A Novel Approach for Removing Instrument-Inherent Wideband Noise of Vector Signal Analyzers: Basic Principles and Impact

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***Abstract*— The recent developments in communication standards are clearly showing a trend towards higher signal bandwidths and higher modulation orders. As a direct consequence, the EVM performance requirements are becoming much more stringent for the devices under test. This requires a significantly lower measurement uncertainty for the test equipment. In this work, we present a novel approach to remove the instrument-inherent wideband noise of vector signal analyzers. By reducing the measurement uncertainty due to the inherent instrument noise, this approach leads among other improvements to a significant reduction of the residual EVM of the instrument.**

***Keywords*— EVM, Residual EVM, Wideband Noise.**

I. INTRODUCTION

Modern wireless communication standards are continuously aiming to achieve higher throughputs and faster data rates. For this purpose, these standards are increasingly relying on higher signal bandwidths and higher modulation orders. This has direct impact on the Error Vector Magnitude (EVM) performance requirements for the devices under test as well as the test equipment.

For example, and as detailed in [1], the most recent version of the Wi-Fi standard IEEE 802.11be doubled the maximum bandwidth from 160 to 320 MHz and relies now on modulation orders up to 4096 QAM. Consequently, this standard sets the EVM limit when using a 4096 QAM modulation to -38 dB, which is significantly more stringent than the limits in the previous Wi-Fi standards. Since this limit applies on system-level, the EVM requirements on component-level have to be even more stringent to ensure that the overall EVM on system-level is standard-compliant. Therefore, Wi-Fi amplifier and chip manufacturers are already expecting vector signal analyzers to exhibit a residual EVM, i.e. an EVM only given by the instrument's measurement uncertainty, between -53 and -55 dB for a bandwidth of 320 MHz to make sure that they have a sufficient margin for a reliable component characterization.

These requirements represent a real challenge, even for high-end instruments with outstanding RF performance. Therefore, the demand for enhancements that can improve the EVM performance of vector signal analyzers is considerably increasing.

II. I/Q NOISE CANCELLATION APPROACH

When analyzing the EVM of a device under test (DUT) using a vector signal analyzer (VSA), the signal to measure contains not only external noise contributions from the signal path up to the VSA input, but also instrument-inherent noise. In the following chapter, we present an approach that we named I/Q Noise Cancellation (IQNC) that aims to correct the signal to measure in such a way, that the instrument-internal receiver wideband noise is removed.

A. Measurement Setup

To start the explanation of the IQNC algorithm, the expected measurement setup will be described (see Fig. 1).

The ideal signal, s_{ref}, is the input into a DUT. The DUT then adds gain, noise and other distortions to the signal such that the signal to measure becomes

$$s_{to\_meas} = G \cdot s_{ref} + n_{external} + \varepsilon_{external}, \qquad (1)$$

where G denotes the gain, $n_{external}$ the thermal noise contribution from the DUT and $\varepsilon_{external}$ comprises all other distortions.

This signal is measured with the VSA, which also adds its own receiver wideband noise n_{RX} and other distortions ε_{RX}. The measured signal can therefore be written as

$$s_{meas} = G \cdot s_{ref} + n_{total} + \varepsilon_{total}, \qquad (2)$$

where $n_{total} = n_{external} + n_{RX}$ and $\varepsilon_{total}=\varepsilon_{external} + \varepsilon_{RX}$.

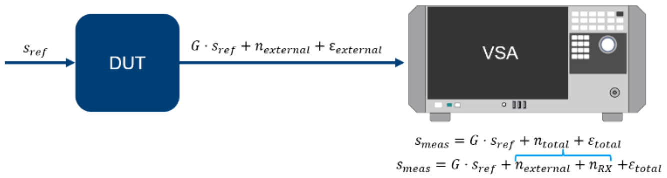


Fig. 1. Measurement setup

As can be seen in (2), the noise contributions from the DUT and the VSA cannot be separated with only one measurement. Therefore, different measurements are required that are explained in the following.

