Performance of an adaptive homodyne receiver in the presence of multipath, Rayleigh-fading and time-varying quadrature errors.

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PERFORMANCE OF AN ADAPTIVE HOMODYNE RECEIVER IN THE PRESENCE OF MULTIPATH, RAYLEIGH-FADING AND TIME-VARYING QUADRATURE ERRORS

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ABSTRACT

In this paper, we carry out a detailed performance analysis of the blind source separation based I/Q corrector operating at the baseband. Performance of the digital I/Q corrector is evaluated not only under time-varying phase and gain errors but also in the presence of multipath and Rayleigh fading channels. Performance under low-SNR and different modulation formats and constellation sizes is also evaluated. What is more, BER improvement after correction is illustrated. The results indicate that the adaptive algorithm offers adequate performance for most communication applications hence, reducing the matching requirements of the analog front-end enabling higher levels of integration.

1. INTRODUCTION

The homodyne/Zero-IF receivers provide high levels of integration. With this architecture, I/Q signal processing is used to downconvert the RF signal to baseband. However, this architecture, in common with all I/Q architectures, is vulnerable to mismatches between the I and Q channels.

Both analog and digital methods for correcting the I/Q mismatches of homodyne receivers have been proposed in the literature [1]-[6]. This paper explores the performance capability of a non-pilot aided adaptive DSP technique developed for the quadrature receivers in [5], [6]. The ability of the algorithm to work under time-varying phase and gain errors as well as under multipath and Rayleigh fading environments has been explored. Its performance under low-SNR and different modulation formats and constellation sizes is also evaluated.

This paper is organized as follows: Section 2 defines the model of the source separation based zero-IF receiver. Section 3 describes the performance measures and simulation results. Concluding remarks are given in Section 4.

2. ADAPTIVE HOMODYNE RECEIVER

2.1 Architecture

A block diagram and the equivalent system for the source separation based homodyne receiver is given in Figure 1. The incoming signal $s(t)$ consists of the desired/wanted signal $s(t)$ at f_{RF} and can be expressed as:

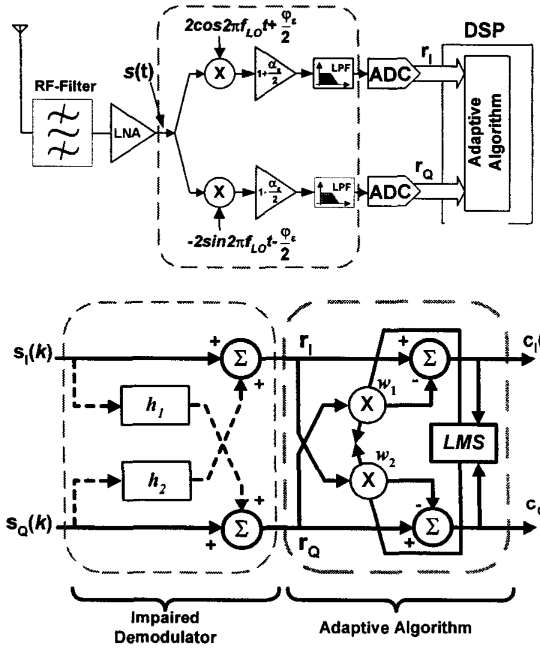

Figure 1 Blind source separation based receiver

$$s(t)=\tfrac{1}{2}[u(t)e^{j2\pi f_{RF}t}+u^{*}(t)e^{-j2\pi f_{RF}t}] \qquad (1)$$

where $u(t)$ is the complex envelope of the wanted signal. To simplify the analysis, the whole phase and gain imbalances between the I and Q channels are modelled as an unbalanced quadrature downconverter [5] and can be expressed as:

