Estimation and Compensation of IQ-Imbalances in Direct Down Converters

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Abstract: - In this paper, a new method for the estimation and the compensation of IQ-imbalances in direct down conversion receivers is presented. The considerations are based on a receiver structure that is developed for the simultaneous down conversion of up to four neighbouring carriers in UMTS base stations. The image suppression of such a system must achieve 60dB at least. This requirement is not fulfilled by the analogue part and hence, an error estimation and compensation in the digital domain is necessary. In laboratory measurements using a W-CDMA signal, the image suppression could be improved by 50.3 dB to a resulting value of 75.1 dB.

Key-Words: - Direct down conversion, image suppression, IQ-imbalance.

1 Introduction

Due to high pressure towards cost reductions on the telecommunication market, a goal of the development is the integration of analogue parts, e.g. of the base station receiver, on ASICs [1]. Direct down converters for the single carrier reception in mobiles like [2] are already existing. However for base stations, there is a demand to process up to four carriers simultaneously which requires a higher bandwidth. According to the 3GPP specifications, e.g. a blocking interferer signal can occur in the receive band. Since the power level of this blocking signal can be much higher than that of the user signal, a high image suppression must be ensured.

2 Receiver Structure

The receiver architecture comparable to [3]-[4] is shown in Fig. 1. It extracts the real and imaginary part from a complex signal converting it directly down from the RF domain to the base band. In the present case, the field of application is the reception of a multi carrier W-CDMA signal in UMTS base stations. The antenna signal is filtered by a bandpass and amplified by a low noise amplifier and a variable gain amplifier. The signal path is divided into the in-phase (I) and the quadrature (Q) paths, each containing a mixer, a lowpass and an amplifier stage. The LO ports of the mixers are driven by CW signals with a frequency *f* equal to the centre frequency of the received multi carrier band. Thus, one of the mixing products occurs around the frequency *2f* while the other one occurs in the baseband. The LO input signals of the mixers must differ by a phase shift of 90°. At the output of the mixers, the baseband signals are lowpass filtered and amplified. Afterwards they are AD-converted. In the subsequent digital domain, the particular channels are separated and the error estimation and compensation is done.

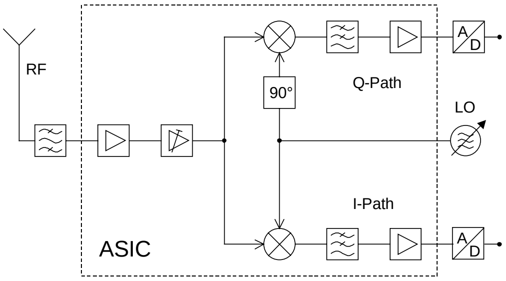

Fig. 1 Block diagram of a direct down conversion receiver.

3 Imbalance Problem

Since in analogue IQ-demodulators, the I and Q paths cannot be built identically and the 90°-phase shifter is not ideal, gain and phase imbalances between the I and the Q signals occur. Thus the following channel separation algorithm cannot separate the particular channels without mutual interference caused by image signals. The power level of these unwanted images depends on the occurring IQ-imbalances as described in [5]. An example in the case of the 3GPP blocking specification is shown in Fig. 2. It represents the worst case of the image problem in the considered base station receiver. In order to detect the channels correctly, the images and therefore the IQ-imbalances must not exceed certain limits. With the approach shown in Fig. 3, the dependency of the image suppression on the gain and phase imbalance can be calculated.

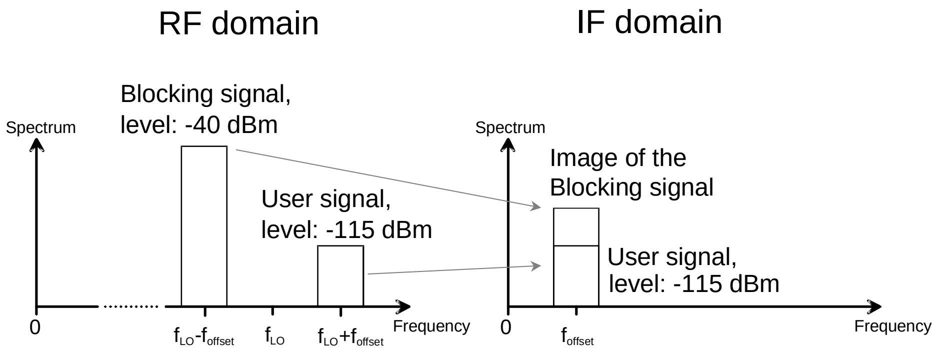

Fig. 2 Illustration of the image problem in the 3GPP blocking specification.

