Using Analog Complex Mixers for Low-IF Mixing

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Abstract

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Image rejection ratio, I/Q imbalance, Gilbert-cell, carrier aggregation, 6G wireless receiver

I. INTRODUCTION

Complex signal processing is commonly used in receiver circuits [1], [2]. In traditional direct downconversion IQ mixers, the IQ base is necessary for capturing the phase information, but it also cancels its image signal, if the output is treated as a complex signal [3]. In intermediate-frequency (IF) mixers, complex mixers are often used to cancel the image band or channel and hence minimize the need of RF filtering [4].

Complex mixers provide two main advantages over traditional IQ mixers: the ability to downconvert one desired band to DC, without upconverting its corresponding negative frequency components, and their image-rejection ratio is less vulnerable to component mismatches because the total mismatch usually is a product of two (already small) mismatches.

In this paper, we study a circuit shown in Fig. 1, where first a normal IQ mixer performs a direct downconversion of a very broadband input signal from the sub-THz band. Then, complex mixers are used to shift portions of the baseband to DC-centered signal, as illustrated in Fig. 2. This architecture has previously been proposed for carrier aggregation [5], but here our main aim is split and filter the multi-GHz wide baseband signal so that the requirements for the analog-to-digital converters (ADC) will be less demanding.

The receiver concept here is targeted for broadband sub-THz (100-300 GHz) receivers to receive signals with data rates of tens of Gbps. In such cases ADC dynamic range vs. sampling rate will become an issue [6]. In order to achieve sufficient ADC resolution and minimize power consumption, splitting multi-carrier signal to several sub-bands in analog domain becomes an attractive option. Intra-band carrier aggregation in analog domain [5], [8], can be adopted for multiple low-IF component carriers effectively. As shown in Figs. 1 and 2, the carrier aggregated (i.e., multi-carrier) RF signal is first downconverted from carrier frequency (e.g., 300 GHz) to around DC [9]. Then complex mixers can separate positive and negative component carriers and provide I/Q demodulation for each of these separately as shown in Fig. 1.

At sub-THz range the interfering signals are assumed to be small, but IQ mismatches are expected to dominate possible SNR degradation. Hence, this paper studies the mismatch effects in detail.

This paper is structured as follows: In Section II, the mismatch modeling is presented, then the expression for IRR is derived in Section III, results of Monte Carlo simulations are provided in Section IV, a technique to improve the image rejection is given in Section V, and finally conclusions are drawn in Section VI.

II. MODELING I/Q MISMATCH

The ability of a mixer to suppress image frequencies is defined as the image-rejection ratio (IRR) [7], [12]–[15]:

![Fig. 1. Quadrature downconverter mixer followed by two complex mixers.](image-url)
\[ IRR = \frac{\text{Desired signal power}}{\text{Image signal power}} \]  \hspace{1cm} (1)

The level of mismatch between I and Q affect the IRR, choice of IRR for a certain application depends on the desired modulation scheme [16], and the IF range. Most modern digital modulation techniques require an IRR being at least 30-40 dB [17].

The structure of two-stage band-splitting or carrier-aggregation receiver similar to [10] is provided in Fig. 1. It consists of a normal IQ direct downconversion receiver, followed by two complex mixers for moving a portion of wide-band baseband signal to DC. A complex mixer consists of four real mixers. [10] used this for selecting one carrier, while here our purpose is to split a broadband baseband signal into multiple narrower component carriers each having one complex mixer after the IQ downconverter stage. Yet, the mismatch analysis is done for one output only as it applies to all component carriers. In short, the IQ stage provides a complex baseband/IF input signal, and the complex mixers multiply it by either positive or negative LO frequency only, so that the image is attenuated. This mechanism is illustrated in Fig. 2, where plot b shows the output of the IQ mixer, plots c and d depict the outputs of the complex mixers processing separate carriers.

