Improved characterization of feed-forward noise cancellation scheme for microwave amplifiers.

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***Abstract* — The application of feed forward correction principles to cancel noise in amplifiers has proven an efficient tool for enhancing noise performance of microwave amplifiers beyond the present state of the art. An improved experimental characterization of the scheme is presented with results from several amplifiers working at X-band, confirming the validity of the approach with more than 25 dB of noise cancellation for both white and flicker noise. A description of the improved measurement system used to characterize the noise cancellation is also presented, together with a discussion of the limits of the cancellation scheme.**

***Index terms* — Amplifier, feedforward, phase noise, noise measurement, oscillator.**

I. Introduction

Amplitude noise (AM noise) and phase noise (PM noise) are an important concern in system design in several fields, including communications, timekeeping and frequency control. To mention only one case, low-noise oscillators in the microwave range and above are limited in their noise performance by the noise of the amplifier, especially for *1/f*-type noise processes [1]. Moreover, and from a different perspective, the need for wireless communication systems to reduce their energy consumption points to the use of high-efficiency switched-mode amplifiers, which come with the burden of generally worse noise performance than linear amplifiers.

In both scenarios, 1/f-type noise processes (non-white noise closer to the signal carrier), are the ones difficult to reduce. These noise types are mainly generated through multiplicative mechanisms and have fundamentally non-stationary characteristics. The multiplicative origin makes the noise dependent on the carrier power, so that the signal-to-noise ratio cannot be improved by increasing the power of the signal carrier. The fundamental non-stationarity doesn't allow using long time averages to reduce the noise.

The scheme proposed in this paper is based on well-known feed forward techniques, used by the communications industry to cancel harmonic distortion in amplifiers (see e.g. [2], [3], [4]). The noise introduced by the amplifier is detected and then subtracted at the output of the amplifier. Neither the noise detection nor the subtraction involve any kind of modulation/demodulation operation. As a result, the cancellation scheme addresses both PM and AM noise.

There are two main limiting factors in this noise cancellation scheme. One is represented by the intrinsic noise of the detection system that cannot, of course, be cancelled and it sets the *noise floor* of the cancellation scheme. The other manifests itself only at longer times and it is linked to the overall stability of the system parameters. As, for example, transmission lines lengths changes, the phases of the signals rotate: the detected noise is then not perfectly subtracted from the amplifier output signal anymore.

This feed forward noise cancellation technique has been explored in [5] and a first demonstration of its effectiveness has been presented in [6]. Improved results, obtained using more refined measurement techniques are presented in this paper.

II. The feed-forward principle

The feed forward principle is based on the *a posteriori* correction of an unwanted effect in a system. It is fundamentally different from a feedback system in the lack of system behavior conditioning: the distortion or noise is subtracted from the output of the amplifier, while the amplifier characteristics are unchanged. This inherent independence from the nature of the effect that one wants to eliminate makes it an ideal tool to simultaneously cancel noise processes of fundamentally different natures.

The general topology of any feed forward scheme has two main blocks around the non-ideal amplifier: a detection system that isolates the unwanted contributions of the amplifier and a correction system that subtracts them from the output signal. The details of the specific implementation we used to cancel noise are described in the following sections.

A. The conceptual scheme for noise cancellation

A simplified version of this noise cancellation scheme is drawn in Figure 1. The *main amplifier* is shown with gain *G* and the *noise amplifier* with gain *H*. The relevant time delays introduced by various components are indicated with τ_i (i=1,2,3,4), τ_G and τ_H. The γ_i (i=1,2) are the coupling ratios of the various directional couplers.

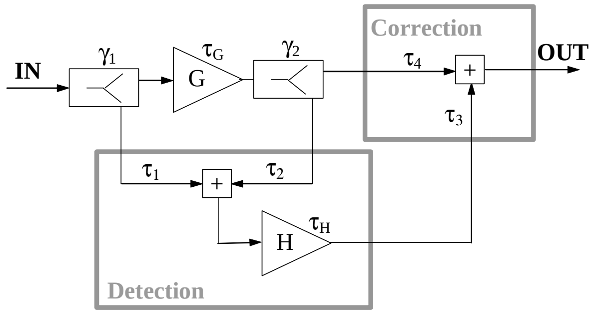

Figure 1. Conceptual illustration of the feed forward scheme for noise cancellation. The amplifier with gain G is the *main amplifier*, while the other (gain H) is the *noise amplifier*. The relevant time delays introduced by various components are indicated with τ_i (i=1,2,3,4) and γ_i (i=1,2) are the coupling ratios of the various directional couplers.