$$x_{LO}=e^{j2\pi f_{LO}t}\left(g_1e^{j\frac{\varphi_\varepsilon}{2}}-g_2e^{-j\frac{\varphi_\varepsilon}{2}}\right)+e^{-j2\pi f_{LO}t}\left(g_1e^{-j\frac{\varphi_\varepsilon}{2}}+g_2e^{j\frac{\varphi_\varepsilon}{2}}\right) \qquad (2)$$

where $g_1=(1+0.5\alpha_\varepsilon)$, $g_2=(1-0.5\alpha_\varepsilon)$ and φ_ε is the phase and α_ε is the gain mismatch between the I and Q channels and $f_{LO}=f_{RF}$. As shown in Figure 1, the received signal $s(t)$ is quadrature mixed with the non-ideal LO signal, x_{LO}, and low-pass filtered resulting in the baseband signal with in-phase and quadrature components:

$$\begin{aligned} r_I(k)&=\overbrace{(1+0.5\alpha_\varepsilon)\cos(\varphi_\varepsilon/2)}^{\psi}s_I(k)+\overbrace{(1+0.5\alpha_\varepsilon)\sin(\varphi_\varepsilon/2)}^{h_2}s_Q(k)\\ r_Q(k)&=\underbrace{(1-0.5\alpha_\varepsilon)\sin(\varphi_\varepsilon/2)}_{h_1}s_I(k)+\underbrace{(1-0.5\alpha_\varepsilon)\cos(\varphi_\varepsilon/2)}_{\gamma}s_Q(k)\end{aligned} \qquad (3)$$

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where ψ and γ are ≈ 1 and can be safely ignored. The in-phase signal $r_I(k)$ is corrupted by the quadrature signal $r_Q(k)$ leaked due to phase and gain mismatches. A leakage from the quadrature signal into the in-phase signal also exists. Ideally the I and Q channels are not correlated with each other. However, in the presence of the quadrature phase and gain errors this relationship no longer exists and they are correlated. The proposed algorithm, depicted in Figure 1, acts as a decorrelator and tries to de-correlate the I and Q channels hence eliminating phase and gain errors. The source estimates, $c_I(z)$ and $c_Q(z)$ can be expressed as:

$$\begin{aligned} c_I(z) &= (1 - w_1 h_2) s_I(z) + (h_1 - w_1) s_Q(z) \\ c_Q(z) &= (h_2 - w_2) s_I(z) + (1 - w_2 h_1) s_Q(z) \end{aligned} \tag{4}$$

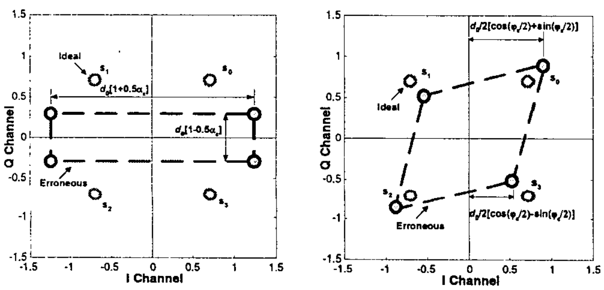
When the coefficients converge, i.e. $w_1 = h_1$ and $w_2 = h_2$ then the source estimates become:

$$\begin{aligned} c_I(z) &= (1 - h_1 h_2) s_I(z) \\ c_Q(z) &= (1 - h_1 h_2) s_Q(z) \end{aligned} \tag{5}$$

As it can be seen from (5) the sources have been separated. Furthermore, $(1 - h_1 h_2) \approx 1$ and can be safely ignored. The description blind or unsupervised implies that we do not know the mixing coefficients h_1, h_2, nor the probability distribution of the sources except that they are not correlated.

2.2 BER for QPSK

The effect of gain and phase mismatches on a QPSK constellation is illustrated in Figure 2.



(a) (b)

Figure 2 QPSK Constellation Diagram in the presence of, (a) Gain Error and (b) Phase Error.

