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

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Efficient Low-Power Design and Implementation of *IQ*-Imbalance Compensator using Early Termination

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***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*-imbalances can cause large degradation in communications receiver's performance. Furthermore, with large signal constellations of *M*-QAM/PSK even modest *IQ*-imbalances results in detrimental performance degradation. Both analog and digital methods for dealing with *IQ*-imbalances 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, α_ε and the phase orthogonality mismatch, φ_ε between the *I* and *Q* branches. The complex baseband equation for the *IQ*-imbalance effects on the ideal received signal $r_{IQ}(k)$ is given as:

$$\begin{aligned} r_{IQ}(k) &= g_1[u_I(k)\cos(\varphi_\varepsilon/2) + u_Q(k)\sin(\varphi_\varepsilon/2)] \\ &\quad + jg_2[u_I(k)\sin(\varphi_\varepsilon/2) + u_Q(k)\cos(\varphi_\varepsilon/2)] \\ &= \tfrac{1}{2}[\underbrace{(2\cos\tfrac{\varphi_\varepsilon}{2} - j\alpha_\varepsilon\sin\tfrac{\varphi_\varepsilon}{2})}_{h_1}u(t) + \underbrace{(\alpha_\varepsilon\cos\tfrac{\varphi_\varepsilon}{2} + j2\sin\tfrac{\varphi_\varepsilon}{2})}_{h_2}u^*(t)] \end{aligned} \tag{1}$$

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

$$\beta = 20\log_{10}\left[1 + 0.5\alpha_\varepsilon / 1 - 0.5\alpha_\varepsilon\right] \tag{2}$$

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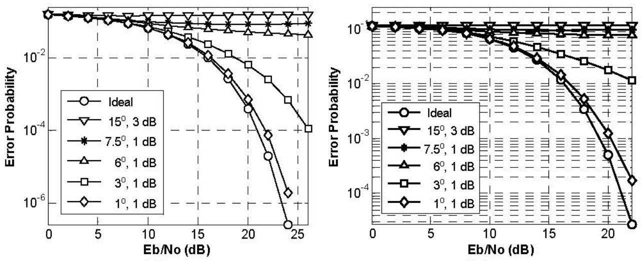
It can be observed that in the presence of *IQ*-imbalances I and Q channels are no longer orthogonal and correlated with each other. Fig. 1 demonstrates the effects of varying the *IQ* phase and gain mismatches on the raw *Bit-Error-Rate* (BER) performances of the systems using (a) 32-PSK and (b) 256-QAM modulation formats. As can be observed the *IQ*-imbalances degrade the system's BER performance greatly.



(a) (b)

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

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 witch each other.

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

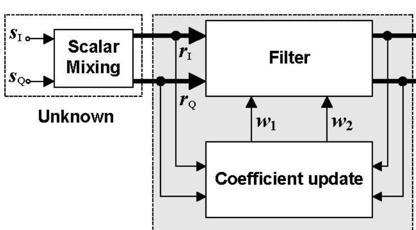


Figure 2. Structure for BSS based adaptive compensator.

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:

$$\begin{aligned} c_I(k) &= (1-w_1h_2)s_I(k)+(h_1-w_1)s_Q(k) \\ c_Q(z) &= (h_2-w_2)s_I(k)+(1-w_2h_1)s_Q(k) \end{aligned} \tag{3}$$

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:

$$\begin{aligned} c_I(k) &= (1-h_1h_2)s_I(k) \\ c_Q(k) &= (1-h_2h_1)s_Q(k) \end{aligned} \tag{4}$$

As can be observed the influence of the IQ-imbalances have been removed. Also, $(1\text{-}h_1h_2) \approx 1$ 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.

