Improved dynamic range for multi-tone signal using model-based pre-distortion

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Abstract- Some test and measurement applications require higher dynamic range for multi-tone signals than a signal generator can generate. Moreover, for other applications it can be interesting to improve the performance of a “low cost” signal generator. The spectral purity of generated signals can be improved by using pre-distorted base-band signals. In this paper, a dynamic grey-box model is described. A pre-distorter is used in order to improve the dynamic range. The results, which are based on measurements, show an improved dynamic range for a three-tone signal of approximately 9 dB and an improved ACPR of 5 dB for a WCDMA signal.

I. Introduction

In many applications a very accurate test signal is often required, e.g. ADC and receiver characterization/testing. Such a signal is often difficult to generate in practice due to the imperfections of the signal generator (SG). By characterizing the SG and use software based methods such as pre-distortion, the dynamic range can be improved. Moreover, in order to reduce production costs it can also be interesting to improve the performance of “low cost” signal generator to fulfill test requirements. The investigation of the imperfections in the signal generator that is done here is one step to compensate the measurements for these impairments. In Figure 1, a block scheme of a SG is shown. The IQ-modulator has a number of imperfections. The mixers, DACs and amplifiers are nonlinear, there can be a phase error, θ_0, in the 90 degree phase shifter, the two signal paths may have different gains and there can be dc offsets on one or both of the signal paths.

Some of these imperfections have been studied previously, see for example [1-4]. In addition to the impairments mentioned above the transmitter may exhibit linear distortion that is not discussed here. In [5, 6], an non-parametric, iterative method to create pure multi-tone signals using only power measurements were presented. However, the drawbacks of iterative correction are the large number of time consuming measurements needed and mainly the fact that this method gives a pre-distortion that is unique for a certain signal. In model-based pre-distortion, the pre-distorted signal is computed from a mathematical model of the imperfections mentioned above. It is thereby valid for all kind of signals as long as the signals are within the working conditions for the model.

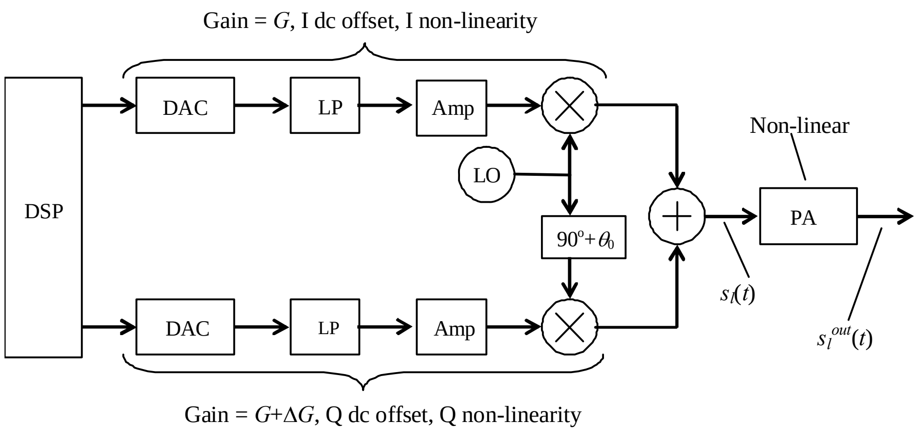

Figure 1: Imperfections on the signal generation side. There are numerous potential sources of error in a direct up-conversion transmitter, like unequal gain between the two paths, phase error in the phase shifter, nonlinearities and dc offsets.

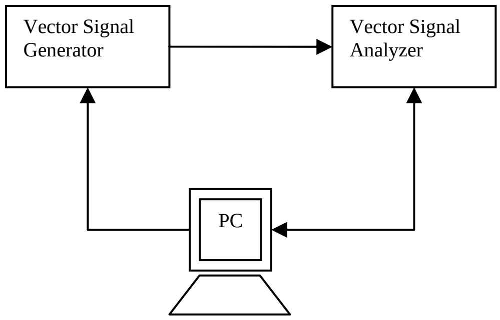

Figure 2: The measurement system. Test signals are generated by the PC and sent to the signal generator. The output signal if collected by the spectrum analyzer and proceded in the PC.

