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Joint Compensation of *IQ*-Imbalance and Carrier Phase Synchronization Errors in Communication Receivers

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Abstract—**This work addresses the joint compensation of *IQ*-imbalances and carrier phase synchronization errors of zero-IF receivers. The compensation scheme based on blind-source-separation which provides simple yet potent means to jointly compensate for these errors independent of modulation format and constellation size used. The low-complexity of the algorithm makes it a suitable option for real-time deployment as well as practical for integration into monolithic receiver designs.**

I. INTRODUCTION

Zero-IF receivers utilize *IQ*-signal processing which theoretically provide infinite image rejection. However, this architecture, in common with all *I*/*Q* architectures, is vulnerable to mismatches between the *I* and *Q* channels. *IQ*-imbalances and Carrier-Phase-Synchronization Errors (CPSE) can cause large degradation in communications receiver's performance. Furthermore, the large signal constellations of *M*-QAM/*M*-PSK impose stringent constraints on the quality of the carrier acquisition algorithms to be used [1]. This coupled with the high data rates at which these systems operate, implies that not only the algorithm must perform well, but it must also at the same time be simple to implement. Papers dealing separately with *IQ*-imbalances and CPSE have been reported in the literature. [2] – [4]. In this paper we analyze the effects of *IQ*-imbalances and CPSE on the analog front-end's performance first independently then jointly. We then propose and demonstrate via simulations a simple and feasible adaptive Blind-Source-Separation (BSS) based scheme to jointly eliminate these impairments.

The paper is organized as follows: In Section II we tackle *IQ*-imbalance problem. Section III explains the effects of CPSE. Section IV deals with the joint influence of *IQ*-imbalances and CPSE on the receiver's performance and proposes an adaptive scheme to deal with them. Section V describes the performance analysis and simulation results, while concluding remarks are given in Section VI.

II. *IQ*-IMBALANCES

Receiver architectures that utilize *IQ*-signal processing are vulnerable to mismatches between the *I* and *Q* channels. This can happen at several stages in the receiver: RF splitter used to divide the incoming RF signal equally between the *I* and *Q* paths may introduce phase and gain differences. 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 *I* and *Q* channel mixers. In addition to these, filters and ADCs in the *I* and *Q* paths are not perfectly matched. The effects of these impairments on the receiver's performance can be detrimental. This section is a brief summary of [5] to introduce *IQ*-imbalances.

A. Signal Model

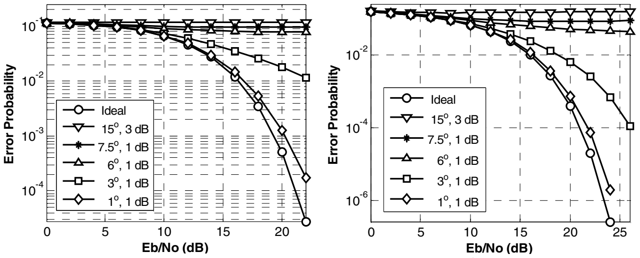
The *IQ*-imbalances can be characterized by two parameters: the amplitude mismatch, α_ε and the phase orthogonality mismatch, φ_ε between the *I* and *Q* branches. The complex baseband equation for the *IQ*-imbalance effects on the ideal received signal $r_{IQ}(k)$ is given as:

$$\begin{aligned}r_{IQ}(k) &= g_1[u_I(k)\cos(\varphi_\varepsilon/2)+u_Q(k)\sin(\varphi_\varepsilon/2)]\\&\quad+jg_2[u_I(k)\sin(\varphi_\varepsilon/2)+u_Q(k)\cos(\varphi_\varepsilon/2)]\\&=\tfrac{1}{2}[(2\cos\tfrac{\varphi_\varepsilon}{2}-j\alpha_\varepsilon\sin\tfrac{\varphi_\varepsilon}{2})u(t)+(\alpha_\varepsilon\cos\tfrac{\varphi_\varepsilon}{2}+j2\sin\tfrac{\varphi_\varepsilon}{2})u^*(t)]\\&=h_1u(t)+h_2u^*(t)\end{aligned}$$

where g_1=(1+0.5α_ε), g_2=(1-0.5α_ε) and ( )* is the complex conjugate. As can be seen there is a cross-talk between *I* and *Q* channels. Amplitude-imbalance, β, in decibels is obtained from amplitude mismatch, α_ε as:

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

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 256-QAM and 32-PSK modulation formats. As can be observed from Fig. 1(a) and (b), *IQ*-imbalances degrade the systems BER performance greatly.



