UNIVERSITY OF WESTMINSTER

WestminsterResearch

http://www.wmin.ac.uk/westminsterresearch

Living and dealing with RF impairments in communication transceivers.

Ediz Cetin
Izzet Kale
Richard Morling

School of Informatics

Living and Dealing with RF Impairments in Communication Transceivers

Ediz Cetin[*], Izzet Kale[*+] and Richard C. S. Morling[*]

[*]Applied DSP and VLSI Research Group
Department of Electronic, Communication and Software Engineering
University of Westminster, London, United Kingdom
[+]Applied DSP and VLSI Research Centre, Eastern Mediterranean University, N. Cyprus
{e.cetin, kalei, morling}@wmin.ac.uk

Abstract—**This paper provides an overview of the sources and effects of the RF impairments limiting and rendering the performance of the future wireless communication transceivers costly as well as hindering their wide-spread use in commercial products. As transmission bandwidths and carrier frequencies increase effect of these impairments worsen. This paper studies and presents analytical evaluations of the performance degradation due to the RF impairments in terms of Bit-Error-Rate and Image Rejection Ratio. The paper also give highlights of the various aspects of the research carried out in mitigating the effects of these impairments primarily in the digital signal processing domain at the baseband as well as providing low-complexity hardware implementations of such algorithms incorporating a number of power and area saving techniques.**

I. INTRODUCTION

Future wireless communications systems are expected to provide ever increasing data rates which require large transmission bandwidths and high carrier frequencies. A crucial part of many commonly used modern day devices is the transceiver which allows these devices to communicate with each other and their respective base stations. Interoperability between different communication standards as well as navigation based services such as Galileo and GPS is of high importance to provide the value added services in a variety of sectors and provision of seamless quality of service for users. However, in order to provide such seamless operation, the mobile-terminal should be able to process a variety of different communication standards as well as navigation signals implying a multi-mode transceiver. What is more, an important step into the market is the availability of such hybrid low-cost, low-power and small norm factor multi-mode terminals for consumer applications. In the industry today a lot of effort is expended on developing such hybrid highly integrated multi-mode terminals. One of the key aspects in implementing a radio transceiver is the RF front-end where filtering, amplification and frequency translation operations are carried out. However, transceiver architectures that are amenable to high-levels of integration and support the large transmission bandwidths and high carrier frequencies needed for increased data throughput will inevitably suffer from RF impairments [1]-[18] limiting their performance and hence hindering their wide-spread use in commercial products.

In order to be able to generate effective solutions, we need to have a better understanding of the effects of these RF impairments and how they manifest themselves in real-life applications. In order to realistically evaluate the performance of any practical communication system design RF impairments must be taken into account. Furthermore, by understanding these impairments we can develop algorithms in order to deal with them in the digital domain without compromising system performance. Application of these advanced digital signal processing techniques to single and multi-carrier wireless transceivers will eliminate the need for discrete off-chip components resulting in reduced complexity, lower cost and low-power transceivers with enhanced performance. These will subsequently manifest themselves in simpler RF front-ends and relaxed ADC analog circuit requirements resulting in a major step towards "true" integration of low-power single-chip radio transceivers.

This paper sets about looking into the sources of these RF impairments, their effects on the performance of the communication transceivers and the use of advanced digital signal processing techniques in mitigating their effects for communication transceivers.

The paper is organized as follows: Section II investigates the RF impairments and their influence on receiver's performance, and outlines solutions to mitigate them. Furthermore, simulation results are also given in this section. Low-complexity hardware implementation of such algorithm is given in Section III while concluding remarks are given in Section IV.

II. RF IMPAIRMENTS

RF impairments associated with transceivers can be classified into the following categories: phase and gain

mismatches in the *In-phase* (*I*) and *Quadrature* (*Q*) paths of the quadrature up-converter at the transmitter and the quadrature downconverter at the receiver, carrier phase and frequency synchronization errors, phase noise and power-amplifier non-nonlinearities. Furthermore, these impairments not only apply to single carrier communications but also to the multi-carrier communications i.e. MIMO-OFDM. A number of techniques have been proposed in the literature dealing with these impairments [2]-[18]. In the remaining sections of the paper we will concentre on the RF impairments of the quadrature modulator and the demodulator.

