Efficient low-power design and implementation of IQ-imbalance compensator using early termination.

Ediz Cetin¹
Izzet Kale¹,²
Richard C.S. Morling¹

¹ School of Informatics, University of Westminster
² Applied DSP and VLSI Research Centre, Eastern Mediterranean University


This material is posted here with permission of the IEEE. Such permission of the IEEE does not in any way imply IEEE endorsement of any of the University of Westminster's products or services. Internal or personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution must be obtained from the IEEE by writing to pubs-permissions@ieee.org. By choosing to view this document, you agree to all provisions of the copyright laws protecting it.

The WestminsterResearch online digital archive at the University of Westminster aims to make the research output of the University available to a wider audience. Copyright and Moral Rights remain with the authors and/or copyright owners. Users are permitted to download and/or print one copy for non-commercial private study or research. Further distribution and any use of material from within this archive for profit-making enterprises or for commercial gain is strictly forbidden.

Whilst further distribution of specific materials from within this archive is forbidden, you may freely distribute the URL of the University of Westminster Eprints (http://www.wmin.ac.uk/westminsterresearch).

In case of abuse or copyright appearing without permission e-mail wattsn@wmin.ac.uk.
Efficient Low-Power Design and Implementation of IQ-Imbalance Compensator using Early Termination

Ediz Cetin*, Izzet Kale** and Richard C.S. Morling*
*Applied DSP and VLSI Research Group, Department of Electronic Systems, University of Westminster, London, W1W 6UW, United Kingdom
**Applied DSP and VLSI Research Centre, Eastern Mediterranean University, Gazimagusa, Mersin 10, KKTC {e.cetin, kalei, morling}@wmin.ac.uk

Abstract—In this paper, we propose a low-complexity architecture for the implementation of adaptive IQ-imbalance compensation in quadrature zero-IF receivers. Our blind IQ-compensation scheme jointly compensates for IQ phase and gain errors without the need for test/pilot tones. The proposed architecture employs early-termination of the iteration process; this enables the powering-down of the parts of the adaptive algorithm thereby saving power. The complexity, in terms of power-down efficiency is evaluated and shows a reduction by 37 - 50 % for 32-PSK and 37 - 58 % for 64-QAM modulated signals.

I. INTRODUCTION

Receivers utilising IQ-signal processing are vulnerable to mismatches between the in-phase (I) and quadrature (Q) channels. IQ-imbalance can cause large degradation in communications receiver’s performance. Furthermore, with large signal constellations of M-QAM/PSK even modest IQ-imbalance results in detrimental performance degradation. Both analog and digital methods for dealing with IQ-imbalance have been reported in the literature [1] – [4]. All of the reported digital approaches are software based and thus not suitable for direct hardware implementation. This paper deals with efficient low-power implementation of such software based IQ-compensation algorithm developed and analysed in [5]. This paper highlights a key technique to significantly reduce the power consumption of the adaptive algorithm. Power consumption reduction by predicting when the adaptive algorithm has converged to a good solution and stopping the adaptation of the adaptive filter at that point is discussed. Simulation case studies show that the proposed technique can achieve significant computation and hence energy savings.

The paper is organized as follows: In Section II we tackle IQ-imbalance problem and give brief description of the adaptive IQ-imbalance compensation algorithm. Section III explains the early termination strategy and sets about establishing criterion for early termination. Section IV describes the performance analysis and simulation results, while concluding remarks are given in Section V.

II. IQ-IMBALANCES AND ADAPTIVE IQ-IMBALANCE COMPENSATION ALGORITHM

This section is a brief summary of [5] which introduces the IQ-imbalances and Blind-Source-Separation (BSS) based adaptive compensation scheme.

A. IQ-Imbalances

Sources of IQ-imbalances in the receiver are: the RF splitter used to divide the incoming RF signal equally between the I and Q paths which may introduce phase and gain differences as well as the differences in the length of the two RF paths can result in phase imbalance. The quadrature 90° phase-splitter used to generate the I and Q Local-Oscillator (LO) signals that drive the I and Q channel mixers may not be exactly 90°. Furthermore, there might be differences in conversion losses between the output ports of the I and Q channel mixers. In addition to these, filters and ADCs in the I and Q paths are not perfectly matched.

