Impact of Phase Calibration on EVM Measurement Quality

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***Abstract*—In this paper, the calibrated measurement of wideband modulated signals by mixer-based large-signal network analyzers (LSNAs) will be evaluated, with a focus on the impact of the phase calibration in the error vector magnitude (EVM). The influence of the phase-reference standard on the EVM_{RMS} will be addressed. The uncertainties of the EVM_{RMS} results will also be analyzed.**

***Index Terms*—modulated signal measurements, uncertainties.**

I. Introduction

Large-signal network analysis is becoming increasingly important to radio engineers. With the prospects of 5G communications migrating to even higher frequencies, a measurement apparatus capable of measuring wideband signals, together with mismatch correction, is important.

The LSNA is an instrument suitable for this task. One popular version is built upon a mixer-based network analyzer architecture. It is capable of measuring signals up to very high frequencies, well within the mm-Wave regions that are being considered for 5G communications.

This instrument's instantaneous bandwidth is limited, but at the expense of a longer measurement time, it is capable of measuring very wideband signals, frequency by frequency. An always present phase-reference, together with an additional phase calibration procedure, are used to obtain a phase-calibrated result. During the phase calibration procedure, a phase-reference standard needs to be measured, which usually is a pre-characterized comb-generator, [1].

When using an LSNA to measure a modulated signal and determine some of its signal quality metrics, such as EVM, a signal with a long period needs to be preferably used, as will be further discussed in section II. This requires increasing the period of the comb-generator, which causes the output power of each frequency tone from comb-generator to decrease, [2].

In this work, the dependence of the EVM on the phase calibration procedure is evaluated when using an LSNA to measure modulated signals. The EVM calculations were performed using an implementation of the definition in [3]. The uncertainty analysis was performed with the National Institute of Standards and Technology's (NIST) Microwave Uncertainty Framework (MUF). The uncertainty calculated for each signal measurement was propagated through the EVM calculation algorithm to provide final EVM results with uncertainties, following what was done in [4].

II. The requirement for a long duration signal

When measuring the EVM of a modulated signal, the deviation of each measured symbol position in the constellation from its corresponding ideal position is assessed, [3]. For this metric to be calculated accurately and well determined statistically, a large number of values need to be measured at each constellation point.

This means that the greater the number of symbols at each constellation point, the more accurately the EVM will correspond to the device's behavior. This requires a signal that has a higher period, so that more symbols can be represented.

This necessity is accentuated when measuring high-order modulation signals. For example, to measure the EVM of a 64-quadrature amplitude modulation (QAM) modulation, a signal with 64 symbols may give only one symbol per constellation point. Thus, the number of symbols needed is proportional to the order of the modulation.

A. Impact on the LSNA measurement

When using the LSNA to evaluate the EVM of modulated signals, two contrary conditions need to be considered: on the one hand, the number of symbols to evaluate needs to be as high as possible, so that the obtained EVM values are statistically meaningful; on the other hand, the maximum period duration of the signal is limited by the minimum frequency spacing that can be achieved.

The period of the signal is limited by the minimum frequency spacing achievable by the phase-calibrated measurement. As previously mentioned, when using a comb-generator as a phase-reference, its output power decreases with the frequency spacing, [2]. This means that the signal-to-noise ratio (SNR) of the comb-generator reading also decreases (if other conditions are maintained).

It is worth remembering that the low SNR affects two wave acquisitions: the wave from the calibration comb-generator and the wave from the reference comb-generator. The calibration comb-generator is only measured during the phase calibration stage, usually through the LSNA's internal coupler, which means an even lower power will be received; therefore, it will limit the measurement in terms of SNR. The reference comb-generator is used at all times, including during the phase calibration stage. This influence through different (and simultaneous) contributions means that the low output power per tone of the comb-generators may have a considerable impact in the final absolute phase results. Note that this does