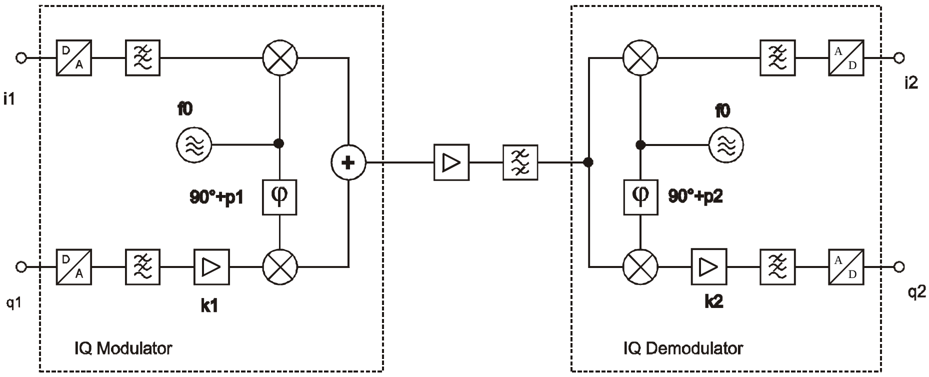

Fig. 3 Approach for the calculation of the image suppression.

The parameters k_1 and k_2 model the gain imbalances of the transmitter and receiver and the parameters p_1 and p_2 model the phase imbalances of the transmitter and the receiver respectively.

The transfer function of the chain is.

$$i_2 = \frac{1}{2}\left[i_1\right] \tag{1a}$$

$$q_2 = \frac{1}{2}\left[k_2 q_1 \cos(p_2) - k_2 i_1 \sin(p_2)\right] \tag{1b}$$

i_1 and q_1 are the inphase and quadrature input signals in the time domain and i_2 and k_2 are the inphase and quadrature output signals in the time domain.

In the following the factors 1/2 in (1a) and (1b) will be neglected for simplification and only the demodulator for the receiver is considered.

The image suppression can be derived by feeding the demodulator with a CW signal.

$$i_1 = \cos(\omega t) \tag{2a}$$

$$q_1 = \sin(\omega t) \tag{2b}$$

With (2a) and (2b) the output signal can be calculated.

$$i_2 = \cos(\omega t) \tag{3a}$$

$$q_2 = k_2 \sin(\omega t - p_2) \tag{3b}$$

The coefficients for the wanted and the image frequency can be calculated via fourier transform of the signal in the time domain. The fourier coefficients are.

$$\underline{d}_{+\omega} = \frac{1}{2}\left[1 + k_2 \cos(p_2) + jk_2 \sin(p_2)\right] \tag{4a}$$

$$\underline{d}_{-\omega} = \frac{1}{2}\left[1 - k_2 \cos(p_2) + jk_2 \sin(p_2)\right] \tag{4b}$$

$\underline{d}_{+\omega}$ is the fourier coefficient at the wanted signal and $\underline{d}_{-\omega}$ the fourier coefficient at the image signal respectively.

With equation (4a) and equation (4b) the image suppression can be derived.

$$a_{\mathrm{Im}age} = 20\log\left[\frac{\left|\underline{d}_{+\omega}\right|}{\left|\underline{d}_{-\omega}\right|}\right] \quad a_{\mathrm{Im}age} \geq 0 \tag{5a}$$

$$a_{\mathrm{Im}age} = 10\log\left[\frac{1+2k_2\cos(p_2)+k_2^2}{1-2k_2\cos(p_2)+k_2^2}\right] \tag{5b}$$

With equation (5b) the image suppression can be calculated for given amplitude and phase imbalances of a demodulator. The result can be seen in Fig. 4. In order to obtain an image suppression of 60 dB or more which is required e.g. for the correct detection of the UMTS channels, the gain imbalance must not exceed 0.01 dB and the phase imbalance must not exceed 0.1 degrees.