II. Method

The purpose is to improve the dynamic range of the SG. In order to reduce the distortion due to the intermodulation (IM) products in the SG a model-based pre-distortion is proposed. To build the pre-distorter, it is necessary to derive the model for the SG. In this paper a grey box modeling approach is used for modeling the SG i.e. partials knowledge of its internal architecture, as well as the mathematical analysis given in [4] will be taken in consideration.

The test setup used in this paper work is described in Figure 2. It consists of a SG (Rhode & Schwarz SMU200A), a signal analyzer (SA) (Rhode & Schwarz FSQ 26), and a personal computer (PC). The SG that will be modeled contains of two independent signal generators in one cabinet. Each channel are equiped with an arbitrary wave generator (AWG) with two digital to analog converter (DAC) up to 100MHz. The baseband signals are up-converted directly to the RF in the IQ-modulator. Finally, a power amplifier (PA) increase the signal to the required output power level. More details about the test set up-can be found in [4].

A model is a representation of a system by using a set of mathematical functions. Usually a system modelling is classified according to how much priori information about the system is available. That is, a white box model is a system where all the information is available, when there is no priori information of the system it is considered as a black box, and if the internal structure of a device is partial known and used in the modelling process it is denominated as a grey box modeling approach.

The number of coefficients in a grey box model can easily grow cumbersome. In order to reduce the complexity of the model negligible coefficients has been omitted. This is done by the following method: First the normalized means square error (NMSE) of the complete model is calculated, thereafter the negligible coefficients are reduced and a new NMSE is computed and compared with the complete model.

A single sinusoid is not a suitable signal for excitation when an identification of nonlinear terms is required. Instead, if a multi-tone is used, those nonlinear terms can be identified. In this paper, a three-tone technique was used for measuring nonlinear distortion. However, the method used is not limited to a three-tone signal. It can be extended to an arbitrary number of tones.

Pre-distortion technique relies on the concept of adding signals to the wanted input signal to produce at the output of the overall system the signal of interest without distortion [7]. It is simply to use the inverse of the SG model when generating the signal to the AWG.

III. Theory

Since a grey box approach is used to estimate the output of the SG the information of its internal structure mentioned in Section II, will be further described. The basic architecture of any AWG can be explained as follows: The samples defining the waveform are stored in a waveform-memory, this stored signal feeds a DAC at the rate defined by the time-resolution of the DAC and finally the signal is filtered and amplified. A block scheme of the SG is illustrated in Figure 1.

The input signal, $s(t)$, which will feed both DAC in the IQ-modulator, can be in general expressed in its envelope $r(t)$ and phase $\varphi(t)$ given by

$$s(t) = \mathrm{Re}\left\{ r(t) e^{j(\omega_c + \varphi(t))} \right\} \tag{1}$$

$$r(t) = \sqrt{x(t)^2 + y(t)^2} \tag{2}$$

$$\varphi = \arctan\left(\frac{y(t)}{x(y)} \right) \tag{3}$$

where ω_c is the carrier frequency and $x(t)$ and $y(t)$ are the in-phase (I) and quadrature-phase (Q) signal respectively. Now taken in consideration the impairments introduced by the IQ modulator, the complex envelope [8] output signal becomes.

$$s_l(t) = g_I(x(t)) - g_Q(y(t))\sin\theta_0 + jg_Q(y(t))\cos\theta_0 \tag{4}$$

where $g_I(\cdot)$ and $g_Q(\cdot)$ represents the nonlinear transfer functions in I and Q signal paths, respectively, and θ_0 is the phase error in the 90 degree phase shifter. To study these nonlinear functions a good approximation is to express them by polynomials series.

$$\begin{aligned} g_I(x(t)) &= a_0 + a_1x(t) + a_2x(t) + \dots \\ g_Q(y(t)) &= b_0 + b_1y(t) + b_2y(t) + \dots \end{aligned} \tag{5}$$

Let

$$d(t) = x(t) + jy(t) \tag{6}$$

$$x(t) = \frac{d(t) + d^*(t)}{2} \tag{7}$$

$$y(t) = j\frac{d(t) - d^*(t)}{2} \tag{8}$$

Then, by inserting (5) - (8) into (4) a static model of the IQ modulator will be expressed. The number of coefficients grows rapidly with the order of non-linearities that will be considered. A detailed expression for a fifth order static IQ modulator model is given in [4] and it contains of 13 coefficients. The number of coefficient can be reduced. The method for omitting negligible coefficient is given in Section II, but there are also other, aditional methods that can be used. When the method is applied for a SG the phase imbalance and the dc offset in the IQ-modulator can be adjusted in a first step, which simplifies the model and reduce the number of coefficients. An experience from this project is that that is the preferable method instead of using pre-distortion to compensate for IQ imbalance.