The IQ-imbalances can be characterized by two parameters: the amplitude mismatch, \( \alpha_a \) and the phase orthogonality mismatch, \( \varphi_p \) between the I and Q branches. The complex baseband equation for the IQ-imbalance effects on the ideal received signal \( r_{\text{IQR}}(k) \) is given as:

\[
r_{\text{IQR}}(k) = g_1[i_1(k) \cos(\varphi_p / 2) + u_Q(k) \sin(\varphi_p / 2)] \\
+ j g_2[i_1(k) \sin(\varphi_p / 2) + u_Q(k) \cos(\varphi_p / 2)] \\
+ \frac{1}{2}[2 \cos(\varphi_p / 2) - j \alpha_e \sin(\varphi_p / 2)] a(t) + (\alpha_e \cos(\varphi_p / 2) + j 2 \sin(\varphi_p / 2) \alpha_e^* a(t)]
\]

where \( g_1 = (1+0.5\alpha_e), \ g_2 = (1-0.5\alpha_e) \) and \( (*)^* \) is the complex conjugate. Amplitude-imbalance, \( \beta \), in decibels is obtained from amplitude mismatch, \( \alpha_e \) as:

\[
\beta = 20 \log_{10}\left[1 + 0.5\alpha_e / 1 - 0.5\alpha_e\right]
\]
It can be observed that in the presence of IQ-imbalances I and Q channels are no longer orthogonal and correlated with each other. Fig. 1 demonstrates the effects of varying the IQ phase and gain mismatches on the raw Bit-Error-Rate (BER) performances of the systems using (a) 32-PSK and (b) 256-QAM modulation formats. As can be observed the IQ-imbalances degrade the system’s BER performance greatly.

![Figure 1. The effects of IQ-imbalances on BER of (a) 32-PSK and (b) 256-QAM modulated signals.](image)

This degradation in performance is surely not desirable and must be compensated. Next sub-section outlines an adaptive algorithm developed for compensating for these impairments.

B. Blind-Source-Separation based Adaptive Compensation

Our approach to the problem is to develop an adaptive BSS based system that can operate without pilot/test tones, by simply processing the received signals. The only assumption we make is that the I and Q components of the received signal, $r_I(k)$ and $r_Q(k)$, in the absence of impairments are orthogonal and not correlated with each other.

Overall structure of the proposed approach is depicted in Fig. 2, with IQ-imbalances modeled as unknown scalar mixing matrix.

![Figure 2. Structure for BSS based adaptive compensator.](image)

In the proposed approach the filter block consists of 2-taps, $w_1$ and $w_2$. Output signals $c_I$ and $c_Q$ can be expressed as a function of transmitted signals as:

$$c_I(k) = (1 - w_1 h_2) s_I(k) + (h_2 - w_1) s_Q(k)$$
$$c_Q(z) = (h_2 - w_2) s_I(k) + (1 - w_2 h_1) s_Q(k)$$

where $h_1$ and $h_2$ are given in (1). When the filters converge, i.e. $w_1 = h_1$ and $w_2 = h_2$ then the source estimates become:

$$c_I(k) = (1 - h_1 h_2) s_I(k)$$
$$c_Q(k) = (1 - h_2 h_1) s_Q(k)$$

As can be observed the influence of the IQ-imbalances have been removed. Also, $(1 - h_1 h_2) \approx 1$ and can be safely ignored. The coefficient update can be done with any algorithm depending on the desired performance. Least-Mean-Square (LMS) and Recursive-Least-Squares (RLS) algorithms being the most obvious ones resulting in different convergence speeds and computational complexities. The LMS [6] algorithm is used in this paper due to its low-complexity making it suitable for real-time systems and practical for integration into the receiver signal processing chains.

III. EARLY TERMINATION SCHEME FOR LOW-POWER

The goal of the early termination scheme is to determine when the algorithm has converged to a good enough solution in order to stop the excess computations that are contributing little to the final solution hence reducing power consumption. In rare cases the adaptive algorithm will require the maximum number of iterations to guarantee good convergence. However, the average number of iterations is typically much smaller than the worst case scenario. This section deals with the design of such early termination circuit enabling reduced power. Mean Image-Rejection-Ratio (IRR) was used as a performance measure. This is a measure to show how good the hardware implementation is working in eliminating IQ-imbalances, the higher the IRR the better the performance. This can be mathematically expressed in decibels as [5]:

$$IRR(\sigma_x, \sigma_z) = 10 \log \left( \frac{2 - 2 \cos \sigma_x + 0.5 \sigma_z^2}{2 + 2 \cos \sigma_x + 0.5 \sigma_z^2} \right)$$

A. Image-Rejection-Ratio and the Number of Iterations

In order to establish the link between the IRR that can be achieved and the number of iterations required, we have carried out simulation case studies utilising 32-PSK and 64-QAM modulation formats. Phase and gain errors are randomly distributed between 0 - 30° and 1 - 3 dB respectively. Results are averaged over 100 experiments. Fig. 3 depicts these studies. Table 1 on the other hand shows the number of iterations required to achieve a given IRR.