(a) (b)

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

III. CARRIER PHASE SYNCHRONIZATION ERRORS

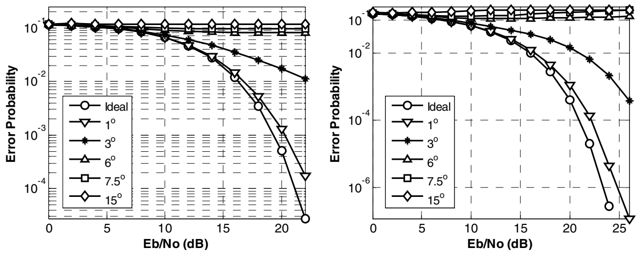
In order for the receiver to make the proper symbol decisions it must have a good phase reference [1]. However, the phase of the quadrature oscillators used by the transmitter is unknown at the receiver. This section studies the effects of these synchronization errors and is a brief summary of [6].

A. Signal Model

In the following we assume that the system does not have any *IQ*-imbalances. The complex baseband equation for the received signal $r_{IQ}(k)$ with CPSE is given as [6]:

$$r_{IQ}(k) = u(t)e^{j\phi} \tag{2}$$

where, $\phi = \theta - \hat{\theta}$ is the CPSE in radians between the transmitters phase θ and the receivers phase estimate $\hat{\theta}$. The effect of the synchronization error ϕ is to rotate the projection of the received signal in the signal space distorting the quadrature mixer's coordinate system. Clearly, $\phi \cong 0$ is required to achieve theoretical performance. As ϕ grows larger, the projection of a particular constellation point rotates in the signal space and gets closer to the edge of its decision region. As a result, it takes less noise power to perturb the projection and move it into the wrong decision region. BER degradation due to imperfect carrier phase synchronization for 256-QAM and 32-PSK modulation schemes is shown in Fig. 2.



(a) (b)

Figure 2. The effects of CPSE on BER of (a) 256-QAM and (b) 32-PSK modulated signals.

IV. JOINT *IQ*-IMBALANCE AND CARRIER PHASE SYNCHRONIZATION ERROR COMPENSATION

Section II of this paper studied *IQ*-imbalances and Section III studied carrier phase synchronization errors separately. We presented the influence of those errors on the raw BER. In this section we analyse the joint influence of them and propose simple yet potent digital signal processing algorithm based on BSS to alleviate their effects.

A. Signal Model

To study the combined effects of *IQ*-imbalance and CPSE, we concatenate the models for both effects as they are descried in the corresponding sections. The receiver model of Fig. 3 incorporates both *IQ*-imbalances and CPSE errors as impaired LO signals.

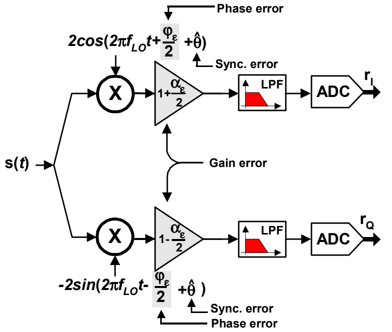


Figure 3. Receiver model incorporating *IQ*-imbalances and Carrier-Phase-Synchronization Errors

Transmitted signal $s(t)$ can be expressed as:

$$s(t) = u(t)e^{j2\pi f_{RF}t}e^{j\theta} + u^{*}(t)e^{j2\pi f_{RF}t}e^{-j\theta} \tag{3}$$

The impaired LO signals can be expressed as:

$$\begin{aligned} I_{LO} &= 2g_1\cos(2\pi f_{LO}t + \varphi_\varepsilon/2 + \hat{\theta}) \\ &= e^{j2\pi f_{LO}t}e^{j(\varphi_\varepsilon/2+\hat{\theta})} + e^{-j2\pi f_{LO}t}e^{-j(\varphi_\varepsilon/2+\hat{\theta})} \\ Q_{LO} &= -2g_2\sin(2\pi f_{LO}t - \varphi_\varepsilon/2 + \hat{\theta}) \\ &= e^{j2\pi f_{LO}t}e^{-j(\varphi_\varepsilon/2-\hat{\theta})} - e^{-j2\pi f_{LO}t}e^{j(\varphi_\varepsilon/2-\hat{\theta})} \end{aligned} \tag{4}$$