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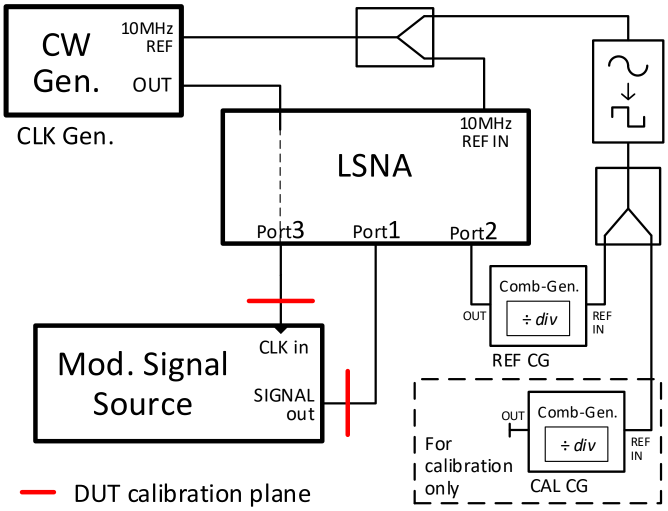

Fig. 1. Block diagram of the measurement setup used.

not result from a higher phase-noise at the output of the comb-generator, but from a lower measurement SNR.

III. Measurement Setup

A block diagram of the measurement setup is shown in Fig. 1. The setup was configured around the LSNA (a Keysight N5245A[1]), with two Keysight U9391F[1] comb-generators.

A. Measurement configuration

The clock (CLK) frequency used for the generation of all the signals was 2 GHz, and the carrier frequency was 630 MHz (within the 1st Nyquist zone of the modulated signal source). Signals with three different modulations were evaluated: 64-QAM, 16-QAM and QPSK, all with a baseband symbol rate of 480 MSymbols/s. Additional settings applied to all signals: a raised cosine baseband filter with a roll-off factor β of 0.35; and the signal bandwidth was truncated to 712.5 MHz (approximately 10% more than $(1+\beta)\times$ symbol rate).

All the modulated signals were predistorted in order to generate the lowest EVM values, [4], based on a characterization of the modulated signal source, [5], realized with the same LSNA. The low EVM of the signals was confirmed by measuring them using an equivalent-time oscilloscope.

The duration of all signals was 800 nsec, which resulted in a total of 384 Symbols. Since the different modulation schemes have a different number of constellation points, a constant symbol duration for all different signals leads to a different number of symbols per constellation position, for each signal. The number of symbols per constellation position for each modulation scheme is as follows:

QPSK $\rightarrow$ 92 symbols per constellation point
16-QAM $\rightarrow$ 24 symbols per constellation point
64-QAM $\rightarrow$ 6 symbols per constellation point

[1]We use brand names only to describe the experiment accurately. National Institute of Standards and Technology (NIST) does not endorse commercial products. Other products may work as well or better.

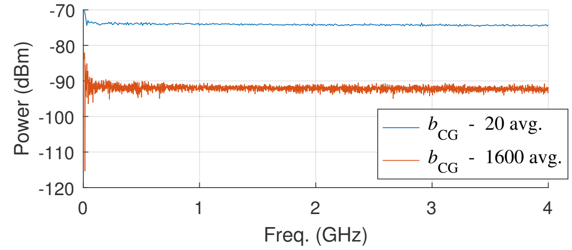

Fig. 2. Magnitude spectra of the calibrated incident and reflected waves from a single reading of the calibration comb-generator, with two different frequency spacing configurations: 10 MHz and 1.25 MHz. Measurements from 10 MHz to 4 GHz, in frequency steps equal to the comb-generator frequency spacing. The LSNA's IF BW for the 10 MHz reading was 100 Hz, while for the 1.25 MHz spacing, it was 30 Hz.

The symbols for each modulation scheme were generated randomly and independently, but with the following constraint: the number of symbols per constellation position needs to be the same, i.e. the symbols need to be well distributed throughout the constellation.

The frequency of the phase-reference was set to 1.25 MHz (10 MHz $\div$ 8), which corresponds to a reference period equal to the signal duration under measurement. Due to this low necessary reference frequency, the power of each tone at the output of the comb-generator is very low.

B. Comb-generator power impact

Compared to a 10 MHz frequency spacing, the finer steps led to a power reduction, at the output of each comb-generator, of around 18 dB per tone, as can calculated from [2, eq. (1)].