B. Measurement Steps

For IQNC, different measurements are required to allow the separation of the noise distributions from the DUT and the

VSA, which is necessary for the removal of the receiver wideband noise. All measurements are performed using the same setup as previously described in Section A.

The first measurement is a single capture, where all noise contributions are present. The used measurement result is s_{meas} as defined in (2).

Secondly, a set of measurements is required. The goal of these measurements is to determine an ideal, i.e. noise-free, signal

$$s_{avg} = G \cdot s_{ref} + \varepsilon_{total}. \tag{3}$$

To remove any noise from the signal, averaging is used as depicted in Fig. 2. For the averaging, a repeating signal is required. After taking M captures of this repeating signal, the captures need to be synchronized, so that all M captures have the same starting point. To allow for the mandatory synchronization in time-domain, a pre-defined reference signal s_{ref} is required (i.e. the expected or ideal signal). Synchronization basically provides coherent captures. The synchronized captures are averaged to obtain $s_{avg,M}$, which is the averaged signal after M averages. It should be noted that that s_{avg} as described in (3) can only be achieved if M tends to infinity. For finite values of M, $\frac{1}{M}$th of the original noise power still remains in $s_{avg,M}$.

This needs to be considered in the following estimations. In a first step and for the sake of simplicity, M is assumed to be large enough so that the remaining noise can be neglected, i.e. $s_{avg,M} \approx s_{avg}$.

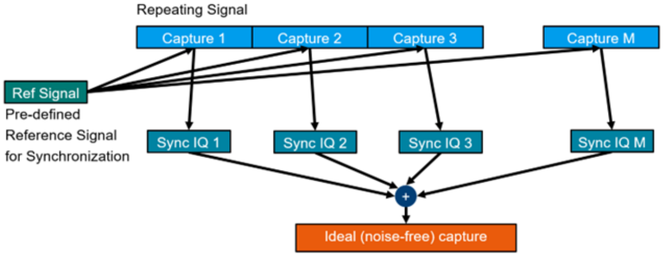


Fig. 2. Measurement steps to determine an ideal (noise-free) signal

A representative total noise signal for the first measurement can be derived from (2) and (3)

$$n_{total} = s_{meas} - s_{avg}. \tag{4}$$

From these complex amplitudes n_{total}, the total noise power N_{total} can be computed.

$$N_{total} = \left\langle \left| s_{meas} - s_{avg} \right|^2 \right\rangle, \tag{5}$$

where $\langle |\cdot|^2 \rangle$ indicates the computation of the RMS power of the I/Q samples.

Lastly, the receiver wideband noise power, N_{RX}, is estimated by measuring with a terminated input. The measurement is done with exactly the same measurement settings as the previous measurements. Re-cabling of the setup is not required if the VSA has an internal switch to terminate the input.

With the knowledge of the receiver wideband noise N_{RX} and the total noise in the measurement N_{total}, the external noise power can be computed, i.e.

$$N_{external} = N_{total} - N_{RX}. \tag{6}$$

We should recall that the goal of IQNC is to estimate a corrected signal based on the measured signal, that only contains external noise contributions, i.e.

$$s_{corrected} = s_{avg} + n_{external}. \tag{7}$$

Since the external noise power $N_{external}$ is already known from (6), we can define the following weighting factor

$$w^2 = \frac{N_{external}}{N_{total}} = \frac{N_{total} - N_{RX}}{N_{total}}. \tag{8}$$

Then, the representative external noise in the I/Q samples $n_{external}$ can be estimated

$$n_{external} = w \cdot n_{total} \tag{9}$$

thus

$$s_{corrected} = s_{avg} + w \cdot n_{total}. \tag{10}$$

Considering now the fact that it is only feasible to use a finite number M of averages, i.e. parts of the noise power remain in the signal after averaging, it can be shown that the corrected signal can be expressed as follows in this case

$$s_{corrected} = s_{avg,M} + w' \cdot n_{total,M}, \tag{11}$$

where $s_{avg,M}$ is the averaged signal after M averages, $n_{total,M}$ is the total measured noise signal, i.e.

$$n_{total,M} = s_{meas} - s_{avg,M} \tag{12}$$

and w' is a weighting factor that is derived in a similar way to w in (8) but includes additional correction factors that account for the impact of the remaining noise.