As can be seen from Figure 2(a), the distance between symbols s_0 and s_1 is $d_0(1+0.5\alpha_\varepsilon)$ and the distance between s_2 and s_3 is $d_0(1-0.5\alpha_\varepsilon)$. In the presence of phase errors each of the symbols in the first and third quadrants, i.e. s_0 and s_2, is located at a distance $0.5 d_0[\cos(0.5\varphi_\varepsilon) + \sin(0.5\varphi_\varepsilon)]$ from the decision boundaries as seen from Figure 2(a). The error probability for the gain error is given as:

$$P_b \approx \frac{1}{2}\left\{Q\left[(1+0.5\alpha_\varepsilon)\sqrt{\frac{2E_b}{N_0}}\right] + Q\left[(1-0.5\alpha_\varepsilon)\sqrt{\frac{2E_b}{N_0}}\right]\right\} \tag{6}$$

and for the phase error:

$$P_b \approx \frac{1}{2}\left\{Q\left[\left(\cos\left(\frac{\varphi_\varepsilon}{2}\right) + \sin\left(\frac{\varphi_\varepsilon}{2}\right)\right)\sqrt{\frac{2E_b}{N_0}}\right] + Q\left[\left(\cos\left(\frac{\varphi_\varepsilon}{2}\right) - \sin\left(\frac{\varphi_\varepsilon}{2}\right)\right)\sqrt{\frac{2E_b}{N_0}}\right]\right\} \tag{7}$$

Equations (6) and (7) express the BER as a function of phase and gain errors for QPSK modulated signals.

3. PERFORMANCE ANALYSIS

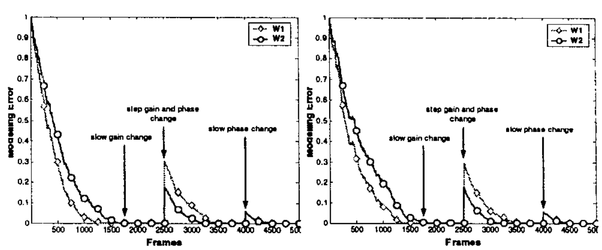
3.1 Simulation Setup

The performance of the proposed structure is analysed considering QPSK and 16-QAM signals with ideal symbol rate sampling. AWGN and Multipath Rayleigh Fading channels were assumed with phase and gain error values varying from 30° to 7.5° and 3dB to 1dB respectively are investigated.

The performance of the adaptive algorithm is characterized by the modelling-error [6]. This gives a global figure for the quality of the identification of the coupling coefficients h_1 and h_2 by w_1 and w_2. It 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. Another performance measure used is the *Image Rejection Ratio* (IRR) [5] that can be achieved. This can be interpreted as the *Signal-to-noise-Ratio* (SNR) in the desired channel.

3.2 Tracking Capabilities

Another performance measure is the capability of the adaptive algorithm in tracking non-stationary environments i.e. time varying phase and gain errors. In order to show the robustness of the proposed approach we start by adapting the coefficients to 15° phase and 0.34 dB of gain error. After 1750 frames, the amplitude imbalance is changed linearly from 0.34 dB to 0.87 dB. After 750 frames, an abrupt change from 0.87 dB to 3 dB is made and the phase error is abruptly changed to 30°. After 1500 frames, the phase error is changed linearly from 30° to reach 40° for the next 500 frames. Figure 3 depicts the tracking capability of the proposed algorithm for (a) QPSK and (b) 16-QAM modulation schemes in the presence of an AWGN channel with an SNR of 20 dB.



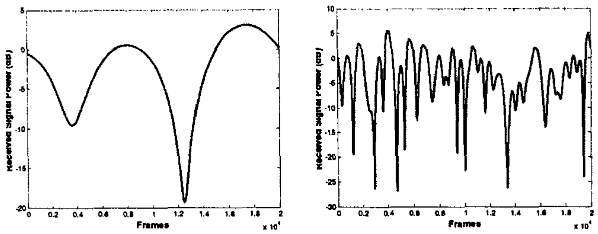
(a) (b)

Figure 3 Tracking capability of the proposed algorithm, (a) QPSK and (b) 16-QAM case.