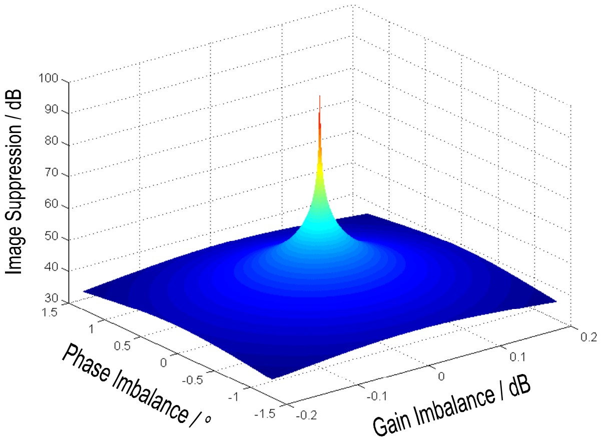

Fig. 4 Image suppression versus IQ-gain and phase imbalance.

4 Error Compensation and Estimation

Due to the imbalance problem mentioned above, a method was developed for the estimation and correction of the signal errors after the channel separation in the digital domain.

The error estimation is done with a calculation of the cross-correlation between two channels that are symmetric about DC. Furthermore, the channel power of each channel is determined. From that, a complex correction factor is extracted that is used in the following error compensation. The error compensation is carried out by weighted subtraction of the image band from the wanted band.

Fig. 5 shows the block diagram of the resulting structure with channel separation as well as error estimation and compensation in the case of a four carrier receiver.

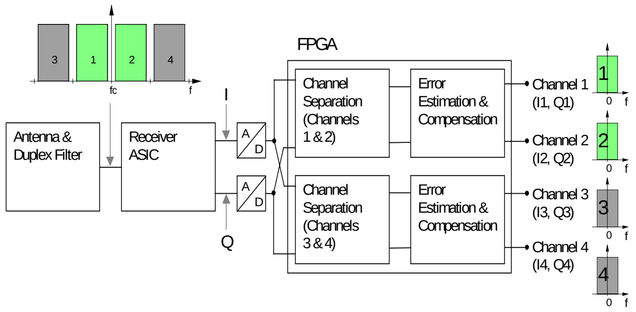

Fig. 5 Block diagram of the complete receiver structure with channel separation and error correction.

A. *Indirect Error Compensation*

The term "indirect error compensation" is used for a method to compensate the IQ demodulator errors by subtracting the error signal introduced by the IQ demodulator at the output of the digital down conversion (DDC). Because these errors are related to the insufficient image rejection of the IQ demodulator they are correlated to the "frequency inverted" output of a down converted channel tuned to the image channel. "Frequency inverted" means that the error signal within the wanted channel has an inverted rotation with respect to the image channel signal. The transfer function of the indirect error compensation stage could be written as.

$$\underline{s}_{out} = \underline{s}_{in,wanted} - \underline{s}^{*}_{in,image} c \tag{6a}$$

$$i_{out} = i_{in,wanted} - aq_{in,image} + bi_{in,image} \tag{6b}$$

$$q_{out} = q_{in,wanted} - ai_{in,image} - bq_{in,image} \tag{6c}$$

$$\underline{c} = a + jb \tag{6d}$$

$\underline{s}_{\mathrm{out}}$ is the wanted complex output signal after correction, $\underline{s}_{\mathrm{in,wanted}}$ is the wanted complex input signal before correction and $\underline{s}^{*}_{\mathrm{in,image}}$ is the frequency inverted complex input image signal. $\underline{c}$ is the complex scaling factor and i_x is the real part and q_x the imaginary part of the signal. Fig. 6 shows a possible indirect compensator block diagram.

For every wanted channel such a stage is necessary. The image channel must also be available for the indirect error compensation. Fig. 7 shows a block diagram of a four channel multicarrier receiver with symmetrically spaced frequency channels. In this case the image of one channel is the wanted signal of its counterpart, so that there is no need for implementing extra downconverters to obtain the image signals needed for the compensators. Only two sets of scaling factors are needed for this case.