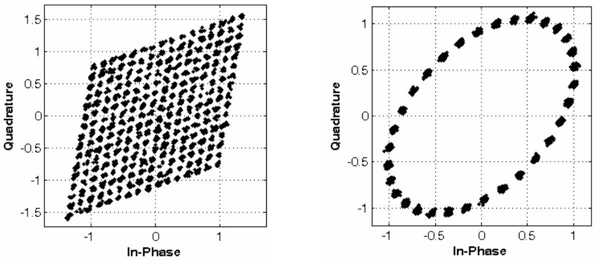
Quadrature downconverting $s(t)$ and low-pass-filtering results in the baseband *I*/*Q* signals:

$$\begin{aligned} r_I &= g_1u(t)e^{-j\varphi_\varepsilon/2}e^{j\phi} + g_1u^{*}(t)e^{j\varphi_\varepsilon/2}e^{-j\phi} \\ r_Q &= jg_2u^{*}(t)e^{-j\varphi_\varepsilon/2}e^{-j\phi} - jg_2u(t)e^{j\varphi_\varepsilon/2}e^{j\phi} \end{aligned} \tag{5}$$

Combining them in complex form $r_I + jr_Q$:

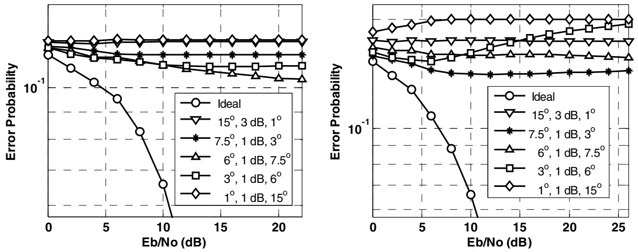
$$\begin{aligned} r_{IQ} &= u(t)\left[e^{j\phi}(g_1e^{-j\varphi_\varepsilon/2} + g_2u(t)e^{j\varphi_\varepsilon/2})\right] \\ &\quad + u^{*}(t)\left[e^{-j\phi}(g_1e^{j\varphi_\varepsilon/2} - g_2e^{-j\varphi_\varepsilon/2})\right] \\ &= h_1u(t) + h_2u^{*}(t) \end{aligned} \tag{6}$$

Fig. 4 shows the received signal constellations for 256-QAM and 32-PSK with *IQ*-imbalances and CPSE of 15°, 3 dB and 1° respectively. Fig. 5 on the other hand depicts raw BER for 256-QAM and 32-PSK for varying *IQ* phase and gain errors between 1°– 15° and 1–3 dB and CPSE varying between 1° –15°. As can be observed from Fig. 5, there is a large degradation in system performance. The resulting loss in performance is obviously undesirable. To combat this performance degradation a simple BSS based scheme is proposed in the next section.



(a) (b)

Figure 4. The effects of *IQ*-imbalances and CPSE on Constellation Diagrams of (a) 256-QAM and (b) 32-PSK modulated signals.



(a) (b)

Figure 5. The effects of Joint *IQ*-imbalances and *CPSE* on BER of (a) 256-QAM and (b) 32-PSK modulated signals.

B. Adaptive Compensation Scheme

Our approach to the problem is to develop an adaptive BSS based system that can operate without pilot/test tones and eliminates the need to strip of data dependent phase otherwise required to compensate for CPSE, 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. Hence, this assumption implies that:

$$E[r_I(k)\times r_Q(k-n)]=0, \qquad \forall n, \tag{7}$$

where $E[\bullet]$ denotes expectation. Overall structure of the proposed approach is depicted in Fig. 6, with *IQ*-imbalances and CPSE modeled as unknown scalar mixing matrix.

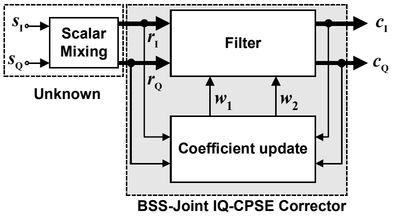


Figure 6. BSS based Joint *IQ*-CPSE corrector.

