# RF Gain Control in Direct Conversion Receivers

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**ABSTRACT**

This paper presents a study of LO selfmixing and RF gain control issues in direct conversion receivers. In cellular systems, that use continuous time frequency duplexing, these can constitute serious problems. The presented topic is of special importance when digitally programmable gain is implemented at the RF frequencies before the downconversion mixers, practically in the LNA. Furthermore, this paper gives circuit solutions to overcome this problem.

## 1. INTRODUCTION

Direct conversion receiver (DCR) is a promising architecture for the integrated radio receivers, especially in wide-band communication systems [1],[2]. Compared to superheterodyne receiver the integration level is considerably higher and thus lower cost can be achieved. The well-known problems related to the DCR architecture, for example the envelope distortion, offsets and 1/f-noise can be solved, at least partially, with the proper circuit solutions and system design [3],[4]. In the modern cellular systems the wanted signal at the receiver input can vary from –110 dBm to –20 dBm and the required noise figure is in the range of a few decibels with small signal powers. To meet these strict specifications the maximum gain of the RF front-end must be in the range of 20 dB to 40 dB. Therefore, to ensure optimal reception also at high signal levels, it may be necessary to distribute adjustable gain between baseband and RF. In addition, the gain has to change during the reception in continuously receiving systems such as direct sequence CDMA. Hence, in order to achieve a reception with an acceptable bit error rate the gain adjustment has to be carried out without significant transients at the baseband signal, which typically will be strongly amplified at the analog baseband before A/D-conversion.

The benefit from the RF front-end gain adjustment is that the tuning transients from the RF circuitry do not fall into baseband frequencies. The low frequency transients are upconverted in the mixers to RF frequencies and then filtered out by the baseband channel selection filter. However, if the gain adjustment circuit is at RF but DC-coupled to the mixer output the RF gain control may abruptly change DC-offset at the mixer output, thus producing transients into baseband. This can happen, for example, when the gain adjustment is implemented at the input transistors of Gilbert cell type mixers.

## 2. DESCRIPTION OF THE PROBLEM

The problem arising from the RF gain adjustment in a DCR is shown in Fig. 1. The local oscillator (LO) operates at the reception frequency. In the DCR, a part of the LO-signal power leaks to the RF input. This signal is then fed back to the mixer input and downconverted with the same LO-signal producing a DC-offset voltage at the mixer output. When the gain of the RF front-end is fixed, the DC-offset from the LO selfmixing remains constant as long as the LO-leakage in the receiver remains constant. This constant DC-offset can be filtered out with various techniques. The options to remove offset depend on the system specifications. In some cases, highpass filtering is suitable, which can be implemented using AC-coupling or a servo feedback loop [5].

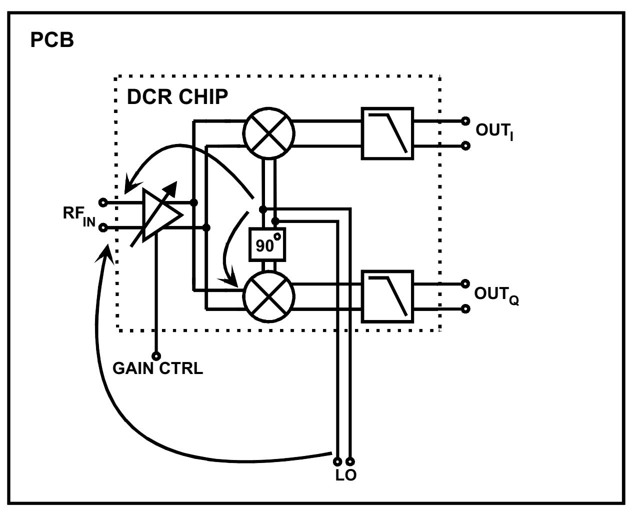


Fig. 1. Coupling paths for LO signal, which can produce DC-offset due to selfmixing.