The matching accuracy between I/Q paths dictates image rejection performance. The gain mismatches of the mixers are modeled as \( \alpha_1, \alpha_2, \) and \( \alpha_3, \) while local oscillator (LO) phase mismatches in the first and second LOs are indicated by \( \phi_1 \) and \( \phi_2, \) respectively. The IRR performance is quite sensitive to these mismatches [18].

A MATLAB script was developed to carry out the computation of all the complex multiplications and enumerate the IRR with respect to different gain and phase mismatches. Simulation results show IRR vs. gain mismatch \( \alpha_1 \) and \( \alpha_2 \) as presented in Fig. 3. Here only two parameters (\( \alpha_1 \) and \( \alpha_2, \) or \( \phi_1 \) and \( \phi_2 \)) are swept at a time in each simulation, while the other three parameters are kept constant, as it is impossible to plot figures with more than three dimensions. The same data in contour plot (Fig. 4) clearly shows that the complex mixer tolerates bigger mismatches: for the same IRR value, the \( \alpha_2 \) range is about twice the gain error \( \alpha_1 \) in the IQ stage.

![Fig. 3. IRR as a function of (a) gain errors (\( \alpha_1 \) and \( \alpha_2 \)), and (b) phase errors (\( \phi_1 \) and \( \phi_2 \)).](image)

**III. DERIVATION OF THE IRR EXPRESSION**

The subsequent analysis follows the idea of [1] and applies it to the complete two-stage mixer. It starts by defining desired
and image signals $D(t)$ and $I(t)$:

$$D(t) = \cos(\omega_D t + \omega_{LO1} t)$$

(2)

$$I(t) = \cos(-\omega_D t + \omega_{LO1} t)$$

(3)

The signals are then multiplied by the first local oscillator (including error models). Assuming upconverted terms are filtered with a low-pass filter, the desired in-phase and quadrature signals (denoted by $P$ and $Q$ in Fig. 1) at the base-band frequency are:

$$P(t) = \frac{\alpha_1 \cos(\omega_D t)}{4} + \frac{\cos(\omega_D t)}{2}$$

(4)

$$Q(t) = \frac{\alpha_1 \sin(\omega_D t - \varphi_1)}{4} - \frac{\sin(\omega_D t - \varphi_1)}{2}$$

and the corresponding image signals may be written as:

$$R(t) = \frac{\alpha_1 \cos(\omega_D t)}{4} + \frac{\cos(\omega_D t)}{2}$$

(5)

$$S(t) = \frac{\sin(\omega_D t + \varphi_1)}{4} - \frac{\alpha_1 \sin(\omega_D t + \varphi_1)}{2}$$

(6)

$$S(t) = \frac{\sin(\omega_D t + \varphi_1)}{4} - \frac{\alpha_1 \sin(\omega_D t + \varphi_1)}{2}$$

(7)

Here $R$ is image of $P$, and $S$ is image of $Q$. The previously obtained four expressions are further multiplied by the second local oscillator using a complex mixer. Ignoring the upconverted terms the following expressions for the desired $I$ and $Q$ paths are obtained:

$$I_D(t) = \frac{1}{16}((\alpha_1 - 2)\alpha_3 + 2\alpha_1 - 4)\cos(\omega_{LO2} t - \omega_D t + \varphi_2 + \varphi_1) + ((-\alpha_1 - 2)\alpha_2 - 2\alpha_1 - 4)\cos(\omega_{LO2} t - \omega_D t)$$

(8)

$$Q_D(t) = \frac{1}{16}((\alpha_1 + 2)\alpha_2 - 2\alpha_1 - 4)\sin(\omega_{LO2} t - \omega_D t + \varphi_2) + ((2 - \alpha_1)\alpha_2 + 2\alpha_1 - 4)\sin(\omega_{LO2} t - \omega_D t + \varphi_1)$$

(9)

The mathematical expression of image rejection ratio may be obtained by making the assumption ($\omega_{LO2} = \omega_D$) and taking the ratio of the desired output magnitude to the magnitude of the image output:

$$\text{IRR (dB)} = 20 \log \left| \frac{I_D + jQ_D}{I_M + jQ_M} \right|$$

(10)

which yields to a pretty comprehensive IRR expression that takes three gain errors and two phase errors into account as in (13).