(11) clearly shows that the IQNC algorithm applies the correction on the raw I/Q data. Therefore, the corrected signal can be provided to a multitude of VSA software applications and the improvements are not limited to the EVM but cover all measurements supported by the corresponding application (e.g. EVM vs symbol, EVM vs carrier etc…)

C. *Plausibility Check*

As already explained in Section B, IQNC aims to remove the instrument-inherent noise and only this noise. Therefore, it is important to verify that none of the external noise contributions is removed after applying the correction described in (11).

For this purpose, a measurement setup with a known external noise is needed. Therefore, a digital test waveform is created by adding Additive White Gaussian Noise (AWGN) until the EVM value is about -40 dB. This waveform is then transmitted from a Vector Signal Generator (VSG) directly into the VSA. The VSG will add its own distortions to the signal. (cf. Fig. 3), but its noise contributions are neglectable compared to the VSA and the modelled noise in the waveform.

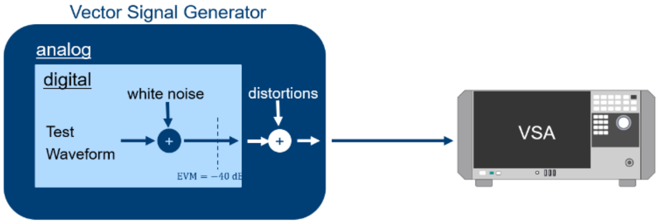


Fig. 3. Measurement Setup for verification measurements

The measurements are performed for different signal-to-noise ratio (SNR) levels in the VSA. This is achieved by increasing the attenuation of the VSA and therefore only influencing the receiver noise. The EVM results over the analyzer attenuation can be seen in Fig. 4.

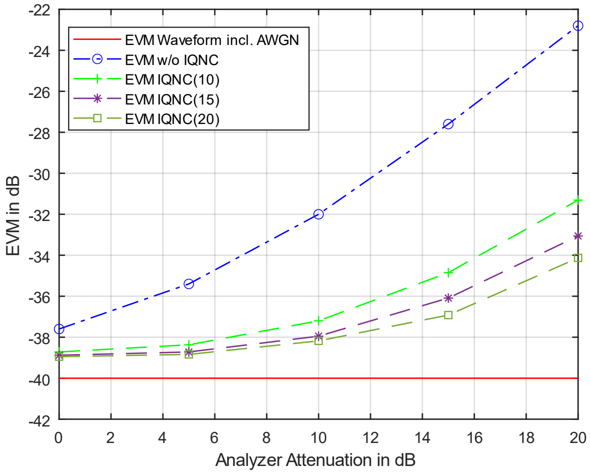


Fig. 4: Measured EVM value over the set analyzer power with and without I/Q Noise Cancellation for the verification measurement

In addition to the measurement results, Fig. 4 also includes a limit to indicate the -40 dB, which represents the external noise and corresponds to the minimum value of the EVM that is allowed after applying the IQNC.

The measurement result without the IQNC increases as expected with the analyzer noise due to the additional VSA receiver noise.

When IQNC is activated, all EVM measurement results show an improvement compared to the measurement where IQNC is off. Additionally, all of these measurements remain well above the limit without reaching it. For the lower attenuation levels, the difference of about 1 dB is caused by the additional noise and distortions in the RF path.