A new problem arises when the RF gain is changed abruptly with digitally controlled steps. The leaked LO-signal passes then through the LNA to the mixer input with a different gain. In association of gain change, the selfmixed DC-offset at the mixer output is changed as well. This is usually a very rapid change, thus producing a transient to the mixer output. These transients can be much higher than the wanted signal and hence they must be removed. The selfmixed LO power at mixer output, which is due to LO leakage to RF input can be estimated as

$$P_{1,2} = P_{LO} - L_{LOtoRF,1,2} + G_{RF,1,2} \qquad (1)$$

where $P_{LO}$ is the local oscillator power (dBm), $L_{LOtoRF,1,2}$ are the LO attenuations to the RF port (dB) and $G_{RF,1,2}$ are the front-end gains from RF input to mixer output with different gain settings (dB). When the gain is changed in the LNA the value for the DC-offset change can be calculated as

$$V_{offset,rms} = \sqrt{0.05 \cdot 10^{\frac{P_1}{10}}} - \sqrt{0.05 \cdot 10^{\frac{P_2}{10}}}. \qquad (2)$$

Here $P_1$ and $P_2$ are the powers with different RF front-end gains at the output of the mixer due to LO selfmixing. These equations give a worst-case DC-offset change, if it is assumed that the LO selfmixing happens in-phase and that the DC-offset is mainly dominated by the LNA gain change. However, the LO leakage to mixer input may change with different LNA gain settings and thus produce additional DC-offset change. Therefore these equations only estimate the DC-offset change.

In the published receivers the typical LO power is at the range of –10 to +10 dBm and the LO-to-RF isolation is typically about 50 to 70 dB. Fig. 2 illustrates the calculated DC-offset change as a function of LO power leakage to the LNA input, as the RF front-end gain is lowered by 3 dB. This change is shown with four different RF front-end gain values. It can be seen that the offset change is easily in the range of mV. If the gain steps are larger at RF then a larger offset change is obviously observed. Fig. 3 shows measured and calculated DC-offset changes at the mixer output for the direct conversion receiver presented in [6]. The calculated result was determined in the following manner. First the gain of the RF front-end was measured with different LO powers and gain settings. Then the LO power at the RF input was measured and the offset change was calculated using Equation (2). In order to minimize the number of bits required in the A/D converter and power consumption of this receiver, a baseband circuitry with the maximum voltage gain of 66 dB follows the RF front-end. A few mV offset change after the downconversion with that baseband gain is enough to produce an offset change of few volts at the input of an A/D-converter, which corrupts the reception.

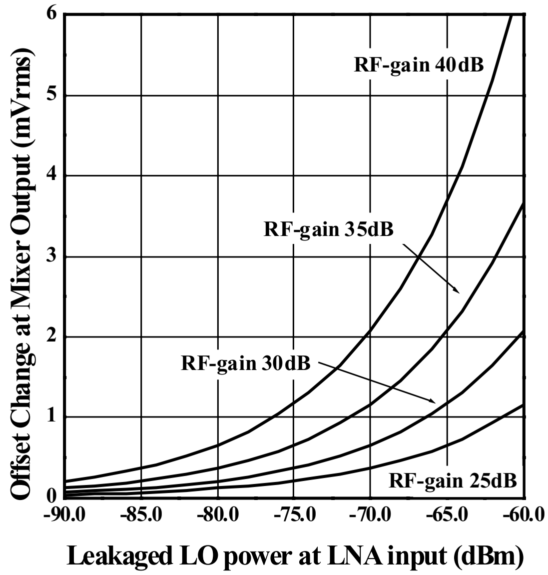


Fig. 2. Calculated DC-offset change at mixer output as a function of LO power leakage to LNA input, when the RF front-end gain is lowered by 3 dB.

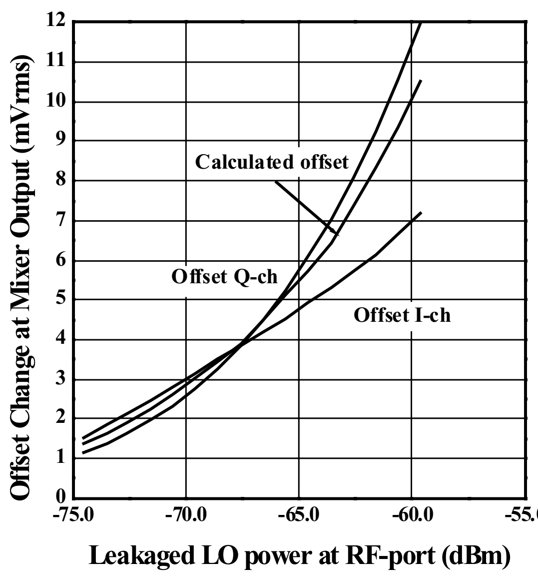


Fig. 3. Measured and calculated DC-offset change, when RF voltage gain is changed 20 dB.

