On the Formal Identity of EVM and NPR Measurement Methods: Conditions for Identity of Error Vector Magnitude and Noise Power Ratio

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***Abstract*— NPR (noise power ratio) and EVM (error vector magnitude) measurements are used to characterize linear or non-linear distortions and degradations in digital modulators, microwave or RF amplifiers and transmission links.**

These methods are also used in system simulations. Each of these methods results in an equivalent noise power that can be added to the thermal noise in the link budget in order to compute the BER (bit error rate).

In this paper we examine the conditions necessary for these two measurements (or simulations) to give the same value for this equivalent noise. From this identity, it is possible to use either one or the other method with the goal to simplify simulation software or test benches particularly in the case of wide bandwidth measurements.

Keywords-component; Measurement; Link Budget; EVM; NPR; BER; Non-linearity;

I. Introduction

NPR (noise power ratio) and EVM (error vector magnitude) measurements are used to characterize linear or non-linear distortions and degradations in digital modulators, microwave and RF amplifiers and generally all transmission links.

NPR is mainly used to measure degradations coming from intermodulation products added to signals by non-linear amplifiers or transducers. It is the ratio, expressed in dB, between signal-plus-noise power and noise power.

EVM is mainly used to measure non-ideality of modulators (such as amplitude or phase imbalance or quadrature phase error) and the total distortion noise added to the signal by a transmission chain. It is the ratio, expressed in %, between noise average amplitude and signal amplitude.

Each method results in a noise power that is the quadratic average of an error between actual and ideal signals. This noise is then added to the thermal noise in the link budget to compute the BER (bit error rate). It allows us to optimize the operating point and the output power of non-linear amplifiers [4].

If both methods are exact and applied to the same equipment or transmission link, with identical measurements conditions, they should evidently give the same value for this noise.

In this paper, we examine the measurement conditions that are correct for both methods and we demonstrate that results are identical.

We also show that in some cases, both methods result in the same error and a correction will be proposed.

Finally, we describe some cases where, using one method instead of the other, one could simplify wide bandwidth test benches or simulation software algorithms.

II. EVM Measurement

An EVM measurement is based on the demodulation of a digital signal that is modulated by a pseudo random bit sequence. The test equipment is a receiver front-end, composed of a carrier recovery frequency and phase loop, a matched filter and a clock recovery frequency and time loop for optimum sampling of the signal. Samples of the signal are then presented as a constellation in the complex IQ plane [3].

These samples may have a static offset, (i.e. the average value of all samples), a complex in IQ plane. It is removed from the samples so that the sum of all the complex vectors associated to samples is zero.

A gain is applied to all samples to obtain the same average power as a template of the ideal signal. A phase rotation is applied to all the samples to minimize the phase error between actual samples and ideal values. Fig. 1 shows the constellations for QPSK (Quadrature phase shift keying) modulation. Errors have been exaggerated for clarity.

It must be noted that EVM measurement of a BPSK (Bi phase shift keying) modulation without noise would always result in ideal constellation points even for a modulator with amplitude and phase distortions as offset would be ignored.

All these actions are done through optimization and result in minimizing the error vector magnitude, which is the quadratic average of the amplitude of the error between actual and ideal values of samples.

The result of EVM measurement is the ratio between the standard deviation of the magnitude of this vector error and the quadratic average of the amplitude of ideal samples. It is generally given as a percentage

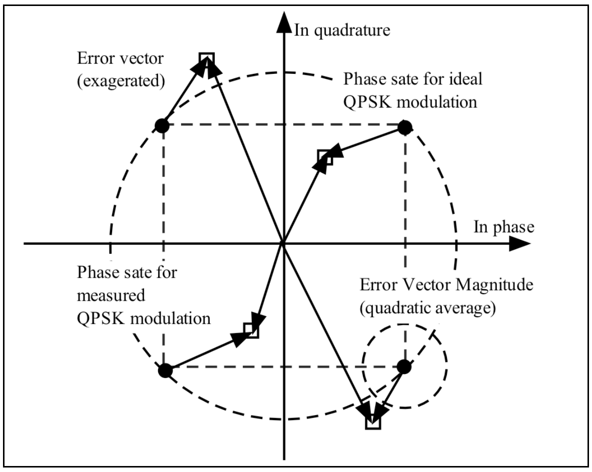

Figure 1. Ideal and actual contellations for QPSK modulation

If we express the ratio of signal or carrier power to equivalent noise power C/N, we have:

$$C / N = (1 / EVM)^2 . \quad (1)$$

EVM measurement is sensitive to amplitude and phase imbalance at the output of the modulator or the complete link. It also measures any additive noise such as ISI (inter symbol interference) or linear distortions due to filters, thermal noise from the modulator itself or the transmission chain and intermodulation noise from non-linear components in the link.