Also the PA which present into the SG will contribute to the distortion at the output. A model for the PA which takes AM/AM and AM/PM distortion is given by

$$z(t) = h(r(t))e^{j\varphi(t)} \tag{9}$$

where $z(t)$ is the PA output and $h(t)$ is the complex function of the combined AM/AM and AM/PM functions represented by $g(\cdot)$ and $f(\cdot)$, respectively.

$$h(t) = g(r(t))e^{f(r(t))} \tag{10}$$

If the AM/PM distortion is small enough then $g(\cdot)$ and $f(\cdot)$ can be represented as polynomials Tailor expanded and $h(\cdot)$ can be given as polynomial with complex coefficients. The expression can be reduced to include only odd order coefficient since only inband distortion is considered [4, 9, 10]. If only the odd-order is considered and the IQ-modulator can be balanced, then (9) can alternative be written as

$$z(t) = h_1 s_l + h_3\left|d\right|^2 d + h_5\left|d\right|^4 d + \dots \tag{11}$$

Due to the spectrum imbalance for the IM products observed in the SG, and since asymmetries of upper and lower 3^{rd} order IM-products are ways of indicating memory effects [11] then, in addition the memory effects will be considerer into the model, therefore the model will also include a delayed sample in order to include the effects of the LP-filters shown in Figure 1, i.e. the output of the SG will be function of the current and previous input values. The model for the used SG will , after parameter reduction be:

$$s_l^{out}(n) = \sum_{m=0}^{M} \left\{ \begin{array}{l} c_0 + c_{1,m} d(n-m) + c_{2,m} \left(\left| d(n-m) \right|^2 d(n-m) + \dfrac{d^{*3}(n-m)}{3} \right) \\ + c_{3,m} \left(\left| d(n-m) \right|^2 d^2(n-m) \right) + c_{4,m} \left| d(n-m) \right|^2 d^{*2}(n-m) \\ + c_{5,m} \left| d(n-m) \right|^4 d(n-m) + c_{6,m} \left| d(n-m) \right|^4 d^{*}(n-m) \end{array} \right\}, \qquad (12)$$

where M is the memory depth of the model. To improve the output of the SG a model-based pre-distortion approach will de used. That is, the waveform stored in the waveform memory is pre-processed so that when it passes the IQ-modulator and the PA results in the required signal. In this summary the pre-distorter has the same form as the SG model. The pre-distorter coefficients are calculated so that the distortion and IM products are cancelled out. Equation (13) shows the expression used for pre-distorter.

$$DPD(n) = \sum_{m=0}^{M} \left\{ \begin{array}{l} q_0 + q_{1,m} d(n-m) + q_{2,m} \left(\left| d(n-m) \right|^2 d(n-m) \right) \\ + q_{3,m} \dfrac{d^{*3}(n-m)}{3} + q_{4,m} \left(\left| d(n-m) \right|^2 d^2(n-m) \right| + d(n-m) \left|^2 d^{*2}(n-m) \right) \\ + q_{5,m} \left| d(n-m) \right|^4 d(n-m) + q_{6,m} \left| d(n-m) \right|^4 d^{*}(n-m) \end{array} \right\} \qquad (13)$$

IV. Results

A 5th order nonlinearity with one time step memory depth was used in these measurements. All coefficients in the complex model of the SG given by (11) were estimated. In order to reduce the model complexity the negligible coefficient were removed. The reduced model were evaluated by measuring the NMSE and compare with the NMSE for the full model. The number of parameters was reduced by 50 % within approximately 1 dB preserved NMSE.