## 3. PROPOSED SOLUTION

The problem from the RF gain control transients can be solved using two different approaches. In the first proposal, a few mV DC-offset change is accepted at the mixer output. In this case, to minimize the effect of the DC-offset change, the RF gain is adjusted when the power of the wanted signal is much higher than the DC-offset change. Hence, the gain adjustment must be done at baseband with the small wanted signal levels. In the second solution the DC-offset change at the mixer output is decreased to a level where it is always much smaller than the actual signal. This requires strong LO signal suppression at the LNA input and is discussed below.

A large part of the LO power can leak to the RF input trough the PCB and bond wires. Therefore, special attention must be paid on the PCB design. For example, the use of orthogonal LO and RF signal wiring both on-chip and PCB reduce the LO power leakage. Furthermore, using on-chip LO driver amplifiers, or placing VCO on the same chip, minimizes the LO power off-chip. Hence, only locally on-chip generated LO can couple to the RF input. As an additional solution the off-chip LO power at the RF frequency can be minimized using a double frequency LO. This solution obviously requires an on-chip divide-by-two circuit. However, the divide-by-two circuit can be used to produce a 90° phase shift between I and Q mixers, instead of using RC or polyphase type passive structures. The limiting factor for divide-by-two circuit is usually the used frequency band. In current technologies, with a reasonable current consumption a 5 GHz input frequency is easily achieved. This is enough to cover most of the current wireless telecommunication systems. To see if the problem can be solved with this kind of structure a test circuit, which used divider shown in Fig. 4, was fabricated. In addition, compared to the previous design [6] to further reduce the LO leakage a mixer shown in Fig. 5 was used. The reverse isolation of the mixer in Fig. 5 is improved by 11 dB by using a cascode transistor between LO switches and input transistor. In the measurements, a LO power at the RF input was decreased from –68dBm to –75 dBm, compared to the previous design. Figs. 6 and 7 illustrate the transients of this circuit when the LNA gain is changed 5 dB and 10 dB, respectively. According to Equation (2) 55 mV and 152 mV should be observed at the baseband output with 5 dB and 10 dB steps, respectively. The measured and calculated values match well in 5 dB step but a larger difference is observed with 10 dB step, which is due to issues already discussed in this paper. The baseband used similar high pass filtering as in [6]. The effect of this high pass filters at the baseband can be clearly observed from these figures.

To further decrease the LO leakage a third chip was implemented. In this chip, the modifications were mainly made on the layout. The limiting LO buffers, which are between the divider and mixers were previously located close to the divider. These were now moved between I and Q mixers very close to the LO switches. The motivation for this was to minimize the LO signal routing path length at the same frequency as RF and also reduce the length of the large power LO signal. Furthermore, a part of the on-chip supply capacitor was placed close to the divider. In the measurements, the LO power at the RF input was below –98 dBm. With this low LO power it becomes difficult to distinguish transients from the noise at baseband output, which is associated with the DC-offset change described above. However, transients could be observed at baseband output when the noise was removed from the results by averaging the output signal.

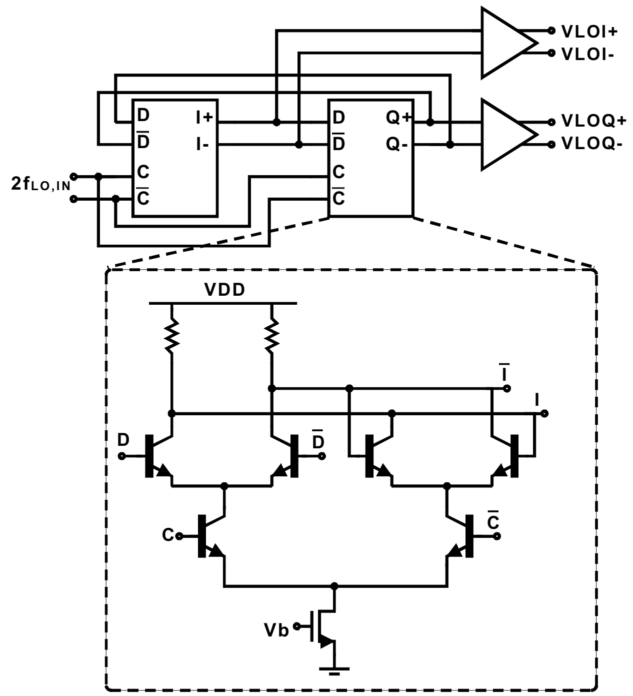


Fig. 4. Schematic of the LO divider.