Receiver architectures that utilize *IQ*-signal processing are vulnerable to mismatches between the *I* and *Q* channels. 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 effects of these impairments on the receiver's performance can be detrimental. This section sets out to establish the influence of these impairments on the receiver's performance utilizing zero-IF and low-IF topologies (IF: *Intermediate Frequency*).

A model of a quadrature downconverter with the *I/Q*-phase and gain mismatch contributions by various stages is shown in Fig. 1(a), whereas Fig. 1(b) shows the analytical model used with all the phase and gain mismatches accumulated and represented by the erroneous LO signals.
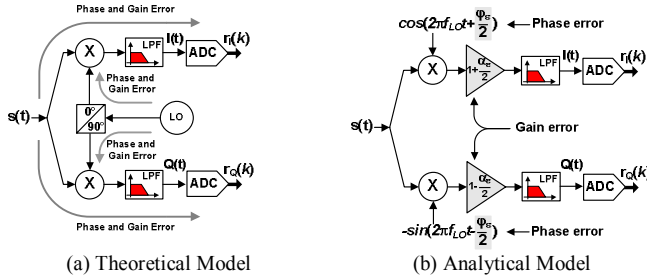

(a) Theoretical Model   (b) Analytical Model

Figure 1.   RF Impairment contribution by various stages

The *IQ*-impairments 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 amplitude-imbalance, β in decibels is obtained from the amplitude mismatch, α_ε as:

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

A.   Signal Model for Zero-IF Receivers

The incoming signal $s(t)$ can be expressed as:

$$s(t) = \Re\left\{u(t)e^{j2\pi f_{RF}t}\right\} \qquad (2)$$

where $u(t)$ is the complex envelope of the received signal at f_{RF}. To simplify the analysis, whole phase and gain imbalances

between the *I* and *Q* channels are modelled as an unbalanced quadrature downconverter. The erroneous complex LO signal, $x_{LO}(t)= I_{LO}+jQ_{LO}$, is given as:

$$x_{LO}(t) = e^{j2\pi f_{LO}t}(g_1 e^{j\frac{\varphi_\varepsilon}{2}} - g_2 e^{-j\frac{\varphi_\varepsilon}{2}}) + e^{-j2\pi f_{LO}t}(g_1 e^{-j\frac{\varphi_\varepsilon}{2}} + g_2 e^{j\frac{\varphi_\varepsilon}{2}}) \quad (3)$$

where $g_1=(1+0.5\alpha_\varepsilon)$, $g_2=(1-0.5\alpha_\varepsilon)$. The received signal $s(t)$ is quadrature mixed with the non-ideal LO signal, x_{LO}, and low-pass filtered resulting in the received baseband signal $r_{BB}(k)$. The complex baseband equation for the *IQ*-imbalance effects on the ideal received signal $r_{BB}(k)$ is given as:

$$r_{BB}(k) = g_1[u_I(k)\cos(\varphi_\varepsilon/2) + u_Q(k)\sin(\varphi_\varepsilon/2)]$$
$$+ jg_2[u_I(k)\sin(\varphi_\varepsilon/2) + u_Q(k)\cos(\varphi_\varepsilon/2)]$$
$$= \frac{1}{2}[\overbrace{(2\cos\frac{\varphi_\varepsilon}{2} - j\alpha_\varepsilon\sin\frac{\varphi_\varepsilon}{2})}^{h_1}u(t) +$$
$$\underbrace{(\alpha_\varepsilon\cos\frac{\varphi_\varepsilon}{2} + j2\sin\frac{\varphi_\varepsilon}{2})}_{h_2}u^*(t)] \qquad (4)$$

where $(\bullet)^*$ is the complex conjugate. Fig. 2(a) depicts this imperfect RF to baseband downconversion in the frequency domain. As can be observed the desired signal is corrupted by the scaled version of the complex conjugate of itself at $-f_{RF}$ which was also downconverted to the baseband due to the RF impairments. In the absence of the RF impairments, only the wanted signal is downconverted to the baseband. Furthermore, the *I* and *Q* signals are no longer orthogonal and they are correlated with each other.