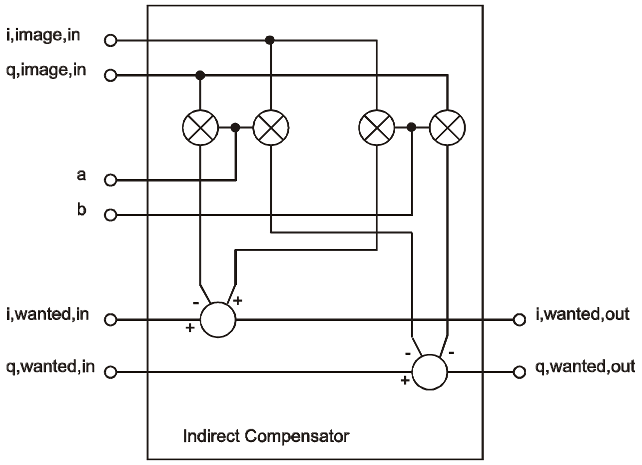

Fig. 6 Block diagram of the indirect compensator stage.

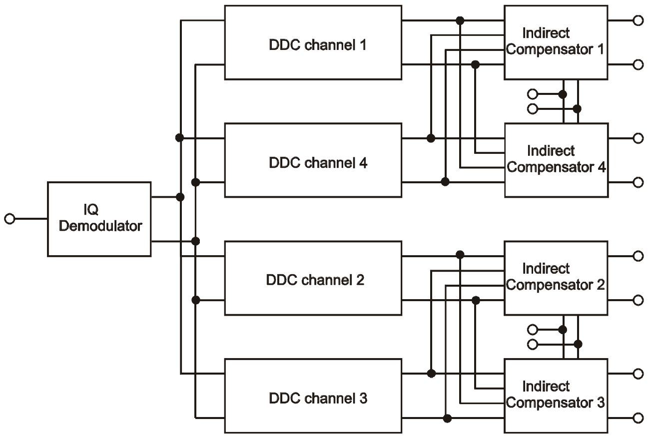

Fig. 7 Indirect compensation for a frequency symmetric four channel receiver.

B. *Error Estimation*

The error estimation functionality is needed to estimate the unknown complex scaling factor. The error estimation is done by correlating the "frequency inverted" signal of the corresponding image channel with the signal of the wanted channel after the direct down conversion stages. The scaled complex correlation coefficient is used to compute the scaling factor used for indirect compensation. Also the amplitude and phase imbalance of the IQ demodulator could be calculated from the scaled correlation coefficient.

$$\underline{xy} = \sum_{i=1}^{n} \begin{aligned} &\left(q_{i,wanted}\, i_{i,image} + i_{i,wanted}\, q_{i,image}\right) + \\ &j\left(q_{i,wanted}\, q_{i,image} - i_{i,wanted}\, i_{i,image}\right) \end{aligned} \qquad (7)$$

$$xxw = \sum_{i=1}^{n} i_{i,wanted}^{2} + q_{i,wanted}^{2} \qquad (8a)$$

$$xxi = \sum_{i=1}^{n} i_{i,image}^{2} + q_{i,image}^{2} \qquad (8b)$$

$$\underline{c} = \frac{\underline{xy}}{xxi}\left[1 - 0.5\left(\frac{xxw}{xxi}\right)^{2}\right] \quad for \quad xxi \geq xxw \qquad (9a)$$

$$\underline{c} = \frac{\underline{xy}}{xxw}\left[1 - 0.5\left(\frac{xxi}{xxw}\right)^{2}\right] \quad for \quad xxi < xxw \qquad (9b)$$

$$k_2 = 1 + 2.047\,\mathrm{Im}\{\underline{c}\} \qquad (10a)$$

$$p_2 = -2\,\mathrm{Re}\{\underline{c}\} \qquad (10b)$$

$\underline{xy}$ is the complex correlation coefficient between the wanted and the image signal. xxw is the energy of the wanted signal sequence and xxi is the energy of the image signal sequence respectively. i_i and q_i are the inphase and quadrature components of the sample i and n is the number of samples taken for correlation. The second term in equation (9a,b) has been found empirically. It has a significant contribution only if the power of the wanted and image signal is about the same. Equation (10a,b) is also found empirically. The number of samples taken for the computations has been varied between one radio timeslot and 1/10 of a timeslot with no significant difference.

5 Simulation Results

In Fig. 8, a simulation result obtained with ADS from Agilent Technologies is shown. As an example, the image suppression with and without error compensation is plotted versus the gain imbalance. The analogue part of the Receiver is included for the simulations. Compared to the image suppression without compensation an theoretical improvement of up to 45 dB can be achieved. As expected, the image supppression is decreasing with increasing gain imbalance. For small imbalance values a saturation of the image suppression occurs. The image suppression is sufficient for gain imbalances up to 4.5 dB.