Fig. 2 shows the calibrated wave b_{CG} (in the outward direction from the comb-generator) when the frequency spacing on the comb-generator was set to 10 MHz and 1.25 MHz for a single acquisition (with no average). Note that b_{CG} looks much noisier in the case of 1.25 MHz frequency spacing, than 10 MHz; besides having a lower power level, as expected. This is easily visible, even considering that the IF BW was reduced from 100 Hz to 30 Hz.

IV. Results

To evaluate the impact of the comb-generator's low output power on the LSNA absolute calibration, different numbers of averages of the comb-generator readings were considered when performing the calibrations. Only the number of the comb-generator readings to average is swept, the raw signals we applied the calibration to were exactly the same (no averaging was done). In this evaluation the number of comb-generator readings we averaged was swept from 20 to 1600. Only 1600 consecutive comb-generator readings were performed, with the lower number of averages being subsets of these 1600 consecutive comb-generator readings.

Fig. 3 shows the nominal EVM_{RMS} results for the different number of comb-generator averages (for all three modulations). As can be seen, in all cases, the EVM_{RMS} decreases for higher number of comb-generator averages, showing the impact that the phase calibration step has on the final measured

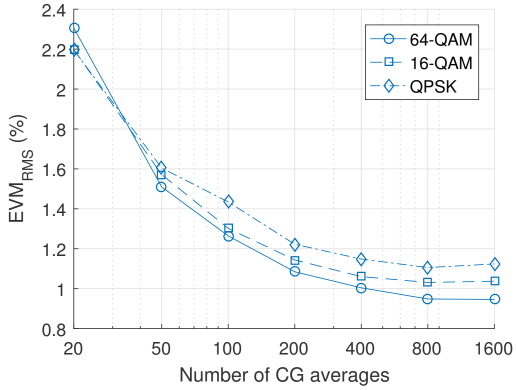

Fig. 3. Nominal EVM_{RMS} values for the three modulations when calibrating the LSNA with the different number of comb-generator averages.

results. It can be seen that the nominal EVM_{RMS} begins to stabilize for more than 800 comb-generator averages.

As a first conclusion, it is worth highlighting the very high number of averages (of comb-generator readings) that were required, so that the impact of the phase calibration on the final results could be reduced. This result illustrates well the attention that should be paid to the phase calibration stage when performing absolute signal measurements.

However, achieving this very high number of reading averages is very time consuming. Specifically, the 1600 readings of the calibration comb-generator took 3 days and 4 hours[2].

A. Uncertainty analysis

The results of the uncertainty analysis presented in this manuscript are only for the 64-QAM modulated signal. Similar results were obtained for the other modulations. The EVM calculation algorithm was developed internally and the uncertainties were propagated from the calibrated signal measurement to the final EVM_{RMS} values.

Before the calculation of the EVM_{RMS} value, the uncertainties of the calibrated signals can also be evaluated. The cumulative standard deviation as a function of frequency (for a bandwidth of 600 MHz around the carrier) was also evaluated for magnitude and phase over the number of comb-generator averages. In Fig. 4 the cumulative magnitude result (summation of dBs) based on both the sensitivity analysis and the Monte-Carlo analysis is shown. In Fig. 5, the cumulative phase result is shown. Note that the cumulative magnitude result does not change with the increase of comb-generator averages, while the cumulative phase result decreases with the increase of comb-generator averages, in a similar way to what was observed for the EVM result in Figs. 6 and 7. Based on this, it was verified that only the phase uncertainty varies with the variation of the number of comb-generator averages.

Fig. 6 shows the obtained nominal EVM_{RMS} as well as the obtained standard deviation from the sensitivity analysis along

[2]The comb-generator readings were performed by acquiring data from only the 3 required receivers. The detailed LSNA settings were: IF BW of 30 Hz, frequency span from 10 MHz to 4 GHz in 1.25 MHz steps, with the 'Stepped sweep' option turned ON for accurate frequency positioning and the 'IF BW reduction at low frequencies' option also turned ON.