For the higher attenuation level, it can be seen that the IQNC can lead to a significant improvement of the EVM, e.g. with 20 averages the improvement is more than 10 dB. However, the EVM is still higher than what can be achieved for the lower attenuation levels. This can be explained by the numerical and signal processing limitations that certainly apply here. Indeed, we are correcting here for noise that is superimposed on a signal that is 100-10,000 times louder than the noise itself. Quantization errors in the Digital-Analog-Converters will certainly also limit the EVM improvement. The other reason can be seen when comparing the traces for the different numbers of averages: the higher the number of averages, the higher the improvement for the higher receiver noise values. For a high receiver noise, more averages are needed to estimate the total noise correctly. If the number of averages is too low, the total noise is estimated conservatively and therefore the receiver wideband noise is not completely removed.

On the left side of the graphs, the low receiver noise area, the difference between the results for the different numbers of averages is small.

As a summary, the verification measurements show that IQNC only removes the receiver noise and the external noise remains present in the corrected signal.

D. *Bathtub curve explanation*

When considering an EVM over signal power curve, commonly known as “bathtub” curve, three main contributors to the EVM are usually taken into consideration, the thermal noise, e.g. receiver wideband noise, the phase noise and the non-linear behavior, i.e. intermodulation products e.g. of the transmitter.

As explained in [2], it is commonly assumed for bathtub curves that on the left side, e.g. for low power levels, noise has the major influence on the EVM and on the right side, e.g. for high power levels, The EVM is dominated by the non-linear behavior. In the middle, the phase noise is the limit.

Fig. 5 shows the measurement results when using an IEEE 802.11be signal with a bandwidth of 320 MHz to compare the residual EVM of a VSA without IQNC and when IQNC with 20 averages is activated. In addition to that, Fig. 5 includes a simulation combining the three major contributors to the EVM (thermal noise, phase noise and non-linear behavior). The three contributors are added linearly and then plotted logarithmically. The resulting bathtub curve represents the physical limit for the measurement setup.

As expected, on the left side, where the noise is the main contributor to the EVM, the IQNC can improve the measurement up to the physical limit. The difference between the measured signal without IQNC and the simulated results is the influence of the receiver wideband noise.

On the right side, where the non-linear behavior is the main contributor, the IQNC cannot improve the EVM value since the results are not influenced by the receiver wideband noise. However, this again proves that IQNC works as intended and only removes noise contributions from the test instrument.

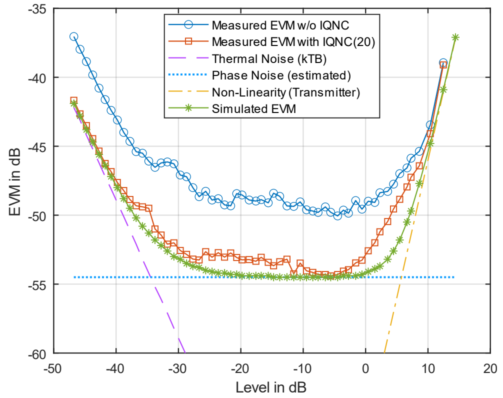
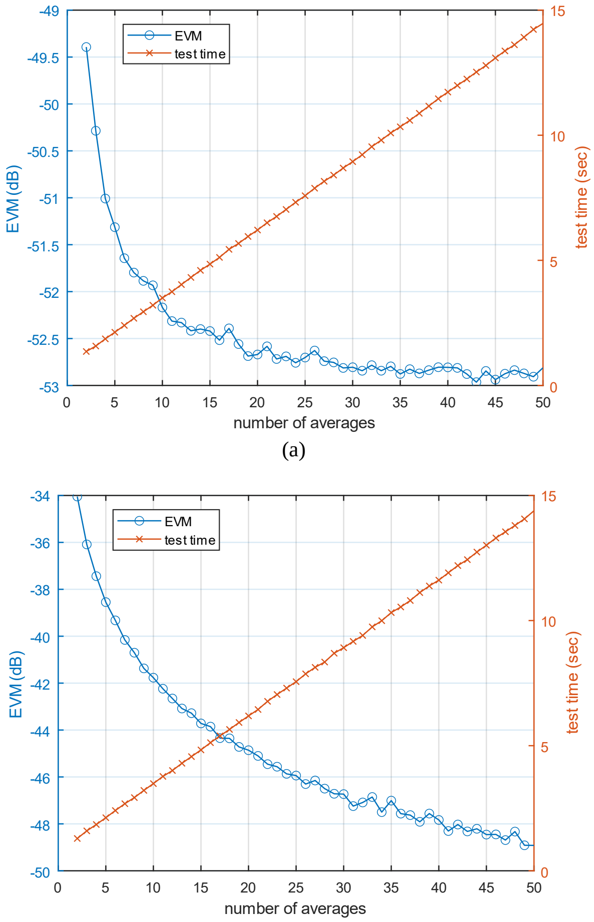


