Automatic Feed-Forward Cancellation of Modulated Harmonic

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Abstract — This paper presents an algorithm for the simultaneous linearization and cancellation of modulated harmonics of broadband power amplifiers (PA). The algorithm relies on a joint system identification of the nonlinearity, memory effects and group delay of both the main and harmonic cancellation channels using a recently reported cubic spline basis. The filter-less cancellation of the modulated harmonics uses both the method of predistortion and feedforward distortion while the synchronized PA linearization relies solely on digital predistortion. Experimental verification with a broadband PA yields a reduction of 31 dB of the third harmonic to 59 dBc below the main channel. Simultaneously the linearization provides -40 dB NMSE and 49.5 and 50 dBc ACPR at the fundamental frequency.

Index Terms — Harmonic cancellation, PA linearization, digital predistortion, cubic spline, concurrent multiband PA.

I. INTRODUCTION

Growing demand for higher data rate pushes the development of ultra-wideband and multiband systems. When the separation between two bands becomes large, harmonics of the lower band signal start to interfere with the higher band’s signal. In order to suppress the interfering harmonic in concurrent multi-band transmission system, the solution of using bulky and lossy switchable filter banks is common practice. However, digitally-controlled feed-forward harmonic cancellation is emerging as an alternative solution because of the frequency programming flexibility this filter-less solution brings to multi-band transmission system.

Active harmonic cancellation uses an upper band channel to send a cancelling signal which is in opposite-phase (180 phase shift) to the modulated RF harmonics generated by the broadband nonlinear power amplifier (PA) from the lower band signal. The system requires thus the careful characterization of the modulated harmonics [1]. Further, due to the upper band channel’s group delay, nonlinearity and dispersion, a frequency-selective correction for the gain, phase shift and time delay must be applied to the cancelling signal so that it exactly cancels the harmonics at the coupler placed after the PA. In a previous report [1] this three-fold adaptation of the cancelling signal was performed manually. In this work, a joint PA distortion modelling and compensation algorithm is developed to ensure that the cancellation is automatic.

The remainder of this paper is organized as follows. Section II explains the principle of the digitally supported feed-forward harmonic cancellation. Section III describes the measurement test bed that is used as a proof of concept for demonstrating the filter-less cancellation of the modulated third harmonic signal generated by a wide band PA. Section IV presents the results obtained to validate the theory.

II. AUTOMATIC CANCELLATION ALGORITHM

A. Feed-forward harmonic cancellation

Figure 1 shows the feedforward harmonic cancellation scheme. In the phase of concept-proving, the upper band channel is only used to send a cancelling signal to sum it up with the signal in the lower band channel after the PA. The output of the PA contains the amplified fundamental signal and different orders of harmonics caused by the PA’s nonlinearity. As indicated in Section I, the cancelling signal is 180 degree out of phase from one of the p-th order harmonic which is meant to be cancelled. Therefore, the p-th harmonic should be cancelled at the combiner after the PA when it is summed up with its 180 degree out-of-phase version. The negative version of the p-th harmonic is generated digitally based on the behavioral model of the PA to predict the real harmonic. To achieve effective cancelling result, two key features are required: (1) the accurate harmonic modelling and (2) the accurate modelling and compensation for the channel’s distortion and delays in the cancelling signal by upper channel.

![Fig. 1. Digital feed forward harmonic cancellation scheme.](image-url)

The first key point can be guaranteed by using effective modelling tools such as memory polynomial in case of a moderately nonlinear PA [1]. On the other hand, fast and accurate modelling and compensation for the cancelling channel’s distortion remains a hurdle in the way of harmonic cancellation’s application in practical time-variant transmission system. Given the distortions and delay of the upper band channel, the cancelling signal needs to be predistorted to compensate for those distortions to exactly cancel the modulated harmonic at the PA output. Therefore, accurate model of the distortions and delay is also required to achieve proper compensation. Previous digitally supported feed-forward harmonic cancellation scheme [1] adopted a manual
adjustment of the cancelling signal’s amplitude, phase and time delay based on a trial-and-error method. This work presents a faster and more accurate modelling and predistortion algorithm to enable the automatic feedforward cancellation of the \(p\)-th harmonic of PA.