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:

$$\begin{aligned} c_I(k)&=(1-w_1h_2)s_I(k)+(h_1-w_1)s_Q(k)\\ c_Q(z)&=(h_2-w_2)s_I(k)+(1-w_2h_1)s_Q(k) \end{aligned} \tag{8}$$

When the filters converge, i.e. $w_1=h_1$ and $w_2=h_2$ then the source estimates become:

$$\begin{aligned} c_I(k)&=(1-h_1h_2)s_I(k)\\ c_Q(k)&=(1-h_2h_1)s_Q(k) \end{aligned} \tag{9}$$

As it can be observed from (9) the joint influence of *IQ*-imbalances and CPSE have been removed. Also, $(1\text{-}h_1h_2)\approx 1$ and can be safely ignored.

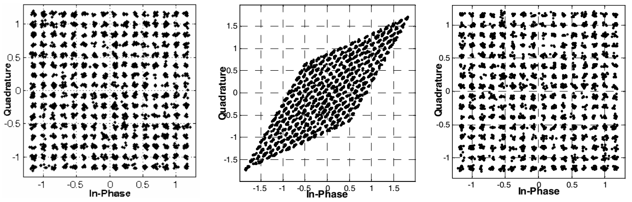
The coefficient update can be done with any algorithm depending on the desired performance. Least-Mean-Square (LMS) and Recursive-Least-Squares (RLS) algorithms being the most obvious ones resulting in different convergence speeds and computational complexities. The LMS [7] algorithm is used in this paper due to its low-complexity making it suitable for real-time systems and practical for integration into receiver signal processing chains.

V. PERFORMANCE EVALUATION

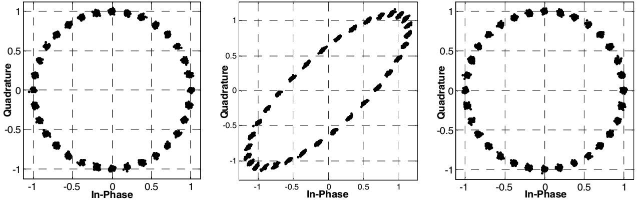
The effectiveness of the joint compensation scheme is demonstrated in this section. The simulation results are presented in three separate sections. The first set of results show constellation diagrams of the received signals in the presence of *IQ*-imbalances and CPSE. The second set of results shows plots of raw BER surfaces for varying *IQ* phase and gain imbalances and CPSE. The third set-of results depicts Modelling-Error (ME) [6] performance measure. All these sections depict results of 2-case studies carried out for 256-QAM and 32-PSK modulated signals. For Case-Study 1 (CS1) *IQ* phase and gain errors are set to 15° and 3 dB and CPSE is set to 1°, whereas for CS2 these values are 7.5°, 1 dB and 3° respectively. Channel is assumed to be AWGN and large impairment values are used to demonstrate the effectiveness of the proposed approach.

A. Constellation Diagrams

Figs. 7 and 8 depict the constellation diagrams for CS1 and CS2.



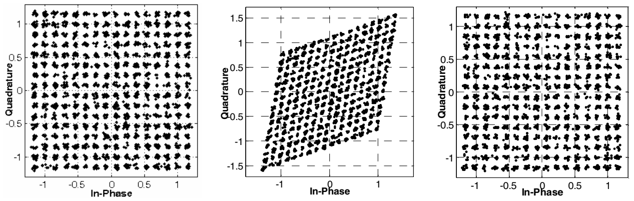
(a) Ideal (b) Corrupted (c) Compensated



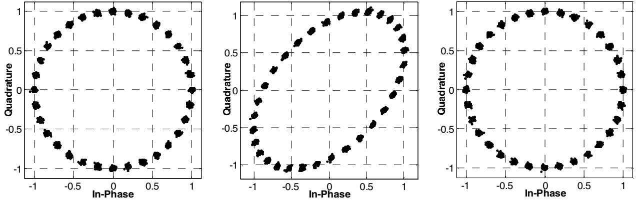
(d) Ideal (e) Corrupted (f) Compensated

Figure 7. Constellation Diagrams for CS1- [φ_ε=15°, β=3 dB, ϕ=1°]

Figs. 7/8 (b) is the constellation diagram of the corrupted uncompensated received signal and (c) is the constellation diagram of the compensated received signal. Ideal signal constellation is shown in (a). It can be seen that the compensator has correctly jointly compensated for both *IQ*-imbalances and CPSE.