A good modulator would have an EVM of 1 to 2 % giving an equivalent C/N of 34 to 40 dB.

From the definition of the method used to produce the EVM measurement, it is clear that EVM can be measured before and after a non-linear chain, amplifier or transducer used in a digital transmission link. This gives us access to the distortions coming from the non-linear components.

The signal generator and modulator before the device under test (DUT) must meet a first condition: the static offset in the signal at their output must be as small as possible. The EVM measurement bench would not measure such an offset. However this static offset would have a strong influence on non-linear distortions at the output of the non-linear components of the link.

An obvious source of such an error would be any local oscillator spurious in the modulated signal. Such a spurious should be more than 40 dB down from the carrier power.

III. NPR MEASUREMENT

Three main methods permit to compute or measure NPR. We will briefly present them and propose a definition that applies to all of them.

A. Analytical method

It is generally easier to measure intermodulation products produced by a small number of pure continuous waves (CW) and then to compute the NPR that would be obtained in the case of a great number of carriers with a regular spacing in frequency, identical amplitudes and random phases so that all intermodulation products are incoherent and can be added in power. Such an analytical method can be found in [1].

B. Notch method

The notch method is based on the use of a signal composed of white Gaussian noise in a bandwidth equal to the channel to be measured. In the center of this bandwidth, a smaller bandwidth of the signal (less than 10%) is removed by a notch filter, thus giving a ratio between PSD (power spectral density) in the signal and residual PSD in the notch of more than 40 dB.

This signal drives the non-linear device under test (DUT). At the output, intermodulation noise fills in the notch up to a PSD level that is compared to the PSD level outside the notch, which comes from the sum of signal and intermodulation noise.

The ratio between these two levels is called the measured noise power ratio NPR, Fig. 2. This power ratio is such that the carrier to equivalent noise power ratio is:

$$C / N = NPR_{measured} - 1 \quad (2)$$

We will call true NPR the ratio $NPR_{measured}$-1 that is equal to the C/N ratio that should be used in link budgets.

The residual PSD of input signal in the notch, generally around 40 dB for microwave test benches, will limit the NPR that can be measured.

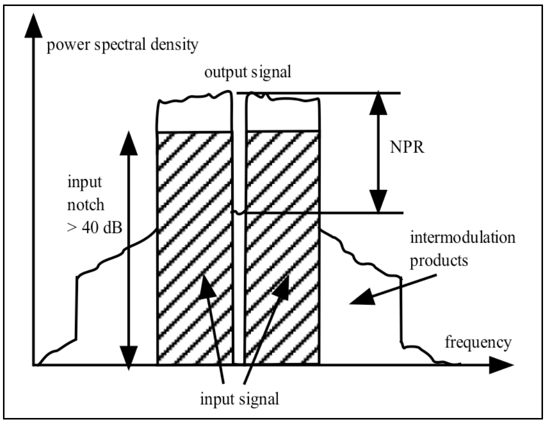

Figure 2. NPR measurement with the notch method

C. Equivalent gain method

The equivalent gain method was first proposed in [2] for computation of NPR in CDMA links. It may be applied to any type of signals.

In this method, the distorted signal at the output of the non-linearity is divided in a signal component that is correlated with the input signal and a noise component that has zero correlation with the input signal. The ratio between the output signal component and the input signal is called the equivalent gain (a complex, amplitude and phase gain).

The equivalent gain is computed through a correlation of input and output signals for a delay that minimizes the noise component. The noise component is obtained by removing the output signal component from the output signal.

The NPR (true C/N) is the ratio between both components (signal and noise) of the output signal.