B.   Signal Model for Low-IF Receivers

For the low-IF case, the incoming signal, $s(t)$, consists of the wanted signal $u(t)$ at f_{RF} and unwanted image signal $i(t)$ at f_{IMG} where $f_{IMG} = f_{RF} - 2f_{IF}$. Hence, the incoming signal $s(t)$ can be expressed as:

$$s(t) = \Re\left\{u(t)e^{j2\pi f_{RF}t}\right\} + \Re\left\{i(t)e^{j2\pi f_{IMG}t}\right\} \qquad (5)$$

where $u(t)$ and $i(t)$ are the complex envelopes of the wanted and image signals respectively. As shown in Fig. 2(b), the received signal $s(t)$ is quadrature mixed with the non-ideal LO signal, x_{LO}, given in (3) and low-pass filtered resulting in an IF signal $r_{IF}(t)$ which can be expressed as:

$$r_{IF}(t) = \frac{1}{2}[u(t)(g_1 e^{-j\frac{\varphi_\varepsilon}{2}} + g_2 e^{j\frac{\varphi_\varepsilon}{2}})e^{j2\pi f_{IF}t} + u^*(t)(g_1 e^{j\frac{\varphi_\varepsilon}{2}} - g_2 e^{-j\frac{\varphi_\varepsilon}{2}})e^{-j2\pi f_{IF}t}] \quad (6)$$
$$+ \frac{1}{2}[i^*(t)(g_1 e^{j\frac{\varphi_\varepsilon}{2}} - g_2 e^{-j\frac{\varphi_\varepsilon}{2}})e^{j2\pi f_{IF}t} + i(t)(g_1 e^{-j\frac{\varphi_\varepsilon}{2}} + g_2 e^{j\frac{\varphi_\varepsilon}{2}})e^{-j2\pi f_{IF}t}]$$

where the desired signal $u(t)$ is corrupted by the image $i^*(t)$ leaked in-band due to RF impairments. There is also a leakage from the desired signal into the image channel. A frequency domain illustration of this is given Fig. 2(b). In a fully balanced system, however, the wanted signal and the interferer are downconverted to opposite frequencies $+f_{IF}$ and $-f_{IF}$. The *I* and *Q* signals of $r_{IF}(t)$ are then converted into the digital domain. Following this, another mixer stage takes care of the final downconversion from the IF to baseband. As this conversion stage takes place in the digital domain, the *I* and *Q* channels are matched hence, ideal mixing is assumed leading to the baseband signal $r_{BB}(k)$. The complex baseband equation for the *IQ*-imbalance effects on the ideal received signal $r_{BB}(k)$ is given as:

$$r_{BB}(k)=u(t)(\overbrace{g_1e^{-j\frac{\varphi_\varepsilon}{2}}+g_2e^{j\frac{\varphi_\varepsilon}{2}}}^{h_1})+i^*(t)(\overbrace{g_1e^{j\frac{\varphi_\varepsilon}{2}}-g_2e^{-j\frac{\varphi_\varepsilon}{2}}}^{h_2})\quad(7)$$

As can be observed from Fig. 2(b), the desired signal $u(t)$ is corrupted by the interferer $i^*(t)$ scaled by h_2 leaked in-band due to phase and gain mismatches.
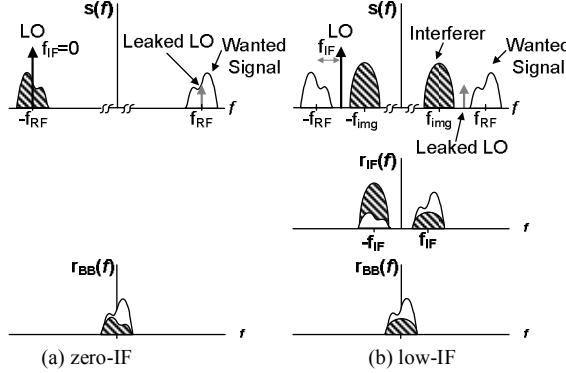

Figure 2.   RF-to Baseband downconversion with RF impairments

To examine the performance of the quadrature mixer, we define the *Image-Rejection Ratio* (IRR) as the ratio between the image signal to desired signal (h_2/h_1). This is a function of phase and gain errors (α_ε, φ_ε) and is given in decibels as [14]:

$$IRR(\alpha_\varepsilon,\varphi_\varepsilon)=10\log\left(\frac{2-2\cos\varphi_\varepsilon+0.5\alpha_\varepsilon^2(1+\cos\varphi_\varepsilon)}{2+2\cos\varphi_\varepsilon+0.5\alpha_\varepsilon^2(1-\cos\varphi_\varepsilon)}\right)\quad(8)$$

