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A fully analog calibration technique for phase and gain mismatches in image-reject receivers

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ABSTRACT

A systematic approach to *I*/*Q* mismatch calibration in image-reject receivers is presented in this paper. A new error detection algorithm is proposed, which automatically calibrates for phase and gain mismatches limiting the performance of image-reject receivers. A dual-loop feedback is employed which looks for the minimum phase/gain error using a 2-dimensional analog-based search algorithm and then finds the minimum value for the error. An experimental CMOS prototype RF front-end for cognitive radio applications operating at 400–800 MHz is proposed and simulated in the 0.18 μm CMOS technology, achieving an image rejection ratio (IRR) better than 55-dB in post-layout simulation. The comprehensive mathematical model of this analog algorithm is thoroughly studied in the appendix and the convergence is verified theoretically.

1. Introduction

With the ever-increasing need for more wireless applications, the frequency spectrum is being populated progressively. This has underscored the need for multi-standard, multi-band and/or cognitive radios (CRs) in recent years. It is generally believed that the next generation of radios should be able to operate from hundreds of megahertz to about 10 GHz to address the communication needs in a variety of applications [1]. A cognitive radio is a fully reconfigurable wireless black-box which automatically observes the radio environment, senses and analyzes the spectrum, and subsequently utilizes any unoccupied channel in a wide frequency range, e.g. from 100 MHz (lower VHF band) to about 10 GHz [2,3].

Cognitive radio receivers pose many challenges at all levels of abstraction [2]. One major issue that rises in CR receivers is the problem of image, which is becoming more pronounced as the frequency spectrum is being overly crowded. The image signal degrades SNR, corrupts signal detection, increases the noise floor, lowers the dynamic range (DR), and desensitizes the receiver, all of which degrade the performance of the RX chain [4]. One method to address the issue of image is to use image reject receivers, namely Weaver and Hartley architectures [5],[6]. However, the image signal may still not be cancelled completely and fall into the desired RF band as a direct consequence of *I*/*Q* imbalance. These imbalances are caused by phase/gain mismatch of high-frequency local oscillator (LO), asymmetries in the circuit layout, component mismatches, transistors threshold voltage mismatches, etc. [7]. If all the mismatches are lumped in the gain and phase error of the LO, it is shown that with the typical values of gain and phase errors of 1% and 3°, respectively, the image rejection ratio (IRR) of only 30–40 dB can be achieved [4,8,9]. As a result, for more IRR values new calibration techniques should be employed to alleviate this issue.

Extensive efforts have been made in the past to improve IRR using different techniques, among which [10–18] are analog, [19–30] are digital, and [31–34] are hybrid. There have also been state-of-the-art very recent works [35–37]. Lerstaveesin and Song [38] have proposed three different methods of calibration, namely analog, digital, and hybrid, which is based on an adaptive zero-forcing feedback concept using only sign bits, without complicated digital processing. In [17], the phase and gain errors are detected separately by means of four extra multipliers, then two high-gain negative feedback loops force the error to zero to achieve a high IRR. In [34] a sign-sign LMS calibration technique has been introduced which substantially improves the IRR of Weaver receiver without compromising the noise, linearity, or gain of the receiver. [28] has presented a compensation technique based on the use of the LO signal as a reference for error measurements, in which mismatch parameters are first estimated by an algorithm in the DSP processor and later used to correct the down-converted *I*/*Q* signals digitally during normal operation. Recently, [29] has proposed a receiver

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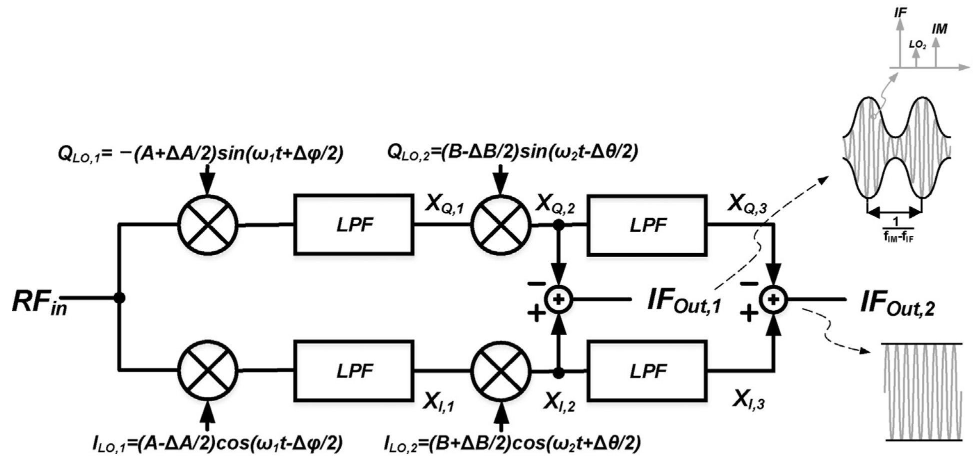

Fig. 1. Schematic of the Weaver architecture.

based on dual carrier aggregation, which requires complex mixers and employs four extra amplifiers in the I and the Q paths to cancel the image. In [30], a recursive estimation and compensation technique is suggested to compensate for the frequency-dependent impairments in direct conversion transmitters.