D. Common definition for all NPR measurement methods

All three (true) NPR methods accept the following definition: the measured noise is the smallest part of the output signal that is not correlated with the input signal.

The true NPR (C/N) is the ratio between the power of the part of the output signal that is correlated with the input signal and the power of this noise.

In each measurement method, this noise may include thermal noise that will not be removed by the optimization of the delay in the correlation computation and possibly ISI that can be minimized by optimum choice of sampling time. It will also include modulator imbalance if an ideal input signal is used for correlation computation.

The equivalent gain method is a direct application of this definition. The notch method and analytical method can be shown to obey to this definition. They rely on measurement of intermodulation products or noise in a part of the spectrum where there is no input signal power. So the product of spectra of input signal and measured output noise is identically zero. This ensures a null correlation between input signal and measured output noise. In this particular case, the correlation is null for any delay between input and output used in the correlation computation. The delay is optimized to give the highest possible equivalent gain and NPR.

IV. Identity conditions

First we will show that EVM also obeys the definition given for NPR then we will add some necessary conditions on the NPR measurement.

A. EVM obeys the NPR definition

After removing the offset from the signal, which must be near zero to obtain a correct value when measuring a non-linear link, the EVM analyzer filters the measured signal through the matched filter. The impulse response of this filter is the time-inverted impulse response of the shaping filter that produced the input signal. So the output of the matched filter is the correlation of the measured signal with the ideal input signal shape for one filtered symbol of modulation.

Minimizing the average error by adjusting the amplitude and phase of samples with respect to ideal samples is identical to the optimization of equivalent gain and noise. When the lowest possible average error vector magnitude is obtained, the correlation between ideal signal and noise is null. The NPR defined by input-output correlation will give the same result if the input signal is digitally modulated by a random sequence of symbols and if the intermodulation noise power is measured after an identical matched filter.

B. Necessity to filter measured intermodulation noise

Intermodulation noise has a much larger bandwidth than the input signal. Third order intermodulation products span three times the bandwidth of the signal. In addition, the noise is not white but exhibits a level change of 1.8 dB in the signal bandwidth. It decreases by tens of dB outside three times the signal bandwidth where only fifth order and higher intermodulation products will be present.

If the signal that is used for measurement has a bandwidth larger than about 10 % of the occupied bandwidth, intermodulation noise cannot be supposed to be white. It is no longer accurate enough to use the noise power in a bandwidth equal to the symbol rate. A matched filter should be used for any NPR measurement for a low number of carriers.

In the case of more than 8 carriers, the worst-case PSD measurement at the center of the bandwidth can be used. It would give nearly the same result for noise power in true matched filter or in symbol rate bandwidth.

We find that the condition of using a matched filter in NPR measurements is a necessary improvement in measurement accuracy even if the goal is not to compare NPR to EVM measurements. Using a matched filter is even more important if we carry out ACPR (adjacent channel power ratio) measurements, as the slope of intermodulation products PSD outside the channel bandwidth is much higher.

C. Optimum sampling

For a more accurate value, one should measure NPR at optimum sampling point in each symbol after filtering the output signal and noise (for optimum, instead of average inter symbol interference).

D. Order of magnitude of measurement errors

Both EVM and NPR seem to be limited by the quality of the test bench equipment that generates the test signal before the non-linearity rather than by the accuracy of the measurement equipment of the output signal. It is difficult to achieve floor limits better than 40 dB NPR or 1% EVM.

It must be stressed that the EVM or NPR value measured directly at the output of the generator or modulator cannot be subtracted in any way from the value measured after the non-linearity. All these values are quadratic averages of magnitude of vectors of which we do not know the phase. In some cases, the non-linearity could even benefit from the error induced by the generator. Then, the real effect of the non-linearity would be the sum of the amplitude of noise measured before and after the non-linearity. With a 40 dB floor test bench and a 40 dB non-linearity measurement, the true value can be anywhere between $-\infty$ and -34 dB. The only solution is to decrease as much as possible the EVM or NPR measured before the non-linearity. The use of digital generators and modulators seems to be the way to go.

V. Common errors in EVM and NPR measurements

The formal identity between EVM and NPR is such that it is possible to find cases where both types of measurement exhibit the same systematic error. We call this an error because the measured value, while obeying exactly to the definition of an EVM or an NPR measurement, would give a wrong BER if it were used in a link budget. These errors have been reproduced by simulation and by measurement.