The detection system compares, through a summing point (+), a portion of the amplifier's input and output signals. The time delays τ_1 and τ_2 are adjusted so that the signals at the summing point have a 180-degree phase difference, resulting in the elimination of the carrier. The noise associated with the input signal that is not generated by the *main amplifier* is cancelled with the carrier because it is present on both sides of the summer. Finally, the output of the detection system is essentially the noise introduced by the *main amplifier*, amplified with gain *H* by the *noise amplifier*.

The correction system then adjusts the time delays τ_3 and τ_4 in order to have the noise coming from the detection system with opposite phase with respect to the noise associated with the amplifier output signal. Therefore, the *main amplifier* noise is cancelled through the second summing point at the output of the correction system.

The detected noise has not been downconverted. This avoids the introduction of the noise associated with the frequency mixer that would be used to downconvert the signal to baseband.

It is important to notice that to successfully cancel the noise from the output signal it is necessary to have the *time* delays properly matched as well as having equal amplitudes and opposite phases. The higher the bandwidth of the noise process that one wants to eliminate, the more critical the delay matching condition.

Proper choice of the coupling ratios labeled γ_1 and γ_1 is also important to maximize the amount of noise cancellation.

III. EXPERIMENTAL CHARACTERIZATION

A. *The experimental setup*

The test setup used is shown in Figure 2. All the parts in the system are commercially available. The *main amplifier* is a power microwave amplifier with gain G = 30dB and 1-dB compression point at P_{out} = +30dBm, while the *noise amplifier* is a low-power, low-noise amplifier with gain H = 30dB and 1-dB compression point at P_{out} = +10dBm. The carrier signal used for the characterization of the system is 10 GHz.

The directional coupler D_1 is such that the direct path will go to the first summer SUM_1, and has a coupling ratio of 6 dB. The summer, SUM_1, is a Wilkinson power combiner, while the variable attenuator α_1 and the variable phase shifter φ_1 set the correct amplitude and phase to cancel the carrier. The isolator ISO_1 is necessary to prevent input signal leakage to the output summer SUM_2.

The detected noise is amplified by the *noise amplifier* (gain *H*) and sent to the output summing point SUM_2. The directional coupler D_3 allows monitoring to minimize the residual carrier at SUM_1.

The variable attenuator α_2 and the variable phase shifter φ_2 set the correct amplitude and phase for the noise cancellation at the summer SUM_2, also a Wilkinson power combiner. The isolators ISO_2 and ISO_3 have the purpose of increasing the directivity of the power combiner, preserving the quality of the cancellation process.

The new Reduced Noise Amplifier (RNA), identified by the labels IN and OUT in Figure 2, has a net gain of 20 dB and a 1-dB compression point at P_{out}= 25 dBm.

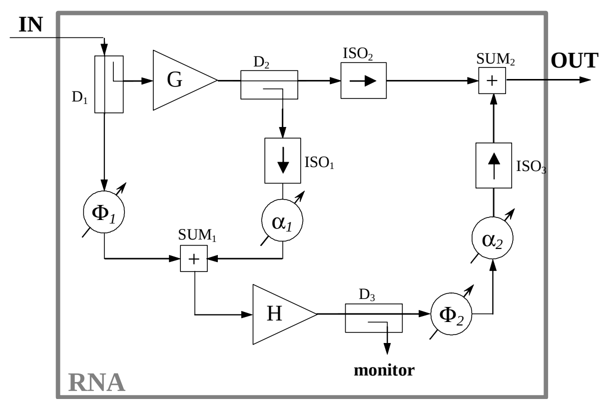

Figure 2. Experimental setup for the Reduced Noise Amplifier (RNA) The carrier signal used to characterize the system is 10GHz.