Analogous derivations for IRR formula are found in literature [3], but what makes the given formula in this work stand out, is the fact that it considers all the possible mismatches in all different paths. The validity of the mentioned formula was verified by comparing it against the MATLAB model described in Section II.

$$\text{IRR (dB)} = 20 \log \left( \frac{A \cos(\varphi_2 + \varphi_1)^2 + B \cos(\varphi_2 + \varphi_1) + C \sin(\varphi_2)^2 + D \sin(\varphi_2)\sin(\varphi_2) + E \sin(\varphi_2)^2 + F}{A \cos(\varphi_2 - \varphi_1)^2 - B \cos(\varphi_2 - \varphi_1) + C \sin(\varphi_2)^2 - D \sin(\varphi_2)\sin(\varphi_2) + E \sin(\varphi_2)^2 + F} \right)$$

(13)

Where:

$$A = (\alpha_1^2 - 4\alpha_1 + 4)\alpha_3^2 + (4\alpha_1^2 - 16\alpha_1 + 16)\alpha_3$$

(14)

$$B = (((8 - 2\alpha_1^2)\alpha_2 - 4\alpha_1^2 + 16)\alpha_3 + (16 - 4\alpha_1^2)\alpha_2 - 8\alpha_1^2 + 32)$$

(15)

$$C = ((\alpha_1^2 + 4\alpha_1 + 4)\alpha_2^2 + (-4\alpha_1^2 - 16\alpha_1 - 16)\alpha_2 + 4\alpha_1^2 + 16\alpha_1 + 16)$$

(16)

$$D = (((8 - 2\alpha_1^2)\alpha_2 + 4\alpha_1^2 - 16)\alpha_3 + (4\alpha_1^2 - 16)\alpha_2 - 8\alpha_1^2 + 32)$$

(17)

$$E = ((\alpha_1^2 - 4\alpha_1 + 4)\alpha_3^2 + (-4\alpha_1^2 + 16\alpha_1 - 16)\alpha_3 + 4\alpha_1^2 - 16\alpha_1 + 16)$$

(18)

$$F = (\alpha_1^2 + 4\alpha_1 + 4)\alpha_2^2 + (4\alpha_1^2 + 16\alpha_1 + 16)\alpha_2 + 4\alpha_1^2 + 16\alpha_1 + 16$$

(19)

**IV. MONTE CARLO SIMULATION RESULTS**

Monte Carlo simulation is a statistical way of analysing effects of random errors with known distributions. In this work, Monte Carlo simulations are done both at behavioral (system) level and at circuit-level. Fig. 5 depicts results of Monte Carlo simulation for 500,000 samples at system level for IQ mixer, complex mixer, and the combination of them. The plots show the probability density functions (PDF) of IRR, when gain mismatch of 0.02 is introduced to the mixers. The probability density distributions show that a complex mixer alone is least sensitive to gain mismatches, having about 4 dB higher IRR. The combination of IQ and complex mixer behaves poorest: it has the low peak value of the IQ mixer,
but also a steeper PDF function. This result indicates that the first mixer stage will be dominating the IRR performance.

Next, transistor-level Monte Carlo analysis was done for an IQ mixer and a complex mixer at an IF of 5 MHz ($f_{LO} = 1.9$ GHz, $f_{RF} = 1.905$ GHz). The IQ mixer and complex mixer use the same Gilbert-cell mixer based on 130 nm SiGe HBT technology which is presented in Fig. 6.