All previous works on I/Q calibration are based on the principle of finding the gain/phase errors, generating the inverted replica of the error, and by summing the two values, neutralizing the effect of the imbalances. More specifically, [38], [29], and [17] share a common insight to I/Q imbalance calibration, wherein complex mixing is exploited in both the analog and digital domain to calibrate for the errors. The analog approaches have employed extra components which dictate increased power consumption and die area. The digital versions suffer from a trade-off between power consumption and operating frequency of the analog-to-digital converters (ADCs). The hybrids lie in between the two categories and are aimed at mitigating the above issues, however, most of them still experience the same difficulties. A possible solution to attain better performance is the analog implementation of a digital calibration system, which is the focus of this paper.

In this paper, a new analog-based method with low complexity, low power consumption, and low component count is presented to achieve high IRR in image-reject receivers. The paper is organized as follows. In Section 2, a new time-domain mathematical analysis of gain/phase error modeling is presented. Section 3 introduces a dual-loop feedback which looks for the minimum phase/gain error using a 2-dimensional analog search algorithm. This algorithm is implemented in Section 4. The proposed circuit and simulations are presented in Section 5 and conclusions are drawn in Section 6.

2. Mathematical analysis and gain/phase error modeling

2.1. Modeling of chain imbalances

Consider the Weaver receiver chain of Fig. 1 and assume low-side injection for both LO's. If the desired signal is at frequency ω_{RF}, the first LO at $\omega_{LO,1}$, and the second LO at $\omega_{LO,2}$, upon the first downconversion, the image of the signal due to LO_1 lies at $2\omega_{LO,1}-\omega_{RF}$ and upon the second downconversion the image due to the second LO lies at $\omega_{RF}-2\omega_{LO,2}-2\omega_{LO,1}$. For the sake of brevity, $\omega_{LO,1}$ and $\omega_{LO,2}$ will be referred to as ω_1 and ω_2, thereafter, respectively.

In non-quadrature receivers, the LO signal has both the positive and the negative frequency components in its spectrum, by contrast, an ideal quadrature receiver has only one of the positive or negative frequency components. Due to gain/phase errors, the latter suffers from leakage of the LO signal from positive to negative frequency or *vice versa* [9]. In [38], it is shown that this leakage is given by $(\alpha - j\theta)/2$ times the amplitude of the LO signal, where α and θ are the gain and phase errors due to chain imbalances, respectively.

As conceptually shown in Fig. 2, three signals are of interest: (1) the desired RF signal, the solid spectrum, (2) the undesired first image signal, the shaded spectrum; and (3) the secondary image, the dashed spectrum. In an ideal Weaver structure, the first image is removed by second downconversion (90° phase shift) followed by the summation at the output, nevertheless, in a real structure with imbalances, this component appears at IF_2, raising the noise floor. Interestingly, this architecture suffers from the problem of secondary image, which upon the second downconversion falls in the positive baseband frequency, as depicted in Fig. 2. This signal coincides with the desired signal at the output summing node, posing difficulties in signal detection. This issue can be alleviated by means of employing a poly-phase filter (PPF) [14] or an N-path filter with a complex baseband impedance [39]. Another solution is to use complex mixing [17,29] and perform I/Q filtering in digital domain.

In any receiver, all the gain and phase errors can be lumped in the first LO [4], as shown in the first I/Q LO of Fig. 2. Due to these errors, the first image cannot be completely suppressed. However, with proper choice of the gain and phase errors of the second LO, the imbalances can be removed effectively. As the second LO resides at a lower frequency as compared to the first LO, the amplitude and phase of the oscillator can be tuned with better precision and

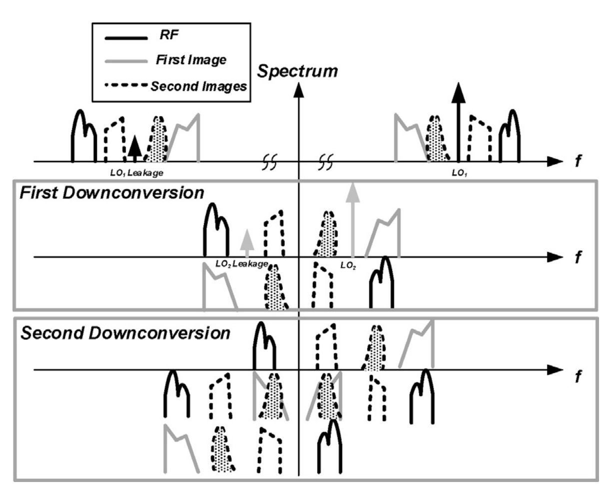

Fig. 2. Effect of LO leakage in the spectrum.