It can be calculated from (8) that, in order to achieve an IRR of 60 dB, phase and gain errors must be 0.01 dB and 0.1° respectively, revealing very stringent, matching requirements. In practice, analog mismatches limit the IRR to 25– 40 dB [13]. Fig. 3 demonstrates the effects of varying the *IQ* phase and gain mismatches on the raw *Bit-Error-Rate* (BER) performances of the systems using 32-PSK and 256-QAM modulation formats.
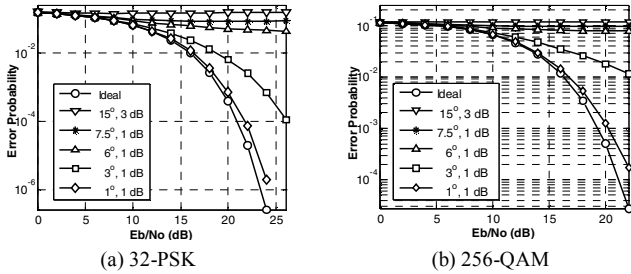

Figure 3.   The effects of *IQ*-imbalances on BER

As can be observed from Fig. 3, *IQ*-imbalances degrade the systems BER performance greatly. This degradation in performance is surely not desirable and must be compensated.

There are a number of solutions reported in the literature [2]-[13] dealing with the RF impairments. Our proposed solution for dealing with these RF impairments is depicted in Fig. 4 [14]-[18]. *Digital Impairment Mitigation Block* (DIMB) processes the digitised low-IF or zero-IF *I* and *Q* signals and estimates the RF impairments in the respective RF front-ends and compensates for them in real-time. Idea behind the proposed approach is based on the simple observation that in the absence of the RF impairments *I* and *Q* channels are

orthogonal to each other and no correlation exists between them for the zero-IF case, and for the low-IF case no correlation exists between the wanted and image signals. However, as shown before this is not the case in the presence of RF impairments.
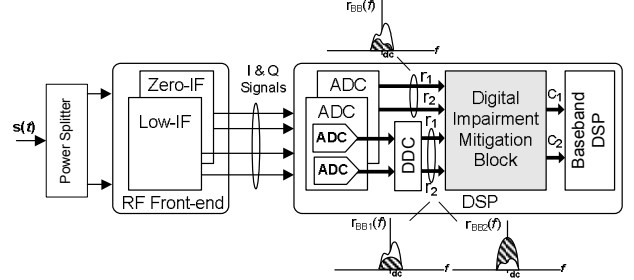

Figure 4.   Proposed solutions for low-IF and zero-IF receivers

For the zero-IF topology, inputs to the DIMB are the *I* and *Q* signals of $r_{BB}(k)$ whereas in the case of low-IF topology they are $+f_{IF}$ signal and $-f_{IF}$ signals, named $r_{BB1}(k)$ and $r_{BB2}(k)$ respectively, downconverted from the IF to baseband by the use of modified *Digital-Down-Converter* (DDC) [16]. Output signals c_1 and c_2 represent the corrected *I* and *Q* channels in the case of the zero-IF topology and the desired and interfering signal in the case of the low-IF topology. Interestingly not only the desired channel is recovered but also the interfering adjacent channel [16].

The performance of the proposed approach is analysed considering 32-PSK and 256-QAM modulated signals with ideal symbol rate sampling. For low-IF simulations, interfering signal is assumed to be 20 dB stronger than the desired one. Fig. 5 depict the simulation results for IRR before and after DIMB for varying phase and gain errors for zero-IF and low-IF topologies using 256-QAM modulated signal. Fig. 6 on the other hand, depicts the BER before and after DIMB for (a) 32-PSK and (b) 256-QAM with various phase and gain errors. As can be observed after compensation the IRR has been enhanced greatly and the BER closely matches the ideal case e.g. RF-impairments have been eliminated. Furthermore, the proposed approach was proven to work under multi-path and fading environments as well as slow and fast varying phase and gain errors and low signal-to-noise ratios [15],[16].
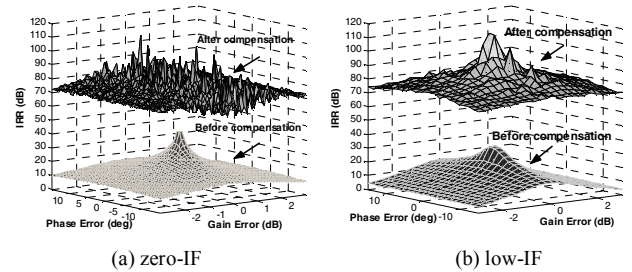