B. *Phase noise measurements*

Although this technique cancels both AM and PM noise, the results presented below focus primarily onto phase noise.

The architecture of a general phase noise measurement system is shown in Figure 3 and can be found described in detail in [7].

The output of an appropriate frequency source is split into two paths, one of which includes the Device Under Test (DUT) while the other includes a variable delay line to equalize the delays at the two ports of the double-balanced mixer.

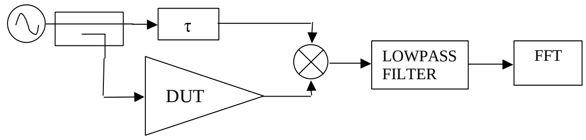

Figure 3. General architecture of a single-channel phase noise measurement system. The double-balanced mixer works as a phase detector. The delay line labeled τ is used to match the delays of the two paths of the measurement system.

The two signals at the mixer port are at the same frequency and kept with 90 degrees of phase difference, so that the mixer works as a phase detector and its output is proportional to the phase difference between the two signal at its LO and RF ports.. The mixer output is then low-pass filtered to prevent aliasing and sampled by a Fast-Fourier Transform (FFT) spectrum analyzer.

In order to insure the insensitivity of the system to the phase noise associated with the frequency source, it is critical to keep the time delays of the two paths of the measurement system well matched

The *noise floor* represents the minimum level of noise measurable by a noise measurement system and in the case of the topology shown in Figure 3 it is mainly due to mixer noise. The noise floor can be measured if the DUT is removed from the scheme, having care of maintaining the same power levels at the mixer ports.

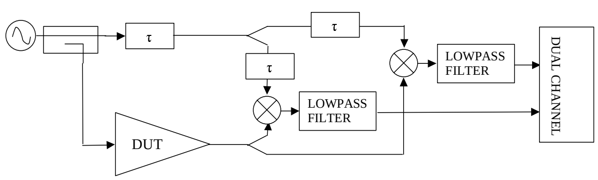

Figure 4. General architecture of a dual-channel cross-correlation phase noise measurement system. There are two copies of the system showed in Figure 3 sharing a frequency source and the DUT.

In previous work [6] it was found that our ability to measure the residual noise of the RNA was limited by the noise floor of the measurement system, which had the topology shown in Figure 3. To overcome this limitation we built a double-channel phase noise measurement system, whose basic architecture is shown in Figure 4.

This system has two copies of the phase noise measurement system described in Figure 3 sharing the same source and the same DUT.

The low-pass filtered spectra at the output of the two mixers are sent to the inputs of a dual-channel FFT spectrum analyzer that executes the product of the sampled spectra. Such product is the mathematical equivalent to the cross-correlation of the sampled processes in the time domain. Completely correlated noise processes will give a cross-correlation result of 1, while uncorrelated ones will result in zero cross-correlation.

As a result of this operation, the noise processes introduced by each of the two mixers, or by components that are not shared by the two channels, are uncorrelated (their cross-correlation is zero) and therefore don't contribute to the final measurement result.

The noise sources shared by the two channels are the frequency source and the DUT. The noise associated with the frequency source noise is eliminated by each channel independently prior to the execution of the cross-correlation, in the same way described for the single-channel case of Figure 3. Only the noise of the DUT is left to contribute to the measurement results.

In practical terms the noise floor of a cross-correlation phase noise measurement system is between 10 and 20 dB lower than the equivalent one-channel measurement system. To exploit the double-channel topology it is crucial to have the time delays of the two channels well matched. The main effect of a time delay mismatch is an abnormally high noise floor (sometimes higher than the single channel equivalent).

In Figure 5 the single-sided phase noise for the RNA and the *main amplifier* alone, measured with the double-channel system described above, are compared with the noise floor of the single-channel system used in [6]. The enhanced sensitivity of the double-channel system allowed measurement of noise levels up to 15 dB below the ones previously measured with the single-channel system.