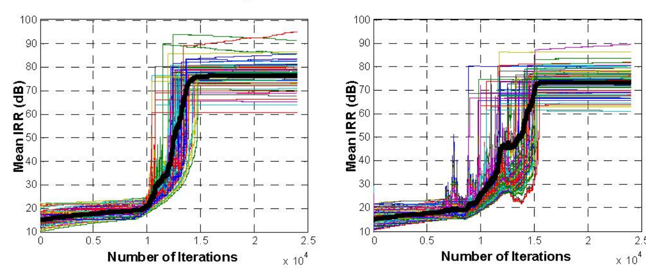
III. Early Termination Scheme For Low-Power

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 worse 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]:

$$IRR(\alpha_\varepsilon,\varphi_\varepsilon) = 10\log\left(\frac{2-2\cos\varphi_\varepsilon+0.5\alpha_\varepsilon^{\,2}(1+\cos\varphi_\varepsilon)}{2+2\cos\varphi_\varepsilon+0.5\alpha_\varepsilon^{\,2}(1-\cos\varphi_\varepsilon)}\right) \tag{5}$$

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 I on the other hand shows the number of iterations required to achieve a given IRR.



(a) (b)

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

In Fig. 3, the solid black line represents the mean IRR averaged over 100 runs. IRR for each run is also super-imposed. 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

IRR (dB)	Number of Iterations Required	
	32-PSK	*64-QAM*
20	9749	8855
30	11490	10640
40	12350	11700
50	12820	13520
60	13330	14330
70	13880	15050

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; thus 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.

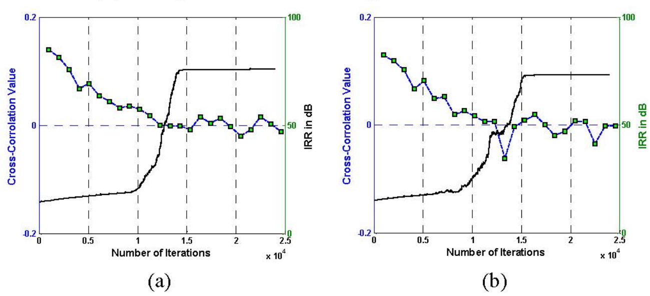


Figure 4. IRR vs Cross-Corrolation for (a) 32-PSK and (b) 64-QAM modulated signals.

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).

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.

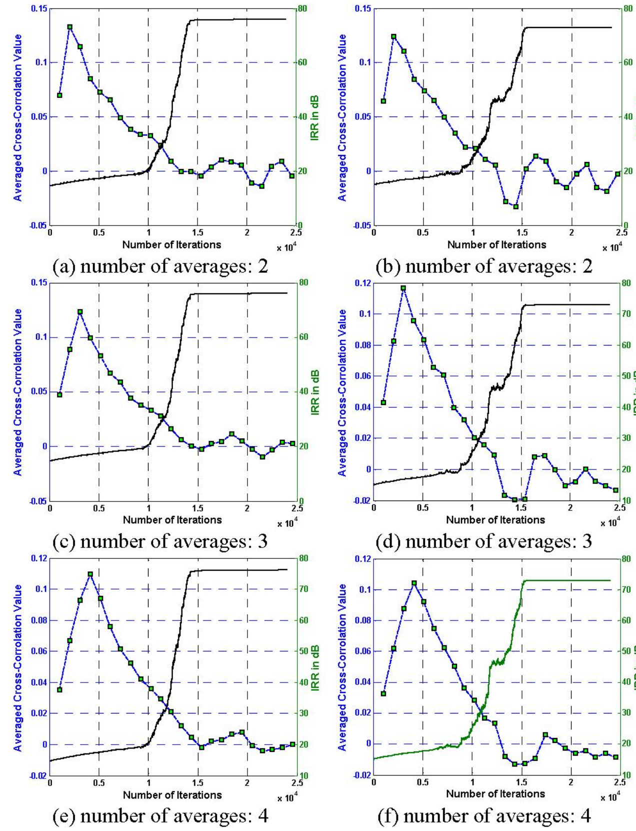


Figure 5. The effects averaging on cross-correlation (a)/(c)/(e) 32-PSK and (b)/(d)/(f) 64-QAM modulated signals.

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.