Figure 5.   IRR before and after compensation for 256-QAM

III.   HARDWARE IMPLEMENTATION

In a portable battery powered device it is desirable to keep the size and power consumption as low as possible. Designing for lower power has become a critical pre-requisite for technical and commercial success. DIMB provides enhancement in performance but its hardware overhead must

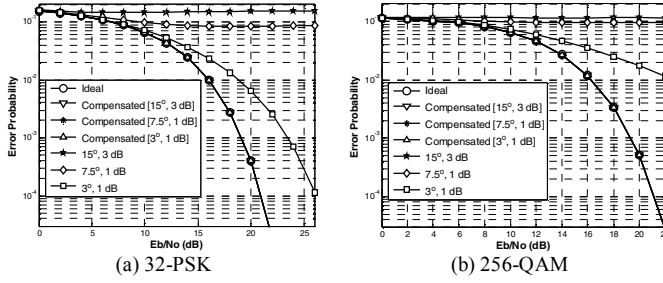be analyzed and reduced. Time-multiplexed low-power implementation of DIMB is shown in Fig. 7 [17], [18].

(a) 32-PSK (b) 256-QAM

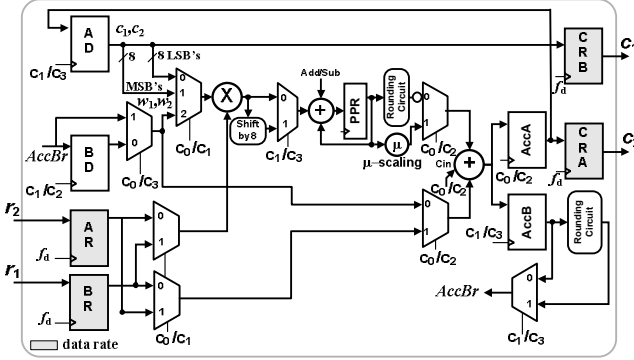Figure 6. BER Curves before and after compensation

Figure 7. Low-power DIMB implementation

This implementation takes four cycles to compute c_1 and c_2 hence it operates four times the data rate, enabling real-time operation. The architecture utilises a number of novel power and area saving techniques. Since the power consumption of the multiplier is a key factor in digital design a simplest power saving technique used is to choose a step-size which is power of two. This can be implemented in hardware as a simple right shift through hardwiring eliminating the need for extra multiplier. More importantly, further power and area savings can be achieved by the use of clever multiplier structures developed in [17]. Using this technique the area of the multiplier can be reduced by 40% when compared to an efficiently designed general-purpose-multiplier without compromising the performance. Another key technique to significantly reduce the power consumption is the use of early-termination technique developed in [18]. The goal of this 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. Low-power implementation of DIMB based on early-termination results in power-down efficiency reduction by 37 - 50 % for 32-PSK and 37 - 58 % for 64-QAM modulated signals.

IV. CONCLUDING REMARKS

Portable consumer multi-mode transceivers require solutions that are compact, cheap and low-power. Furthermore, interoperability of communication systems with navigation systems will become of high importance to provide the value added services in a variety of sectors, providing seamless quality of service for users. An important step into the market is the availability of these hybrid multi-mode terminals for consumer applications. Receiver architectures

that offer high levels of integration however, are susceptible to RF impairments. In order to be able to generate effective solutions, we need to have a better understanding of the effects of these RF impairments and how they manifest themselves in real-life applications. In this paper we analysed the influence of these RF impairments on the receiver's performance and proposed low-complexity solutions dealing with them digitally at the baseband. Furthermore, low-complexity hardware implementation of such solutions was presented utilising a number of novel power and area saving techniques.