**B. System Identification**

![System identification scheme](image)

To conduct the system identification, i.e., to obtain the needed modelling parameters of the two channels, two sets of signal \(x_1\) and \(x_2\) are transmitted simultaneously through the two channels. As shown in Fig. 2, the purple signal \(RF_{\text{feed}}\) sent through the PA channel is for PA channel identification and the red signal \(RF_{\text{harm}}\) sent through the cancelling channel at the frequency band of the \(p\)-th harmonic is used for the cancelling channel identification. A generalized behavioral model is used to represent the multi-harmonic output of the PA channel main channel, as follows:

\[
y_{1,p} = \sum_{m=0}^{M-1} G_{1,p,m} \left| x_1(n-m) \right|^2 \cdot x_1^p(n-m) \quad @p\omega.
\]  

In (1), \(y_{1,p}\) is the output of the system at the fundamental or \(p\)-th harmonic. \(x_1(n-m)\) is the input of the corresponding band with memory delay term \(m\). \(M\) is the memory depth. Memory delay terms are included in the model to account for the frequency dependence of the PA nonlinearities in wideband communication system [2]. \(G_{1,p,m}(\left| x_1(n-m) \right|^2)\) are the gain functions of each delay channel, which are a function of the envelope squares of the signal in the corresponding channel. These gain functions can be implemented in different forms such as memory polynomials and splines, to represent the higher order nonlinearity caused by the PA. This model thus takes into account both the PA’s \(p\)-th modulated harmonics for cancellation purpose as well as its in-band intermodulation terms for in-band linearization purpose. Although the feed-forward cancelling channel is not typically driven in strong saturation, a similar model can also be used as will be discussed next.

There are two requirements for the identification signal \(x_2\) in the cancelling channel (\(RF_{\text{harm}}\) in Fig. 2). First, it has to be uncorrelated to the identification signal \(x_1\) used for the PA channel. Since the identification signal in the cancelling channel occupies the same frequency band as the \(p\)-th harmonic to be cancelled, the two signals will overlap after the coupler combining them. Being uncorrelated enables us to separate them in the digital domain to identify the corresponding gain functions of the two channels. Second, because the channel’s distortion extends over a \(p\)-th time the bandwidth and exhibits an amplitude varying within a certain dynamic range, the identification signal should have a bandwidth that covers the entire frequency band that the \(p\)-th harmonic to be cancelled occupies and exhibits peaks with larger amplitude than the \(p\)-th harmonic of the PA.

At the \(p\)-th harmonic frequency, the received signal is as follows:

\[
y_2(n) = y_{2,1}(n) + y_{1,p}(n) \quad @p\omega \text{ with}
\]

\[
y_{2,1} = \sum_{m=0}^{M-1} G_{2,1,m} \left| x_2(n-m) \right|^2 \cdot x_2(n-m)
\]

\[
y_{1,p} = \sum_{m=0}^{M-1} G_{1,p,m} \left| x_1(n-m) \right|^2 \cdot x_1^p(n-m)
\]

The component \(y_{1,p}\) is the modelled PA \(p\)-th harmonic introduced in (1) and the component \(y_{2,1}\) is the modelled version of the output of the cancelling channel. \(G_{1,p,m}(\left| x_1(n-m) \right|^2)\) is the gain function on which the modelling of \(p\)-th harmonic is based and \(G_{2,1,m}(\left| x_2(n-m) \right|^2)\) is the gain function that models the distortions and delay of the cancelling channel. Utilizing the least-square method, the gain functions in (2) can be readily extracted. For accurate representation, we use cubic-spline [2] with 4 bases to represent the gain functions of the two channels. The fidelity of the model can be verified by comparing the modelled signal \(y_2\) with the measured one.

**C. Digital Predistortion**

![Predistortion and harmonic cancellation scheme](image)

The negative version of the modelled \(y_{1,p}\) should be sent to the PA output to cancel its \(p\)-th harmonic, but in consideration of the second key point mentioned in section II A, this signal has to be pre-distorted in order to compensate for the cancelling-channel’s distortion and delay. Thus digital predistortion (DPD) is used to fulfill this purpose. A block called predistorter is added in the digital domain before the DAC to predistort the cancelling signal \(y_{1,p}\).

