce the noise floor and for use in the uncertainty analysis. Each of the four predistortion iterations and the 10 repeats consisted of 25 oscilloscope measurements [9]. The AWG output at 4 GHz was corrected for the DAC imbalance due to interleaving the two DAC outputs. The measured data at 44 GHz for the predistortion iterations and repeats were corrected for jitter and systematic errors in the oscilloscope's timebase, source and oscilloscope mismatch, and the non-ideal oscilloscope front-end response. Detailed descriptions of these steps can be found in our previous publications [8], [9].

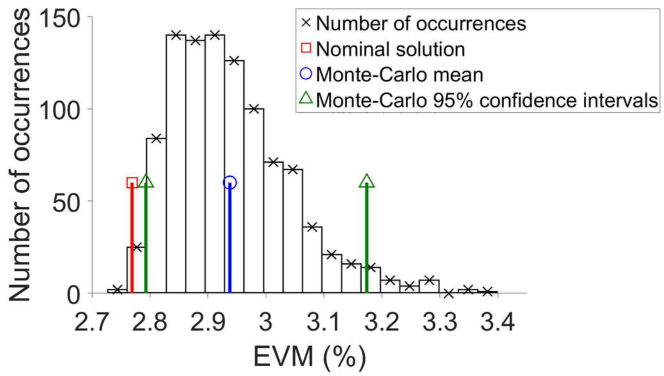

Fig. 3. Uncertainty in EVM for Reference Waveform #3, which includes AWGN, I/Q amplitude imbalance, I/Q phase imbalance, phase offset, and sample delay.

Fig. 3 shows the distribution of EVM obtained for Reference Waveform #3 using a covariance-based uncertainty analysis [16], specifically, the NIST Microwave Uncertainty Framework [17]. It performs both sensitivity and Monte Carlo analyses. The sensitivity analysis provides the knowledge of the dominant uncertainty mechanisms, while the Monte Carlo simulations handle nonlinear functions and noise propagation. The measured signal is calibrated in the NIST Microwave Uncertainty Framework for the source mismatch, uncertainties associated with cable bending, the two adapters A1 and A2, oscilloscope mismatch, and oscilloscope response. The adapters are cascaded and then de-embedded from the signal measurements made on the oscilloscope to calibrate the signal at the reference plane.

Table 3. Comparison of ideal EVM of designed waveforms at IF of 4 GHz and Monte Carlo estimates obtained from measurements at 44 GHz. The 44-GHz hardware introduces additional distortion as compared to the 4-GHz ideal waveform.

Reference Waveform	**Ideal EVM (%)**	**Mean of Monte Carlo distribution (%)**	**95% confidence intervals**	
			Lower (%)	**Upper (%)**
1	1.89e-13	1.58	1.36	1.97
2	1.44	2.14	2.01	2.37
3	2.14	2.94	2.79	3.17
4	4.00	4.28	4.22	4.40
5	3.22	3.55	3.46	3.74
6	3.50	3.95	3.84	4.16
7	4.87	5.06	5.00	5.16

Table 3 compares the ideal EVM values, and the Monte Carlo estimates obtained from the uncertainty analysis. Both sets of EVM were calculated using the P1765 Baseline EVM Algorithm, with the Monte Carlo estimates based on measurements performed at 44 GHz and the ideal value based on the IF waveform.

For the "ideal" Reference Waveform, we measured an EVM of 1.58%. This measured EVM represents the lowest we can achieve with the 44-GHz modulated-signal source shown in Fig. 2. We can see from these measurements that both the EVM and associated uncertainties are close to the ideal values with an offset. The offset can be attributed primarily to the distortion introduced by the source setup, although a small residual component may also be contributed by the reference receiver. Since this distortion may include both linear and nonlinear effects, it is combined in an unknown fashion with the distortion that was intentionally introduced into the Reference Waveforms.

A comparison between the ideal EVM values and the Means of the Monte Carlo distributions in Table 3 shows the offset decreasing as more effects are included, clearly illustrating the nonlinear combination of distortions within the source hardware. For instance, only two waveforms (#4 and #7) used in this work were created using all the deterministic effects and distortions, namely, AWGN, I/Q, and phase distortions. These waveforms show the lowest difference between the ideal and measured EVM values. This indicates that the distortion introduced by the source responds to various waveform impairments in a complicated fashion that would be difficult to model and supports the need for a reference measurement to assess hardware impairments introduced by the user's receiver.

Based on these observations, we believe that the wireless community can use the Reference Waveforms to assess the contribution to EVM from their respective measurement hardware.

IV. Conclusion

We have shown that the P1765 Reference Waveforms can be reliably measured and the EVM estimated, along with its uncertainties, using a modulated-signal source at 44 GHz. With this knowledge, these Reference Waveforms can be used in the configuration depicted in Fig. 1 to compare User Receiver measurements with the Reference Receiver measurements. Additionally, we can also use these waveforms in other experiments as a calibration tool. For instance, these Reference Waveforms can be used to estimate the impact of user receivers, such as vector signal analyzers or large signal network analyzers, on EVM and associated uncertainties, where the Reference measurements would be performed on the calibrated sampling oscilloscope. The uncertainty analysis for such a measurement will need a more complex approach that will be discussed in a future publication. However, the Reference Waveforms' measurements described here can benefit the entire wireless community in standardized wireless system design, test, and measurement.

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