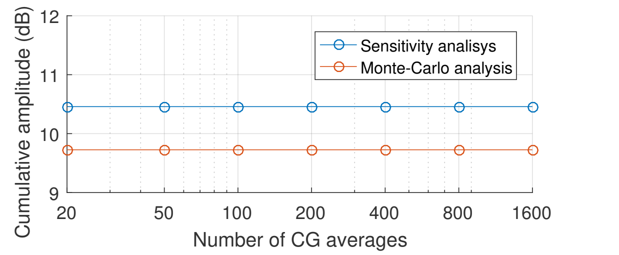

Fig. 4. Sum along frequency of standard uncertainty of reflected wave from sensitivity and from Monte-Carlo analysis

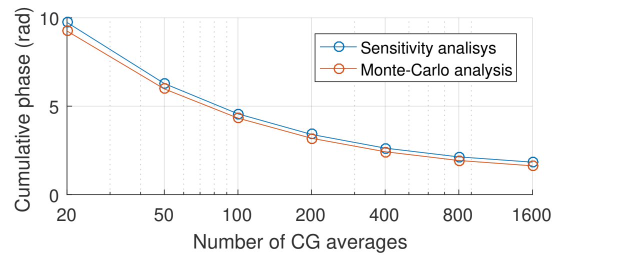

Fig. 5. Sum along frequency of standard uncertainty of reflected wave from sensitivity and from Monte-Carlo analysis

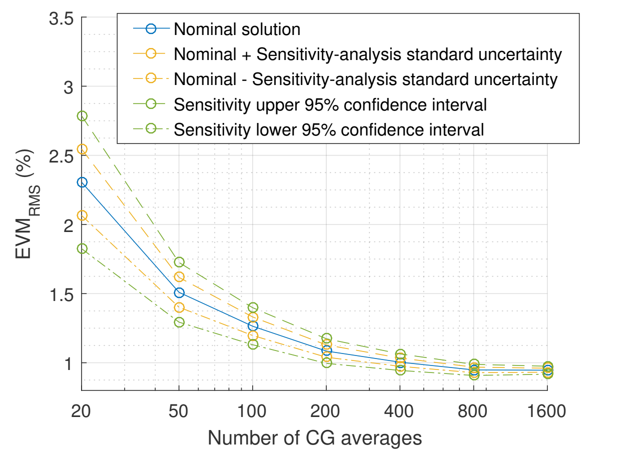

Fig. 6. Nominal EVM_{RMS} value together with standard deviation from sensitivity analysis, for different number of comb-generator averages.

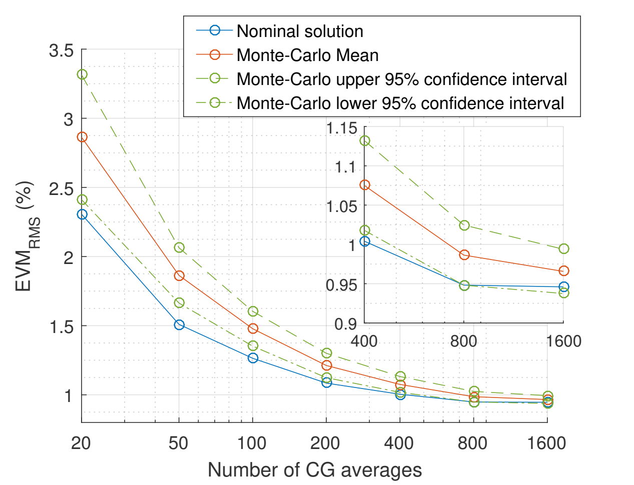

Fig. 7. Nominal EVM_{RMS} value together with Monte-Carlo mean, higher and lower 95% confidence intervals, for different number of comb-generator averages.