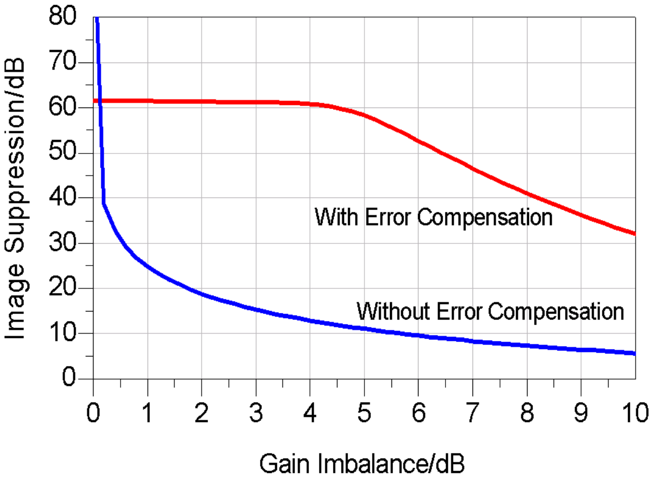

Fig. 8 Simulated image suppression with and without error compensation.

Fig. 9 shows the image with and without image compensator. Without compensator, the image rejection is about 30 dB which is the one of the uncompensated IQ demodulator. With compensator, the image is totally masked by the noise floor. At least 30 dB improvement is achieved in this case.

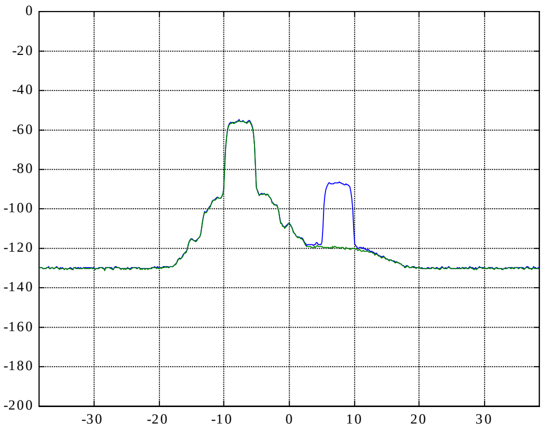

Fig. 9 Main channel and image, with and without compensator.

6 Measurement Results

Measurements have been performed to show the functionality of the error compensation using a set-up shown in Fig. 10.

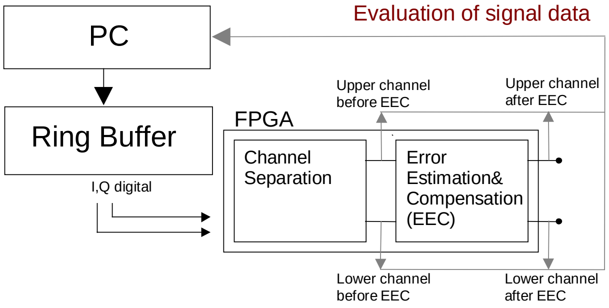

Fig. 10 Set-up used for laboratory measurements.

The input of the FPGA is connected to the digital data source which can be used for a CW as well as for a W-CDMA signal. The signal data in the upper and lower channel are read out from the FPGA before and after the error estimation and compensation part. Finally the data are post-processed in a PC in order to obtain the spectra of the particular channels.

The first measurement is performed using a CW input signal with an amplitude imbalance of 1 dB that was 1.92 MHz above the receiver LO frequency of 1950 MHz. In the error estimation algorithm, 8192 data samples were averaged to calculate the cross-correlation and the channel power values. The spectra of the CW signal in the upper band and its unwanted image in the lower band can be seen in Fig. 11.

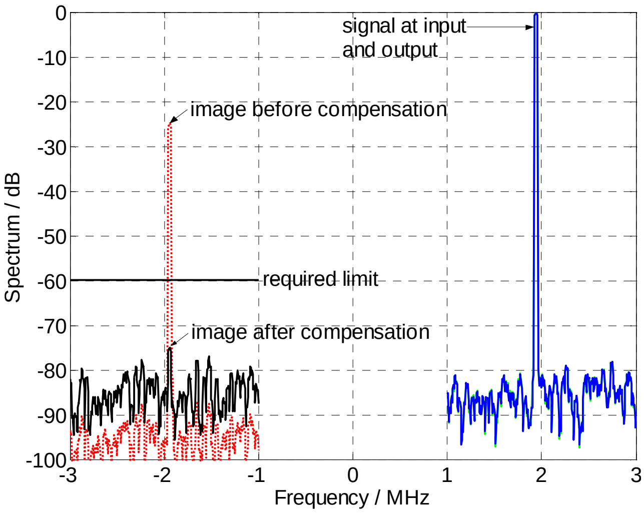

Fig. 11 Spectra of the CW signal in the upper band and its image before and after compensation.

