A Novel Measurement Standard for Nonlinear In-Band Distortion Characterization

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***Abstract* — This paper proposes a novel measurement standard for nonlinear in-band distortion characterization. Based on a previously established theoretical work, it first identifies the main limitations of noise power ratio figure of merit. Then, an appropriate alternative is proposed, along with its required measurement set-up.**

I. INTRODUCTION AND THEORETICAL BACKGROUND

Recent advances on wireless systems determined the need for more accurate nonlinear systems' characterization using multi-tone, or continuous spectra stimuli. Contrary to what happens in the linear domain where superposition applies, the response of any nonlinear system to a general input cannot be derived from the output to a finite set of basis functions. Therefore, the accuracy of characterization, or usefulness of specification of such systems, is intimately dependent on the similarity of the test excitations to the signal handled in real operation.

This has been the driving force for the emergence of many different arbitrary telecommunications signal generators, and the regained interest for substituting the traditional carrier to intermodulation distortion (IMD) ratio figure of merit of nonlinear circuits, C/I, with more evolved specification standards. If former one-tone test results of AM/AM or AM/PM were rapidly recognized to be incapable of describing all forms of distortion arising in presence of a real multi-tone, or full band-limited spectrum excitation, the two-tone stimulus constituted an improvement, but not the solution.

Adjacent-Channel Power Ratio (ACPR) and Noise Power Ratio (NPR) are widely accepted distortion figures of merit specifically created to evaluate signal to adjacent-channel, and signal to co-channel power distortion ratios, of systems subject to supposedly fully loaded band-limited spectra.

However, even from a very simplified nonlinear distortion model it can be easily shown that the necessity of providing a notch in the input spectrum, to allow output co-channel distortion observation, determines a significant impairment on the measurements' accuracy of any NPR test.

So, a new in-band distortion characterization standard and supporting measurement set-up is needed. These are the main objectives of the remainder of this paper.

II. NPR LIMITATIONS AND NOVEL CCPR DISTORTION FIGURE OF MERIT

Let us consider a simple n'th order power series model of a transfer nonlinearity, whose output, $y(t)$, can be related to the input, $x(t)$, by:

$$y(t)= c_1\, x(t)+ c_2\, x(t)^2 + c_3\, x(t)^3 + \cdots + c_n\, x(t)^n \tag{1}$$

Now, assume $x(t)$ is the sum of a large number, K, of closely spaced tones:

$$x(t) = \sum_{k=-K}^{K} X_k\, e^{j w_k t} \tag{2}$$

From the present analysis point of view, $x(t)$ is a good representation of a random band-limited signal if all its w_k are incommensurated: $k_1 w_1 + k_2 w_2 + \ldots + k_K w_K = 0$ if and only if $k_1 = k_2 = \ldots = k_K = 0$. In this situation, the various tones become uncorrelated, which means that their amplitudes are added in power and not in voltage.

So, this $x(t)$ can be viewed as if the input tones were non-uniform samples of a certain power spectral density function, PSD, stimulus.

If now x(t) is passed through our transfer nonlinearity of (1), $y(t)$ becomes composed of a large number of mixing products, that can be divided in several classes. In the linear class, herein considered the signal of interest, only one input frequency is involved in any output component, and its power is given by: $|Y_1(k)|^2 = c_1^2 |X_k|^2$. The second class involves 2nd order products, $Y_2(k_1,k_2)$, of frequencies $w_s = w_{k_1} + w_{k_2}$. These products, as any other even order mixing components, fall near DC, in the difference frequency band, or in the 2nd harmonic (n_{even}'th harmonic band). Therefore, they do not contribute to in-band distortion. The third class refers to 3rd order mixing products, $Y_3(k_1,k_2,k_3)$, whose frequencies are given by $w_s = w_{k_1}+w_{k_2}+w_{k_3}$. If one, and only one, of these frequencies is negative, $Y_3(k_1,k_2,k_3)$ is an in-band distortion component whose output power is $|Y_3(k_1,k_2,k_3)|^2 = (9/16)c_3^2|X_{k_1}X_{k_2}X_{k_3}|^2$.