As can be seen from Figure 3, a sudden change in the mixture coefficients, phase and gain errors, does not cause the algorithm to diverge and the algorithm tracks the changes rapidly and the modelling error is zeroed. In addition, the compensator performance is not affected by time-variant phase and gain errors. This indicates that the proposed method is also capable of tracking time-varying imbalances.

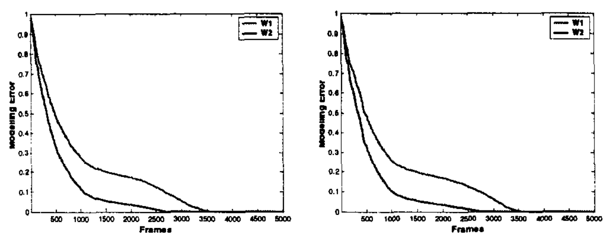
3.3 Multi-path and Fading Channels

Another performance measure is the capability of the adaptive algorithm in fading and multi-path environments. The robustness of the proposed approach in a more realistic environment than the AWGN channel is demonstrated using a Rayleigh Fading channel with multipath. Figure 4 depicts the channel profiles, received signal power over time for (a) slow fading and (b) fast fading with a multipath Rayleigh channel.



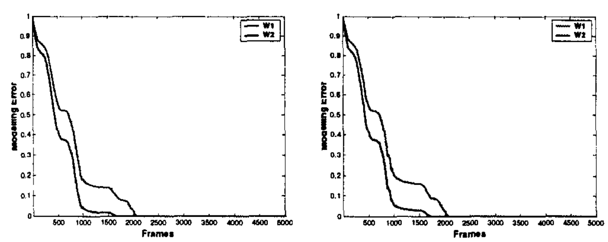
(a) (b)

Figure 4 Channel profiles for (a) slow fading and (b) fast fading, multipath Rayleigh Channel.



(a) (b)

Figure 5 Modelling error for first (a) QPSK and (b) 16-QAM for phase error of 30° and amplitude imbalance of 3 dB, for slow fading.



(a) (b)

Figure 6 Modelling error for first (a) QPSK and (b) 16-QAM for phase error of 30 ° and amplitude imbalance of 3 dB, for fast fading.

As can be seen from Figures 5 and 6, the proposed algorithm is able to work under both slow fading and fast fading multipath channels and the modelling error is effectively zeroed. Table 1 depicts the resulting tap estimates w_1 and w_2, residual gain and phase errors and the steady-state IRR for QPSK and 16-QAM modulated signals in slow and fast fading multipath environments.

3.4 BER Improvement for QPSK

In Section 2.2 the BER degradation for a QPSK signal in the presence of phase and gain errors was derived. The resulting BER after the application of the proposed algorithm is shown in Figure 7 where the ideal BER, BER in the presence of phase error of 30° and an amplitude imbalance of 3dB and the BER after the application of the proposed correction scheme are depicted.

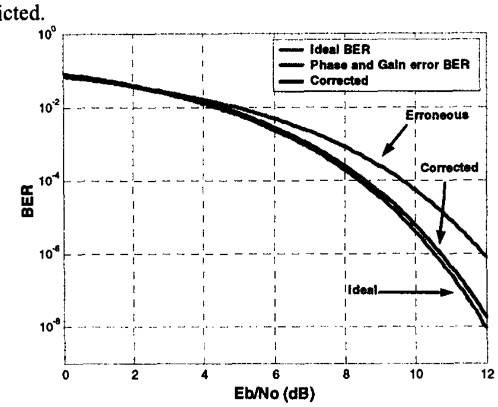


Figure 7 BER improvement.