The parameters of the predistorter are calculated by the method of indirect learning [3]. For this method, the predistorter is an inverse model of the channel, as in (3):
\[ x_2 = \sum_{m=0}^{M-1} G_{2,1,m}^{(i)} \left| y_{2,1}(n-m) \right|^2 y_{2,1}(n-m). \]  

(3)

\[ G_{2,1,m}^{(i)}(y_{2,1}(n-m))^2 \] is the gain function of the inverse model or namely the predistorter. This gain functions can be calculated from \( y_{2,1} \) obtained from the dual band system identification. Then we predistort the cancelling signal \( -y_{1,p} \) by substituting \( -y_{1,p} \) for \( y_{2,1} \) in (3) while using the gain functions of the predistorter \( G_{2,1,m}^{(i)}(y_{1,p}(n-m))^2 \) just extracted:

\[ z_2 = \sum_{m=0}^{M-1} G_{2,1,m}^{(i)} \left| y_{1,p}(n-m) \right|^2 (-y_{1,p}(n-m)). \]  

(4)

\( z_2 \), as shown in Fig. 3, is the predistorted cancelling signal, which will yield the desired \(-y_{1,p}\) signal at the combiner after experiencing all the distortions and delay from the cancelling channel. We use the same predistortion procedure for the desired fundamental signal at the same time to reduce the in-band intermodulation caused by the PA.

III. MEASUREMENT SETUP

The cancellation of the third harmonic generated by a Mini Circuit ZX60-14012L+ PA is done as a proof of concept. Figure 2 shows the system diagram of the test bed setup. A set of 10 MHz bandwidth LTE signal is used as the fundamental signal transmitted in the lower band through the PA channel, and a set of 30 MHz bandwidth WCDMA signal is transmitted in the upper band through the cancelling channel in the system identification procedure. Digital predistortion of the upper band cancelling signal is done within MATLAB and the predistorted data is then stored in an Arria V FPGA which is used to pass the digital data to two 16-bit DACs at a sampling rate of 307.2MHz, incorporated in a dual-band transmitter Texas Instrument board TSW30SH84. Then the fundamental signal in lower band and the cancelling signal (or identifying signal) in the upper band are transmitted simultaneously by the dual band transmitter. The center frequencies are 888.4 MHz and 2665.2 MHz for lower band and upper band signals, respectively. The output signal of the combiner is received by the TSW1266 receiver board after passing a set of filters and switch used to tuned the IQ demodulator to the desired band. Within the receiver, the received data are down-converted, sampled and digitized by the ADC’s at a sampling rate of 614.4MHz and stored in the FPGA, before being passed to MATLAB for analysis.

IV. RESULT AND DISCUSSION

In Fig 4b, the right part shows the comparison of the original third harmonic signal and the cancellation result. The third harmonic is suppressed by 31 dB. Since the upper band does not impact the lower band, the lower band signal can still be linearized by digital predistortion method as shown in Fig 4a.

![Fig. 4](image-url)

Table I summarized the measurement results. Harmonic model NMSE is the normalized mean square error of the modelled 3rd harmonic, i.e., \( y_{1,j} \) compared to the actual 3rd harmonic. Harmonic before and after cancellation is the harmonic strength relative to the fundamental signal.

<table>
<thead>
<tr>
<th>Evaluation Criterion</th>
<th>Measured Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harmonic Model NMSE</td>
<td>-49.5 dB</td>
</tr>
<tr>
<td>Harmonic before cancelling</td>
<td>-28 dBc</td>
</tr>
<tr>
<td>Harmonic after cancelling</td>
<td>-59 dBc</td>
</tr>
<tr>
<td>Harmonic cancellation</td>
<td>31 dB</td>
</tr>
<tr>
<td>Main Channel NMSE after DPD</td>
<td>-40.1 dB</td>
</tr>
<tr>
<td>ACPR after DPD (LSB,USB)</td>
<td>-49.5,-50.3 dB</td>
</tr>
</tbody>
</table>

V. CONCLUSION

This work presents a digital solution for a fast and accurate channel distortion modelling and compensation of broadband PAs that enables an automatic harmonic cancellation via feed-forward and linearization via predistortion.

VI. ACKNOWLEDGEMENT

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REFERENCES