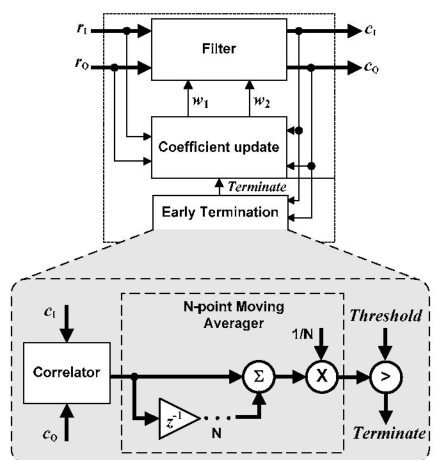


Figure 6. Overall BSS structure with Early Termination Circuit

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_{down} as:

$$P_{down}(\%) = 100 \times \left[1 - \frac{Number\ \ iterations}{Total\ \ Number\ \ of\ \ iterations} \right] \quad (6)$$

This gives us a goodness factor in terms of savings we are making. Higher P_{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_{down} values for small variations of phase (1°-1.3°) and gain (1 – 1.5 dB) errors. For small phase/gain errors P_{down} efficiency is pretty high, as the impairments increase P_{down} efficiency decreases. An interesting trend is achieved for 64-QAM case when P_{down} does not change much with the increased phase error above 10°.

V. CONCLUDING REMARKS

Low-power implementation of an *IQ*-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.

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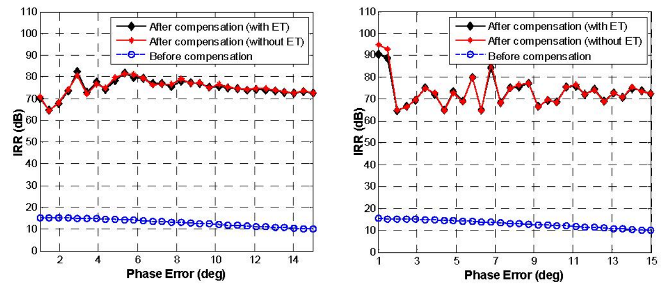
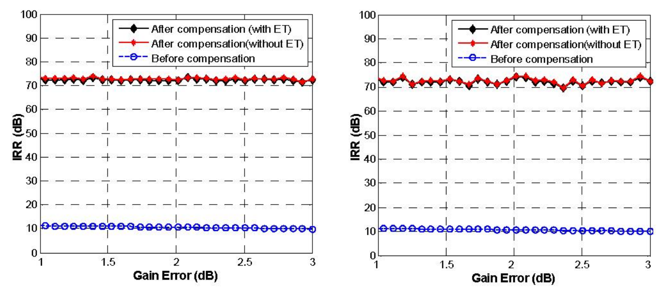


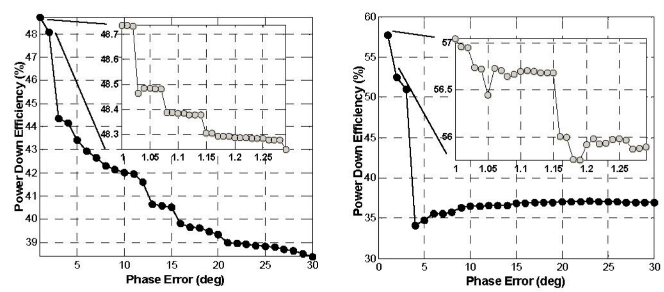
(a) 32-PSK (b) 64-QAM

Figure 7. IRR before and after compensation for varying phase error



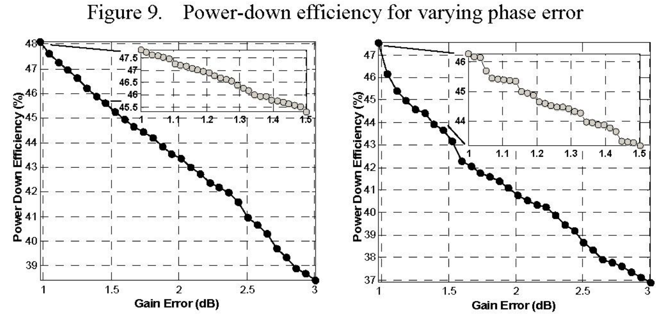
(a) 32-PSK (b) 64-QAM

Figure 8. IRR before and after compensation for varying gain error



(a) 32-PSK (b) 64-QAM

Figure 9. Power-down efficiency for varying phase error



(a) 32-PSK (b) 64-QAM

Figure 10. Power-down efficiency for varying gain error