Now, it is interesting to note that, since the various tones are incommensurated, none of the different 3rd order mixing products has common frequencies, unless the negative frequency is exactly the symmetric of one of the others. For example, if we have $w_{k_3} = -w_{k_2}$, then $w_s = w_{k_1}+w_{k_2}+w_{k_3} = w_{k_1}$, which is coincident with the linear signal component of $Y_1(k_1)$. Since we admitted an input of K tones, there will be K different 3rd order mixing products following over any w_{k_1}. All of these products are correlated in phase to the $Y_1(k_1)$ component and add in voltage, not in power. Thus, they constitute a signal-correlated co-channel distortion form, presenting much higher amplitude than the integrated signal-uncorrelated distortion components falling nearby.

If other higher odd order products would be considered, that situation would even be more notorious. In fact, for a general odd order n_{odd}, total number of mixing products falling over w_{k_1} is such that its power becomes proportional to $K^{(n_{odd}-1)}$. This simple description indicates that when the input drive is increased from small-signal levels (where 3rd order distortion dominates) into saturation, signal-correlated distortion components become more and more important, in comparison to the other signal-uncorrelated co-channel distortion components. Actually, this signal-correlated distortion is nothing more than the origin of AM/AM and AM/PM conversion (truly, AM/PM could only be predicted if the memoryless power series of (1) were replaced by a correspondent dynamic Volterra series), whose distortion power must increase linearly in the deep saturation asymptote, while the signal-uncorrelated IMD tends to be limited in power.

Now, recalling that an NPR test eliminates a certain input signal slice to allow reading of co-channel IMD, it also implicitly eliminates any signal-correlated distortion component, that would appear within the notch position if the system were considered in normal operation. Therefore, an NPR test is totally blind to signal-correlated distortion, and produces misleading co-channel distortion evaluations that are optimistic in about 7dB in the small-signal end [1], and become progressively worse when the device under test, DUT, enters saturation modes.

That NPR figure of merit is thus inadequate, and must be replaced by a new standard accounting for all co-channel IMD forms.

The proposed integrated co-channel distortion figure of merit is called Co-Channel Power Ratio, CCPR, and is defined as:

CCPR: Ratio between total linear output integrated power, and total distortion power collected within the signal bandwidth.

In terms of signal and distortion PSDs a correspondent Signal to Co-Channel Distortion Ratio, SCDR(ω), can be defined for a spot frequency, as:

SCDR(w): Ratio between the linear output signal PSD to the co-channel distortion PSD, measured in the desired spot frequency, w.

III. PROPOSED CCPR AND SCDR(ω) IN-BAND DISTORTION MEASUREMENT SET-UP

The CCPR measurement set-ups that will be presented next are based in the following two basic principles: 1 - any smooth nonlinear system is almost linear if the input drive level is sufficiently low, and 2 - its output signal components always rise linearly with input excitation amplitude (note that gain compression is nothing but the effect caused by the addition of signal-correlated co-channel distortion). These are the same linearization principles of input/output power back-off used in RF amplifiers and mixers, and come naturally from the power series model of (1).

Since co-channel IMD is coincident in frequency with the much higher amplitude output signal components, it is necessary to eliminate the signal from the output, while preserving the input stimulus integrity. For that, a bridge arrangement is a possible solution. Indeed, an undistorted linear version of the output signal is obviously present at the DUT's input. Thus, we only need to pick a sample of it, scale its amplitude and change its phase to cancel-out exactly the output signal. This arrangement is shown in Fig. 1.

The upper arm contains the DUT, while the lower serves for signal cancellation. Because the DUT is linear if ATT attenuation is substantially increased, the bridge is adjusted in that condition. Then, ATT is again reduced to drive the DUT with its expected nominal level. This calibration procedure guarantees that only the signal will be cancelled-out, keeping intact all co-channel distortion components.

If the DUT is a frequency-translating device, like a mixer or modulator, the bridge arrangement cannot be applied directly. In this case, the cancellation arm must also provide the corresponding frequency conversion, which can be obtained using another auxiliary converter. This is shown in Fig. 2.

Unfortunately, the auxiliary converter, AUX-CONV, may also introduce some distortion, which degrades measurement accuracy. To obviate that, one can either use a much linear mixer for AUX-CONV, than the one under test, or simply linearize it by using back-off. That was the solution adopted in the implemented set-up of Fig. 2.