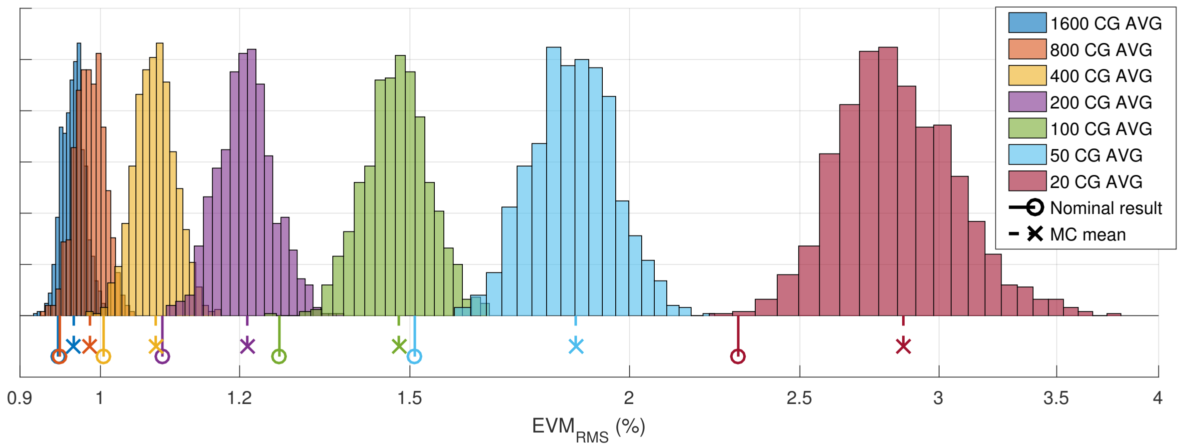

Fig. 8. Monte-Carlo histograms for each number of comb-generator averages used during the calibration stage. Histograms plotted on a logarithmic x-axis.

the number of considered comb-generator averages. Fig. 7 shows the same quantities, but for the results obtained from the Monte-Carlo analysis. The amplitude of the 95% confidence intervals agree for both analyses, however they are shifted to higher EVM_{RMS} values, in Fig. 7, for the Monte-Carlo analysis.

From Fig. 7, it can clearly be seen that when using a low number of comb-generator averages, the nominal EVM_{RMS} results are outside the 95% confidence intervals. Only with 1600 comb-generator averages was the nominal result within the confidence bounds. Similar results were obtained for the other evaluated modulated signals.

From the Monte-Carlo uncertainty analysis, it is also possible to get an histogram for each uncertainty analysis. These are shown in Fig. 8, on a logarithmic x-axis.

In Fig. 8, it can be seen that the nominal results are always at the lower extreme of each histogram. This is expected, as measurement errors are more likely to increase the measured EVM_{RMS}, not reduce it. Furthermore, each histogram gets narrower for a higher number of comb-generator averages, but the histograms are almost never contained within one another. They are consecutively shifted to lower EVM_{RMS} values. Only, from 800 to 1600 comb-generator averages is possible to denote a partial overlap of the histograms.

These results show that increasing the number of averages in the phase calibration improves the EVM measured by the LSNA and decreases the uncertainty of the EVM_{RMS} measurement, as expected. From this, we conclude that using a large number of averages to improve the phase calibration of the LSNA is important, as it allows us to decrease the phase uncertainty of the LSNA measurements and more accurately measure signals with low EVM_{RMS} values. This is especially important when the LSNA is used to predistort a signal, as more averages allow the signal being predistorted to be generated more accurately.

Fig. 8 also illustrates the limitation that the uncertainty of the LSNA places on its ability to measure low values of EVM. For example, Fig. 8 indicates that our LSNA, when calibrated with 20 comb-generator averages may always measure an EVM_{RMS} of about 2.5 % or higher. This is true, even if the actual actual EVM_{RMS} of the signal is much lower, as it was in this case. This suggests that methods should be developed for estimating and subtracting the systematic bias that imperfect instruments with both noise and correlated systematic errors add to EVM measurements.

V. Conclusion

In this work, the measurement of very wideband modulated signals was performed using a mixer-based LSNA. The influence of the comb-generator performance was evaluated for situations in which a low frequency spacing needs to be used. The low output power of the comb-generator, in the conditions of the tests we used, required the averaging of at least 800 comb-generator readings, in order to reduce its influence of the final calibrated EVM_{RMS} results.

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