(a) Ideal (b) Corrupted (c) Compensated

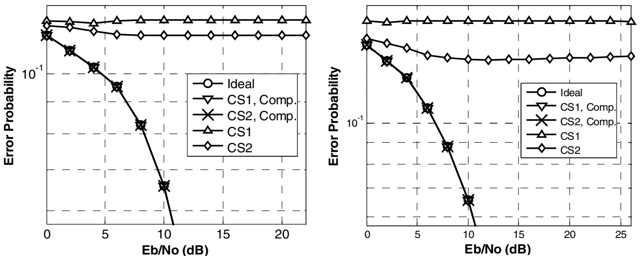


(d) Ideal (e) Corrupted (f) Compensated

Figure 8. Constellation Diagrams for CS2 - [$\varphi_\varepsilon=7.5°$, $\beta=1$ dB, $\phi=3°$]

B. BER Curves

Fig. 9 depicts the BER curves for CS1 and CS2. Signal labels "CS1/2" represents received signals in the presence of impairments and "CS1/2 Comp." Represents compensated signals once the algorithm has converged.



(a) (b)

Figure 9. BER Curves for CS1 and CS2 for (a) 256-QAM and (b) 32-PSK modulated signals.

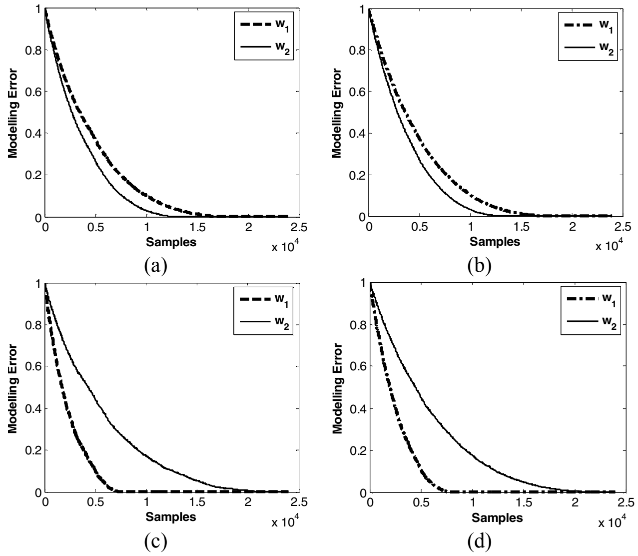
As can be observed from Fig. 9 (a) and (b), after compensation BER closely matches the ideal case i.e. jointly *IQ*-imbalances and CPSE have been compensated.

C. Modelling Errors

The performance of the adaptive algorithm is characterized by the ME. This gives a global figure for the quality of the identification of the unknown mixing coefficients h_1 and h_2 by w_1 and w_2. Furthermore, it provides useful information about the convergence rate of the proposed adaptive algorithm. ME is defined as the squared norm of the difference of the values between the original coefficients used in the mixture and the estimated coefficients, relative to the squared norm of the mixture coefficients. As can be observed from Fig. 10 (a) – (d), de-mixing coefficients w_1 and w_2 matches the mixing coefficients h_1 and h_2 as the ME reaches zero.

VI. CONCLUDING REMARKS

IQ-imbalances and CPSE can cause large degradation in communications receivers' performance. We have presented a compensation method to jointly combat *IQ*-imbalances and CPSE effects based on BSS techniques. The approach is modulation format and constellation size independent and does not require stripping of the modulation dependent phase-shift otherwise required for CPSE compensation. Furthermore, no test/pilot tones are required for the operation of the proposed approach. We have also demonstrated that the proposed approach is able to operate with the large signal constellations of *M*-QAM/*M*-PSK which impose stringent constraints on the quality of *IQ*-compensation and carrier acquisition algorithms to be used. This approach leads to tremendous improvement in performance and allows to greatly relax the front-end mismatch specifications enabling zero-IF receivers employing cheap analog components. The low-computational-complexity of the algorithm makes it a suitable option for real-time operation as well as practical for integration into receiver designs. The compensation algorithm does not require any analog hardware and has very small additional digital complexity.



(a) (b) (c) (d)

Figure 10. Modelling Errors for CS1 and CS2 (a)/(c) 256-QAM and (b)/(d) 32-PSK modulated signals.

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