The procedure that must be followed to measure CCPR is now described. First, the bridge is adjusted for total signal cancellation in the DUT’s linear region, by increasing ATT and adjusting the amplitude and phase of the auxiliary arm. Because we assumed our non frequency-translating DUT had gain (Fig. 1), and our AUX-CONV had to be operated under back-off (Fig. 2), the bridge amplitude adjustment is not done in the auxiliary arm but via the main arm. Then, the DUT drive is returned to its nominal value, and co-channel and adjacent channel distortion observed in the spectrum analyzer.

At this moment we would like to point out that this procedure also provides an additional benefit. Because the much stronger output signal components are cancelled out and only weak distortion levels reach the spectrum analyzer, the dynamic range requirements of this instrument can be relaxed, as compared to normal IMD measurement set-ups [2].

If small-signal CCPR or SCDR(ω) measurements are sought, linear signal components can be directly measured at the output of the DUT since the distortion components present there are not strong enough to cause sensible accuracy loss. However, in the saturation range, this signal information must be obtained from other means. One is to measure the linear signal when the bridge was adjusted, and then rescale this value by the ATT reduction. That requires a calibrated step attenuator. An alternative way consists in measuring the signal present at the auxiliary arm and then reflect its amplitude to the DUT output. That requires the linear characterization of all components present between the DUT and the output coupler, along with the symmetry of this device.

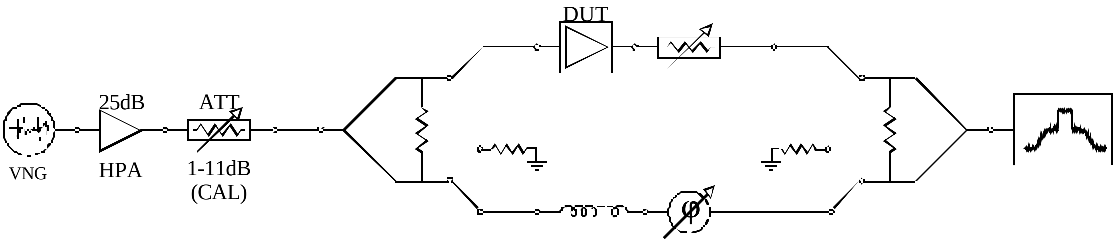

Fig. 1 - Proposed measurement set-up for in-band distortion evaluation of non frequency-translating devices.

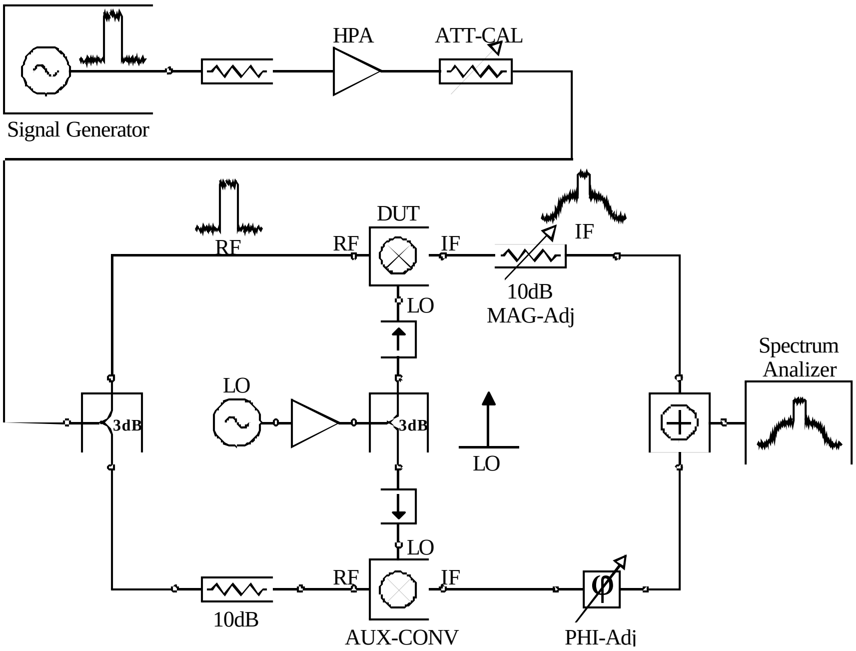

Fig. 2 - Proposed measurement set-up for in-band distortion evaluation of frequency-translating devices.