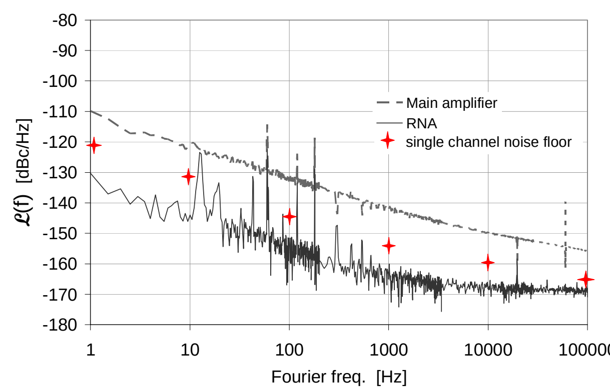

Figure 5. Measured one-sided phase noise power spectral density ***L(f)*** for the *main amplifier* alone (blue dashed line) and for the RNA (solid black line). The *main amplifier* is working in linearity (small signal conditions) whether alone or within the noise cancellation scheme. The RNA has a net gain of 20 dB and 1-dB compression point at P_{out}= 25 dBm for a 10 GHz carrier. The red crosses indicate the noise floor of the single-channel measurement system used in [6].

Both noise measurements are carried with signal levels that allow the *main amplifier* to work well within its linear region (small signal conditions) whether alone or within the noise cancellation system.

The *main amplifier* and the RNA phase noise shown in Figure 5 are summarized for different offset frequencies with respect to the carrier in Table 1, together with the amount of noise eliminated by the noise cancellation system (third row).

Single-sided power spectral density of phase noise $\mathcal{L}$(f)							
	Frequency offset with respect to the carrier at 10 GHz						
	1	**10**	**100**	**1 k**	**10 k**	**100 k**	**Hz**
Main amplifier	-110	-121	-132	-142	-150	-155	dBc/Hz
RNA	-132	-145	-155	-164	-167	-169	dBc/Hz
Cancelled noise	22	24	23	22	17	14	dB

Table 1. Measured single-sided power spectral density of phase noise $\mathcal{L}$(f) for the *main amplifier* alone (first row) and for the RNA (second row). In the third row is the difference between the two noise levels, which is the amount of noise removed by the feed forward noise cancellation system.

The *main amplifier* has been chosen close to the state of the art for commercially available microwave amplifiers.

As clearly shown by the figures in the second row of Table 1, the RNA exhibits close-to-carrier phase noise 23 dB better than the *main amplifier* alone (that is without the noise cancellation system).

This makes the RNA an amplifier working at X-band with a gain of 20dB, a 1-dB compression point at P_{out}=25dBm and a one sided-phase noise of -164 dBc/Hz at 1 kHz from the carrier.

IV. SYSTEMS LIMITATIONS

There are two kinds of limitations in the efficiency of the noise cancellation system: one is caused by the noise of the *noise amplifier* which cannot be eliminated, the other is due to the imperfect phase and amplitude conditions at the two summing points SUM_1 and SUM_2.

The noise figure of the *noise amplifier*, together with the coupling ratio of the first directional coupler (see γ_1 in Figure 1), sets the wideband phase noise level of the RNA. These two factor are responsible for the lower amount of cancellation achieved for offset frequencies above 1 kHz.

The amount of residual multiplicative noise (flicker noise) of the RNA is set primarily by amplitude and/or phase mismatches at both summing points. In particular a larger residual carrier as a result of mismatches at the first summing point increases the amount of multiplicative noise introduced by the *noise amplifier*.

A certain amount of multiplicative phase noise is produced by AM-to-PM conversion, mainly due to pahse mismatches at both summing points.

A detailed first-order analysis of the cancellation mechanism can be found in [6].

V. SUMMARY

An improved characterization of a feed forward noise cancellation scheme has been presented, together with the description of the improved measurement system that allowed it. Noise reductions larger that 20 dB have been repeatedly achieved for close-to-the carrier noise in X-band signals on already high quality power amplifiers.

The noise cancellation system as described in this paper can be applied to any amplifier.

The efficiency of this noise cancellation scheme is independent of the device it is applied to and can be used for any frequency band, making it a simple and powerful tool to enhance amplifiers noise performance.

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