The performances of the memory polynomial pre-distorter were evaluated by measurements on a three tone and a WCDMA signal, respectively. The output power spectrum from the SA before and after the pre-distortion are measured. The results from the three-tone measurements are presented in Figure 3. It shows that the dynamic range has improved by approximately 9 dB from slightly less than 59 dBc to just over 67 dBc. The model was also verified for a WCDMA signal shown in the Figure 4. The improvement obtained in the adjacent channel power ratio (ACPR) is 5.7 dB.

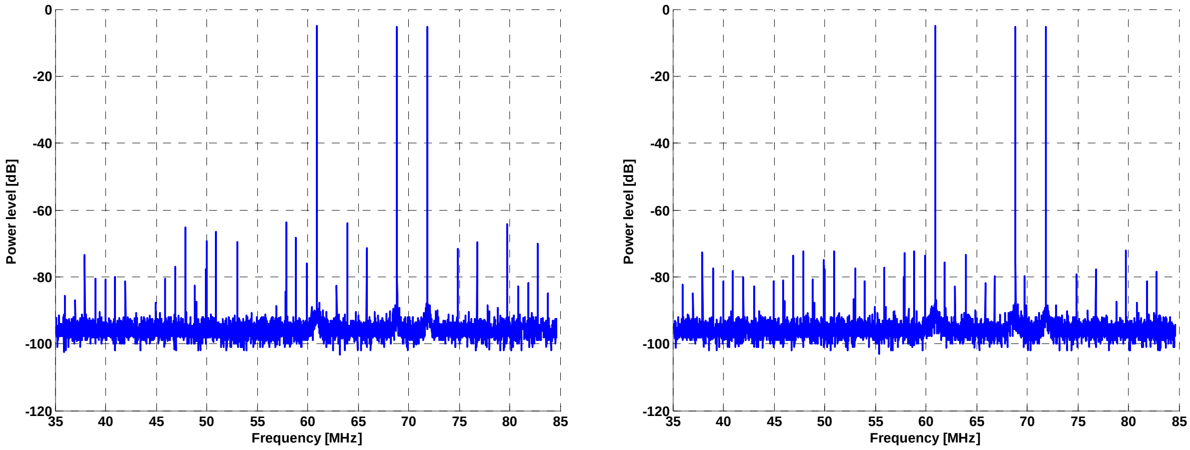

Figure 3: A three-tone signal with 59 dBc spectral purity before correction (left most) and 67 dBc after (right most).

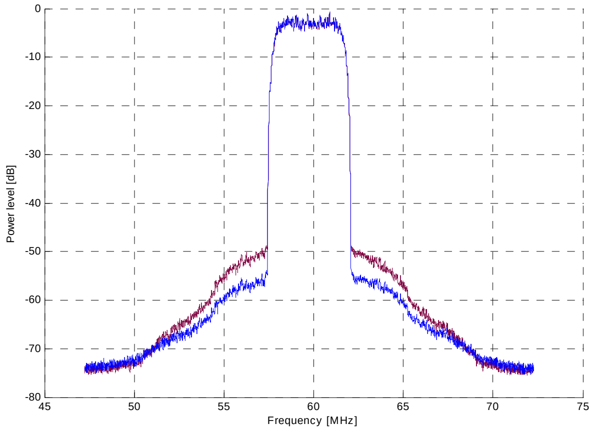

Figure 4: Improvement in ACPR obtained using pre-distortion of the signal generator. The red curve is the signal before the pre-distortion and blue is the signal after the pre-distortion is applied.

V. Conclusions

In this paper a dynamic grey-box model of a signal generator is presented. The model is then applied in a pre-distorter to eliminate unwanted spectral components and thereby improve the spectral purity when using multi-tone signals. The improvement is a requirement for many test and measurement applications, e.g. receiver and ADC characterization and a possibility to reduce cost in other applications. The advantage with a model-based pre-distortion is that it is generally applicable for arbitrary signals. Once the model is estimated, it can be used for almost any signal within the working range the model. The results are base on a fifth order polynomial model with a memory depth of one time step. The model is reduced to 13 coefficients and applied for pre-distortion for two different signals; one three-tone and one WCDMA signal. The results show an increased dynamic range of 9 dB for the three-tone signal and 5.7 dB lower ACPR for the WCDMA signal.

Acknowledgments

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