Fig. 5. Residual EVM over signal power for a 320 MHz wide Wi-Fi 802.11be signal at 6.905 GHz (modulation order 4096 QAM)

E. *Impact of no. of averages on EVM improvement and processing time*

As already briefly mentioned in Section C, a higher number of averages is beneficial for the EVM improvement for a higher amount of receiver noise. However, this will come at the cost of measurement time since more repetitions of the signal are necessary.

In the following, the effect of the number of averages on the EVM as well as the measurement time will be discussed for the same signal (IEEE 802.11be, 320MHz bandwidth, MCS9, center frequency 6.905GHz) at different power levels. In Fig. 6a, an input power level of -10 dBm is used. In this power level range, the receiver noise is present but not dominant. Fig. 6b shows the measurement at a level of -30 dBm, where the receiver noise is the major contributor to the EVM. It should be noted that no pre-amplifier was used in both measurements to make the impact of the number of averages more visible.



(a)

(b)

Fig. 6: EVM and measurement time over number of averages for an IEEE 802.11be, 320MHz bandwidth, MCS9 signal measured at center frequency 6.905GHz and power level (a) -10 dBm, (b) -30 dBm

Regarding the EVM, we see that for the measurement with the higher power level, the resulting EVM quickly converges. After 10 averages, already nearly 2.5 dB of the possible 3.5 dB improvement was reached. After 30 averages, no more improvement could be achieved since already all receiver noise could be removed. In this case, it is not meaningful to use more than 30 averages. Depending on the EVM requirements in the specific use case, even a lower number of averages may be sufficient to fulfill the requirements without unnecessarily increasing the measurement time.

However, for the measurement at the lower power level, it can be seen that the EVM improvement is not yet fully converging for 50 averages and an improvement of more than 12 dB is reached. From the significant improvement, it can be concluded that receiver noise was significantly dominant in the measured signal.
For this power level, a number of averages of 50 or even higher may be reasonable if the best possible result shall be achieved. If only an improvement of 3 dB is required, even 5 averages are enough as they achieve about 4.5 dB improvement.

Thus, the selection of the number of averages is a trade-off between EVM improvement and measurement time and strongly depends on the receiver noise for the measurement setup.

III. CONCLUSION

In this work, we presented a novel approach to remove the instrument-internal receiver wideband noise of vector signal analyzers. To demonstrate the impact on the residual EVM of the instrument, we started with a verification measurement using a signal with a known EVM and showed that this approach leads to plausible results. We demonstrated that this approach can lead to a significant improvement of the residual EVM of the instrument, especially for low input power levels where the EVM is mainly dominated by the wideband noise. Finally, we investigated the impact of varying the number of averages and came to the conclusion that the selection of the number of averages should always depend on the EVM requirements in the specific measurement scenario, to ensure that the EVM measurements are reliably fulfilling these requirements while being performed within a reasonable processing time.

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