3.5 Different Modulation Formats and Low SNR

The performance of the proposed algorithm under low SNR values is shown in Table 2, where the SNR required to achieve 10^{-1} BER is shown. For 8-PSK and 32-PSK as well as 32-QAM and 256-QAM cases the algorithm is able to identify the mixing matrix hence eliminating the phase and gain errors. IRR in the order of 58–93.3 dB after imbalance compensation was shown to be achievable. This IRR is much more than the required amount.

4. CONCLUDING REMARKS

In this paper we have reported on the performance of a source separation based compensator for homodyne receivers. The properties of the algorithm can be summarized as follows:

- The algorithm enables fast and very accurate I/Q imbalance compensation at low cost. Simulation results show IRR values from 58-94 dB after compensation.
- The algorithm compensates for phase and gain imbalances in the whole receiver chain not only those introduced by the quadrature downconverter.
- The algorithm is able to work under multipath and Rayleigh fading environments.
- The algorithm is able to work under low SNR.
- The algorithm works on the fly and is able to track time-varying errors.
- The algorithm works with any type of modulation formats and constellation sizes, since compensation takes place before any modulation specific operation.
- The algorithm is very simple to implement consisting of two, single-tap adaptive filters with LMS coefficient update hardware.

Modulation type		Before Correction					After Correction				
		Gain Error (dB)	Phase Error (deg)	h_1	h_2	IRR (dB)	Gain Error (dB)	Phase Error (deg)	w_1	w_2	IRR (dB)
Slow Fading	QPSK	3	30	0.3018	0.2158	10.0	1.0e-4	4.3e-4	0.3016	0.2156	73.2
	16-QAM						0.0018	4.4e-4	0.3016	0.2156	72.3
Fast Fading	QPSK						0.0121	1.8e-5	0.3020	0.2156	63.1
	16-QAM						0.0059	1.4e-4	0.3020	0.2158	69.2

Table 1 Parameter values for QPSK and 16-QAM for slow and fast fading multipath environments.

Modulation type	Before Correction					After Correction				
	Gain Error (dB)	Phase Error (deg)	h_1	h_2	IRR (dB)	Gain Error (dB)	Phase Error (deg)	w_1	w_2	IRR (dB)
8-PSK SNR= 5.6 Eb/No=0.87	3	30	0.3018	0.2158	10.0	1.9e-4	3.7e-5	0.3018	0.2158	93.3
	2	15	0.1454	0.1155	15.2	0.0145	5.0e-5	0.1453	0.1157	61.5
	1	7.5	0.0691	0.0616	21.2	0.0073	1.7e-6	0.0692	0.0616	67.5
32-PSK SNR=13.7 Eb/No=6.7	3	30	0.3018	0.2158	10.0	0.0012	2.4e-4	0.3017	0.2157	77.3
	2	15	0.1454	0.1155	15.2	0.0034	8.7e-5	0.1454	0.1156	74.1
	1	7.5	0.0691	0.0616	21.2	0.0218	1.9e-4	0.0691	0.0615	57.9
32-QAM SNR=15.5 Eb/No=8.5	3	30	0.3018	0.2158	10.0	9.1e-4	2.4e-4	0.3017	0.2157	77.7
	2	15	0.1454	0.1155	15.2	0.0120	6.8e-5	0.1454	0.1156	63.2
	1	7.5	0.0691	0.0616	21.2	0.0032	7.2e-5	0.0691	0.0616	74.6
256-QAM SNR=24.9 Eb/No=15.9	3	30	0.3018	0.2158	10.0	0.0068	7.1e-5	0.3017	0.2160	68.1
	2	15	0.1454	0.1155	15.2	0.0108	3.9e-5	0.1454	0.1157	64.1
	1	7.5	0.0691	0.0616	21.2	0.0045	4.7e-5	0.0692	0.0617	71.7

Table 2 Parameter values for BER of 10^{-1}.

5. REFERENCES

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