The CW signal is passed through without a noticeable power level change. The image is 24.8 dB below the original CW signal before the error compensation. After the error compensation, the image suppression has reached 70.3 dB. That means that the error estimation and compensation algorithm has increased the image suppression by 45.5 dB.

The second measurement was done with a W-CDMA input signal with a bandwith of 3.84 MHz and an amplitude imbalance of 1 dB. In the error estimation algorithm, again 8192 data samples were averaged to calculate the cross-correlation and the channel power values. The spectra of the W-CDMA signal in the upper band and its unwanted image in the lower band can be seen in Fig. 12.

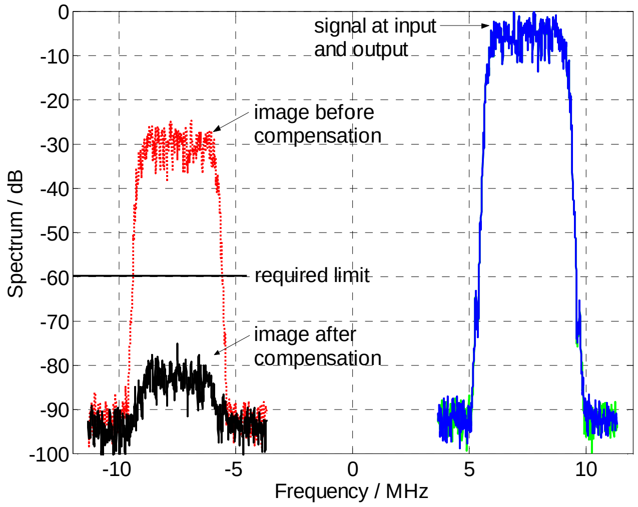

Fig. 12 Spectra of the WCDMA-signal in the upper band and its image before and after compensation.

The W-CDMA signal is also passed through without a significant power level change. The image is 24.8 dB below the original W-CDMA signal before the error compensation. After the error compensation, the image suppression has reached 75.1 dB. That means that the error estimation and compensation algorithm has increased the image suppression by 50.3 dB in this case.

Fig. 13 shows a comparison between measurement and simulation of the image suppression depending on the gain imbalance. Again a W-CDMA signal with 3.84 MHz bandwidth is used. In the error estimation algorithm, again 8192 data samples were averaged to calculate the cross-correlation and the channel power values. The simulation shows good agreement with the measured values even for large imbalances.

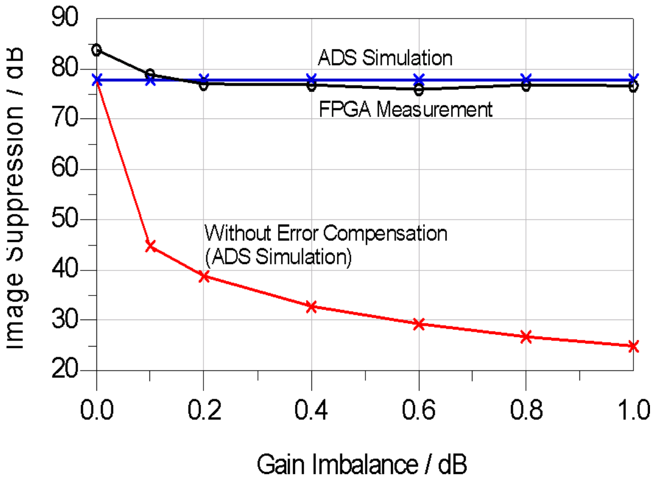

Fig. 13 Comparison between measurement and simulation for the gain imbalance dependent image suppression.

7 Conclusion

This work presents a new method for the estimation and compensation of signal errors resulting from imbalances between the I and Q paths in direct down converters. The functionality is shown in ADS simulations as well as by a laboratory measurements.

Acknowledgement

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