Fig. 3 and Fig. 4 show typical measurements obtained with the set-up of Fig. 1. They include bridge response immediately after calibration, complete DUT’s output (signal plus distortion) and adjacent-channel and co-channel distortion components. Fig. 4 is similar to Fig. 3 except that now the input PSD included a notch, to simulate an NPR test. The impairment of this traditional test is now evident if we compare the total co-channel distortion power in zones of full PSD and within the notch.

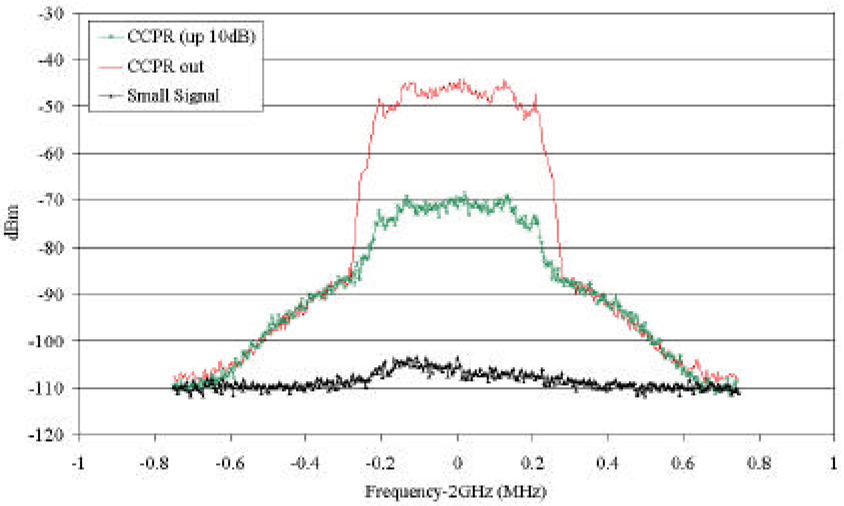

Fig. 3 - Test setup output signals as measured in the bridge adjustment condition, and at nominal DUT's drive level.

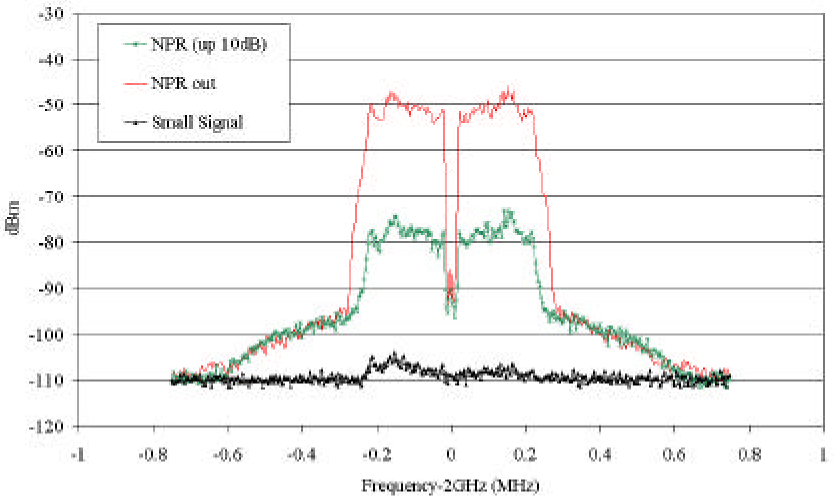

Fig. 4 – Signal-correlated and uncorrelated co-channel distortion power as measured with an NPR driving signal.

IV. CONCLUSIONS

By proving NPR is blind for important signal-correlated distortion components, we justified the need for alternative co-channel distortion specification standards. Therefore, novel CCPR and SCDR(ω) figures of merit were proposed to substitute conventional NPR results, along with appropriate measurement set-ups for both non-frequency translating devices and frequency converters.

ACKNOWLEDGEMENT

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