Monte Carlo simulations were performed in Cadence Virtuoso by taking 300 points (samples), where all the mixer components (transistors, resistors, and the capacitors) were selected in a way that their parameters were varied randomly and simultaneously. The image-rejection ratios (IRR) were measured by taking the root mean square (RMS) voltage amplitude difference (in dB) of the desired frequency and image frequency outputs of the mixers, resulting from a two-tone harmonic balance analysis. The histograms of IRR distribution for both mixers are given in Fig. 7. The distribution width for the complex mixer is narrower, meaning that the complex mixer has a better IRR performance, in other words, it is less prone to device mismatches.

Moreover, it is important to note that the obtained results in Fig. 7 are for relatively large devices, which are by nature
at a lower risk for component mismatches. For reference, the effect of the width of the collector resistors are shown in Table I. Seems that 2 um wide resistors are sufficient. Table 1 shows that using smaller devices offers a slightly poorer IRR.

<table>
<thead>
<tr>
<th>Width</th>
<th>Mean IRR (IQ mixer)</th>
<th>Mean IRR (complex mixer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 um</td>
<td>50.563</td>
<td>51.521</td>
</tr>
<tr>
<td>1 um</td>
<td>51.718</td>
<td>53.700</td>
</tr>
<tr>
<td>2 um</td>
<td>52.002</td>
<td>54.463</td>
</tr>
<tr>
<td>4 um</td>
<td>52.029</td>
<td>54.615</td>
</tr>
</tbody>
</table>

V. IMPROVING THE IMAGE REJECTION

Fig. 8 illustrates again the structure of the images, now with asymmetrical spectra for clarity. If our received signal has carriers A and B (Fig. 8a), the images after IQ downconversion are shown in Fig. 8b. At this stage the dominant image on A is B spectrally reversed, and vice versa. After the complex downconversion carrier B is centered to DC (Fig. 8c), and it contains the image from the IQ stage and the image generated in the complex IF stage. Based on above, the following correction can be applied in the digital domain:

\[
A_{\text{corrected}} = A - c_1 \cdot B - c_3 \cdot \bar{B} \]

(20)

\[
B_{\text{corrected}} = B - c_2 \cdot A - c_4 \cdot \bar{A} \]

(21)

The mixer structure was simulated in a case where IQ stage amplitude mismatch was 6%, phase error 3 degrees, IQ mixer gain errors 2 and -3% degrees, and mismatches in baseband filter gains were 3% and -10%. Coefficients \( c_1, \ldots, c_4 \) were adapted recursively during the sequence, and after the converge was achieved, \( c_1 = -c_4 \) were used to correct the entire sequence. Fig. 9 shows that the original 25 dB image is attenuated by almost 10 dB.

Polyphase filters can be used to selectively reject either positive or negative frequencies, if they are both driven and measured with complex signals [8], [17] shows an example with -40 dB IRR in a complex IF receiver. In the circuit discussed here, the signal after the 1st IQ mixer is centered around DC, and placing a polyphase filter in each complex mixer input improves the image rejection of the complex mixers. However, this has two drawbacks. First, the number of mixers increases, as without the filter we could mix two channels with four mixers simply by changing the sign of one of the product outputs. Second, due to better IRR of the complex mixers the dominant error typically is in the first IQ mixing stage, and that the polyphase filter placed at the input of a complex mixer cannot correct any more. In the numerical simulations, adding the polyphase filter improved the image rejection by about 0.5 dB compared to Fig. 9.

VI. CONCLUSION

This paper analyses an architecture that is intended to split a multi-GHz complex baseband into narrower sub-bands for easier digital processing. The overall architecture consists of an IQ downconverter, followed by complex mixers to mix the sub-bands to DC.

Mismatch effects in the above architecture were analysed analytically, numerically and statistically, mismatch in the IQ stage was deemed to be dominant. An adaptive digital correction scheme to cancel the IQ stage image signal was verified with numerical simulations, and up to 20 dB improvement in the image rejection was predicted.

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REFERENCES