![Figure 3. Mean IRR vs Number of iterations for (a) 32-PSK and (b) 64-QAM modulated signals.](image)

In Fig. 3, the solid black line represents the mean IRR averaged over 100 runs. IRR for each run is also superimposed. As can be observed we do not require the maximum number of iterations to achieve acceptable IRR values. For example on average to achieve 50 dB of IRR the number of iterations required is 12820 and 13520 for 32-
PSK and 64-QAM systems respectively. There is no need to carry on running the adaptive algorithm further than that. This early termination undoubtedly will save power consumption by pruning unnecessary iterations. However, an important issue is knowing when to terminate the algorithm. This will be discussed in the next section.

**TABLE I. **NUMBER OF ITERATIONS REQUIRED FOR A GIVEN IRR

<table>
<thead>
<tr>
<th>IRR (dB)</th>
<th>Number of Iterations Required</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>32-PSK</td>
</tr>
<tr>
<td>20</td>
<td>9749</td>
</tr>
<tr>
<td>30</td>
<td>11490</td>
</tr>
<tr>
<td>40</td>
<td>12350</td>
</tr>
<tr>
<td>50</td>
<td>12820</td>
</tr>
<tr>
<td>60</td>
<td>13330</td>
</tr>
<tr>
<td>70</td>
<td>13880</td>
</tr>
</tbody>
</table>

B. Stopping Criterion and Determination of Threshold

They key to early termination of the adaptation is to have an accurate measure/criterion of when the filter has converged to a good acceptable solution. In this paper we will use cross-correlation between the I and Q signals at the output of the adaptive algorithm as stopping criteria. We will set a threshold on the cross-correlation at the output of the adaptive algorithm; hence, the adaptive algorithm will continue to adapt until the cross-correlation drops below the pre-determined threshold. If the threshold is set too low, the adaptive algorithm will stop earlier than required, degrading the system performance. On the other hand, if the threshold is set too high, the adaptive algorithm will perform needless operations hence consuming power.

Fig. 4 depicts the cross-correlation and IRR for (a) 32-PSK and (b) 64-QAM modulated signals.

![Cross-correlation and IRR graphs](image)

As can be observed the cross-correlation is somewhat noisy to use especially for 64-QAM case. To eliminate this we propose the use of averaging. Performance in terms of number of averages is depicted in Fig. 5 (a) – (f).

![Cross-correlation and IRR graphs](image)

As can be observed averaging smoothed out the cross-correlation values making them more suitable for early-termination use. Number of averages we use, N, is chosen to be four.

![Overall BSS structure with Early Termination Circuit](image)

C. Early Termination Circuit

The overall BSS-based compensator structure incorporating the early termination circuit is shown in Fig. 6. The early-termination block computes the cross-correlation and averages it through an N-point moving averager and then compares the cross-correlation value to the pre-determined threshold and flags a terminate command if the averaged cross-correlation value drops below a threshold.
As can be observed, the hardware overhead due to early-termination is not significant. Divide by N is implemented as a simple shift operation since N is a power of two. In the next section we will analyze the gains one can obtain by using this early-termination block.

IV. PERFORMANCE EVALUATION

The effectiveness of the use of early-termination block is demonstrated in this section.

A. Simulation Set-Up

The performance of the proposed structure is analyzed considering 32-PSK and 64-QAM modulated signals with ideal symbol rate sampling. Channel is assumed to be AWGN and the phase and gain errors are distributed between 1° to 15° and 1 to 3 dB respectively.

To measure the efficiency of the proposed scheme, we define the power-down efficiency $P_{\text{down}}$ as:

$$P_{\text{down}}(\%) = 100 \times \left[1 - \frac{\text{Number iterations}}{\text{Total Number of iterations}}\right]$$

This gives us a good factor in terms of savings we are making. Higher $P_{\text{down}}$ value the higher the energy savings. Furthermore, IRR is also used during the performance evaluation.

B. Results and Discussions

Figs. 7 and 8 depict the IRR performance of the proposed system for varying phase and gain errors. As can be observed the use of early-termination has caused no degradation to IRR that can be achieved. Furthermore, by observing Figs. 9 and 10, we can see that the use of early-termination results in worse case power-down efficiency of 36%. Insets in these figures show $P_{\text{down}}$ values for small variations of phase (1°-1.3°) and gain (1 – 1.5 dB) errors. For small phase/gain errors $P_{\text{down}}$ efficiency is pretty high, as the impairments increase $P_{\text{down}}$ efficiency decreases. An interesting trend is observed for 64-QAM case where $P_{\text{down}}$ does not change much with the increased phase error above 10°.

V. CONCLUDING REMARKS

Low-power implementation of an I/Q imbalance compensation method based on early-termination to significantly reduce the power consumption has been presented and analysed. Simulation results show that the proposed technique can achieve significant computation and hence energy savings. In terms of power-down efficiency a reduction by 37 - 50 % for 32-PSK and 37 - 58 % for 64-QAM modulated signals can be achieved.

REFERENCES