The input signal is a phase-modulated carrier with added white Gaussian noise. A strongly non-linear amplifier, such as a non-linearized travelling wave tube amplifier near saturation, amplifies this signal.

Fig. 3 shows the resulting constellation diagram.

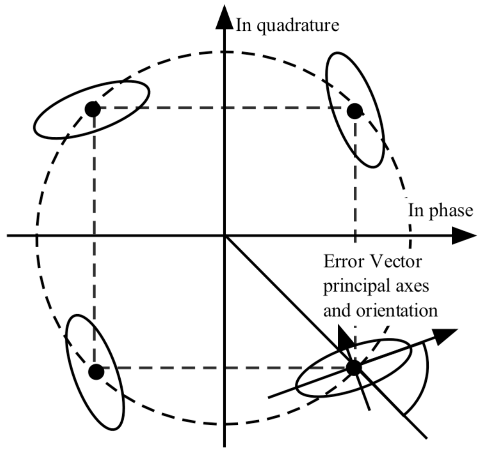

Figure 3. Distortion of noise in a strong non-linearity

For simulation purpose and understanding of the phenomenon, we may use a soft limiter with a large non-linear AM/PM phase curve. The noise at the output of the non-linearity is no longer equivalent to a white Gaussian noise with equal and uncorrelated in-phase and in-quadrature components. In fact, the noise around each ideal point in the constellation is no longer independent of the signal itself. It has the shape of an ellipsis instead of a circle around each ideal signal sample. It would be necessary to use at least 3 values to describe it correctly: either 2 orthogonal projections (x and y or amplitude and phase) with a correlation between both or projections on 2 principal axes and axes orientation.

This leads to an error of up to 3 dB on the noise to be used in the link budget as both EVM and NPR give an average value for noise whereas more than half or all the noise could be phase noise. The effect of phase only noise on a phase-modulated carrier would be 3 dB higher than that of uncorrelated additive Gaussian noise with the same power. EVM and NPR measurements find no correlation between this noise and the signal because they add all noise balls around all points in the constellation thus adding correlations with opposite signs.

One way to correct this error is to measure only the phase noise, either by computation or by adding a hard limiter in the measurement or simulation process before measuring the noise power. This would eliminate the amplitude component of the noise. The measured noise power should be doubled to obtain the equivalent white Gaussian noise power to be used in link budget.

VI. NEW MEASUREMENT PROCEDURES

Both NPR and EVM measurement methods are limited today by the availability and quality of wide bandwidth generating equipment, either white Gaussian noise with GHz bandwidth or modulated digital signals with Gb/s rates.

Identity of EVM and NPR permits to measure NPR in a wideband multiplex of modulated carriers by measuring EVM on one of the carriers. This can be done with existing commercial equipment. For a single or a small number of modulated and filtered carriers, EVM will give access to NPR in the true nominal conditions of use of the channel and with a commercial test bench rather than a specific one.

On the other hand, EVM measurement equipment would benefit from the equivalent gain method. EVM could use the correlation of the measured output signal with a replica of the ideal input signal to obtain a direct and more accurate value for the gain (amplitude and phase), noise power and delay instead of successive approximations.

Finally, EVM and NPR measurements and simulations could measure projections of noise on two orthogonal axis and correlation between projections (ideally amplitude and phase projections) or at least only the most harmful phase projection in addition to the average noise value.

VII. CONCLUSION

Through the detailed study of EVM and NPR measurement methods, we showed that they are formally identical as long as some measurement conditions are met. Both methods obey the same mathematical definition of noise at the output of the link as the part of the signal that is uncorrelated, in average, with the ideal or input signal.

The main conditions are: no static offset in the modulator output, random sequence of symbols, filtering the intermodulation noise before measurement of NPR. They do not over-constraint the test benches and in addition they are necessary for unbiased measurements.

In some cases, we could simplify test benches by using commercial EVM equipment instead of specific NPR equipment. An algorithm based on NPR equivalent gain and correlation could improve EVM computation. Finally, this study shows that both methods may be wrong by up to 3 dB in some cases and that they could be improved.

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