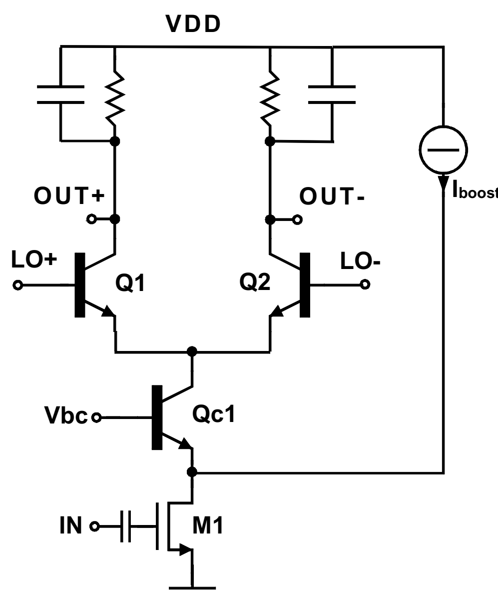


Fig. 5. Schematic of the used mixer.

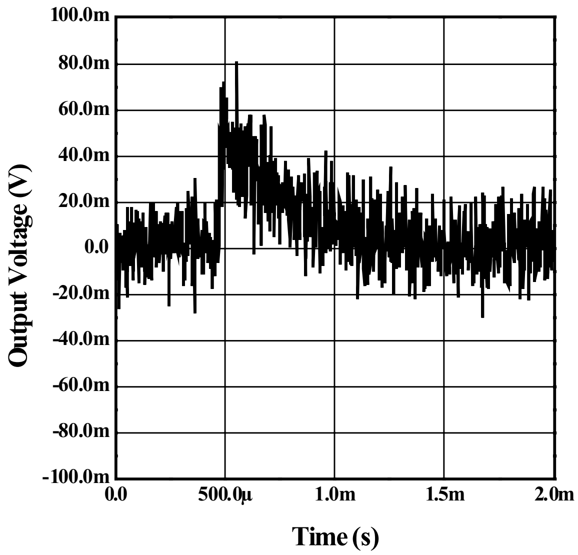


Fig. 6. The transient at baseband output when LNA gain is increased 5 dB.

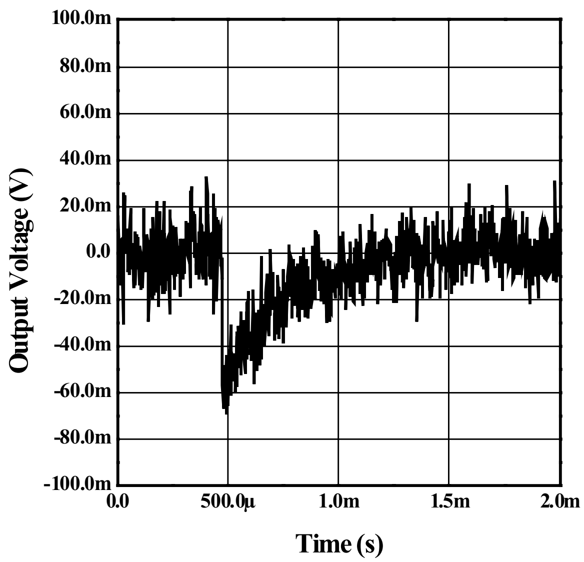


Fig. 7. The transient at baseband output when LNA gain is decreased 10 dB.

## 4. CONCLUSION

A design consideration of implementing RF gain control for the integrated direct conversion receivers is introduced. A digitally adjustable RF gain in receivers, which have a continuous reception can cause problems due to the LO selfmixing. This problem has been analyzed and solutions to reduce and overcome this problem have been presented.

## 5. ACKNOWLEDGMENTS

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