REFERENCES

[1] Behzad R, "Design Considerations for Direct-Conversion Receivers", IEEE Trans. on Circuits & Systems I: vol.44, No, 6, pp. 428-435, 1997.

[2] Crols J. and M.J. Steyaert, "Low-IF Topology for High Performance Analog Front Ends of Fully Integrated Receivers", IEEE Transactions on Circuits and systems- II, vol. 45, no.3, pp. 269-282 March 1998.

[3] Churchill F.E., Ogar G.W. and B.J. Thompson, "The Correction of I and Q Errors in a Coherent Processor", IEEE Trans. on Aerospace and Electronic Systems, vol. AES-17, no.1, pp. 131-137, January 1981

[4] Valkama M., M. Renfors, and V. Koivunen, "Advanced methods for I/Q imbalance compensation in communication receivers," IEEE Trans. Signal Processing, vol. 49, pp. 2335–2344, Oct. 2001.

[5] Windisch, M. and G. Fettweis, "Performance analysis for blind I/Q imbalance compensation in low-IF receivers", International Symp. on Control, Communications and Signal Processing, pp: 323 – 326, 2004

[6] Xinping Huang and Caron, M. ,"Performance of a type-based digital predistorter for solid-state power amplifier linearization" IEEE Intl. Symposium on Circuits and Systems, vol.2, pp.1710-13, May 2005.

[7] Tuthill J., and Cantoni A., "Automatic digital pre-compensation in IQ modulators" IEEE International Conference on Acoustics, Speech, and Signal Processing, vol.3, pp. 1621-24, March 1999.

[8] Roman, T. Visuri, S. Koivunen, V., "Blind Frequency Synchronization in OFDM via Diagonality Criterion", IEEE Trans. on Signal Processing, vol. 54, issue. 8, pp.3125-35, Aug. 2006.

[9] Rykaczewski, P. Brakensiek, J. Jondral, F.K., "Decision directed methods of I/Q imbalance compensation in OFDM systems" IEEE Vehicular Technology Conference, vol. 1, pp. 484-87, Sept. 2004.

[10] Tarighat, A., Sayed, A.H., "MIMO OFDM Receivers for Systems with IQ Imbalances", IEEE Trans. on Sig. Proc., vol. 53, pp. 3583-96, 2005

[11] Dogancay, K., "Blind compensation of nonlinear distortion for bandlimited signals" IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 52, issue 9, pp. 1872-82, Sept. 2005.

[12] E. Mensink, E. A. M. Klumperink, and B. Nauta, "Distortion cancellation by polyphase multipath circuits," IEEE Trans. on Circuits Systems I, Regular Papers, vol. 52, no. 9, pp. 1785–1794, Sep. 2005

[13] Chen C. C., C. C. Huang, "On the architecture and performance of a hybrid image rejection receiver", IEEE Journal on Selected Areas in Communications, vol. 19, pp. 1029 -1040, June 2001.

[14] Cetin, E., I. Kale and R. C. S. Morling, "On the Structure, Convergence and Performance of an Adaptive I/Q Mismatch Corrector", IEEE Veh. Tech. Conf., vol. 4, pp. 2288-92, Sept. 2002.

[15] Cetin, E., I. Kale and R. C. S. Morling, "Performance of an Adaptive Homodyne Receiver in the Presence of Multipath, Rayleigh-Fading and Time-varying Quadrature Errors", IEEE International Symposium on Circuits and Systems, (ISCAS 2003), vol. 4, pp. 69-72, May 2003.

[16] Cetin, E., I. Kale and R. C. S. Morling, "Adaptive Self-Calibrating Image Rejection Receiver", IEEE International Conference on Communications (ICC 2004), vol. 5, pp. 2731-2735, June 2004.

[17] Cetin, E., S. S. Demirsoy, I. Kale and R.C.S. Morling, "Efficient FPGA Implementation of an Adaptive IQ-Imbalance Corrector for Communication Receivers Using Reduced Range Multipliers" Proc. European Signal Processing Conference (EUSIPCO), September 2005

[18] Cetin, E., I. Kale and R. C. S. Morling, "Efficient Low-Power Design and Implementation of IQ-Imbalance Compensator using Early Termination", IEEE International Symposium on Circuits and Systems, (ISCAS 2006), May 2006.