# The Image-Reject Continuous-Time Quadrature Bandpass ΔΣ Modulator

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***Abstract-*** This paper presents the design of an image-reject continuous-time (CT) quadrature bandpass (QBP) ΔΣ modulator using a tailored signal-transfer-function (STF) design. The quadrature delta-sigma noise shaping with polyphase filter implementations and strategic IF placement effectively improve image rejection internally. The Fifth-order CT QBP ΔΣ modulator planned for WiMAX and Bluetooth standards, illustrates clearly the totally elimination of image generation and the correctly signal process. This led to remove the baseband filter and PGA at the price of a very challenging ADC with merged-in cited functionalities. So, less analog components, low power consumption and high performance for the low-IF receiver.

## I. Introduction

Obtaining adequate image rejection with on-chip circuits poses the main obstacle to full integration of a Superheterodyne wireless receiver (RX). In a zero-IF RX, the image of one half of a channel is the other half of the same channel; thus it is sufficient to reject the image by, say, 15 dB or so relative to the final required signal-to-noise ratio (SNR), and this is easily obtained with conventional quadrature down-conversion. However, zero-IF suffers from several drawbacks such as DC offset and flicker noise, which cannot be easily eliminated without also removing valuable spectral energy around DC in the down-converted spectrum. By contrast, a low-IF receiver down-converts the desired channel to frequencies beyond the flicker noise corner. Although the IF amplifiers and filters operate at frequencies substantially the same as in a zero-IF receiver, the image now consists of some other unrelated channel two times the IF away in frequency, which may be substantially larger than the desired channel. Active or passive image rejection filters, double quadrature mixers, can improve image rejection [1].
This paper presents a ΔΣ ADC with merged filtering and PGA. It combines well-known features of a continuous-time ΔΣ ADC [2], such as the anti-aliasing behavior and the low power consumption, with a filtering STF. This filtering STF with a customized design reject the image internally, enabling receivers that translate directly to digital low-IF. The merged design is easier to implement than the conventional baseband while it provides the same functionality. In this architecture (Figure 1), a CT QBP ΔΣ modulator is used that is tailor-made for the low-IF receiver .

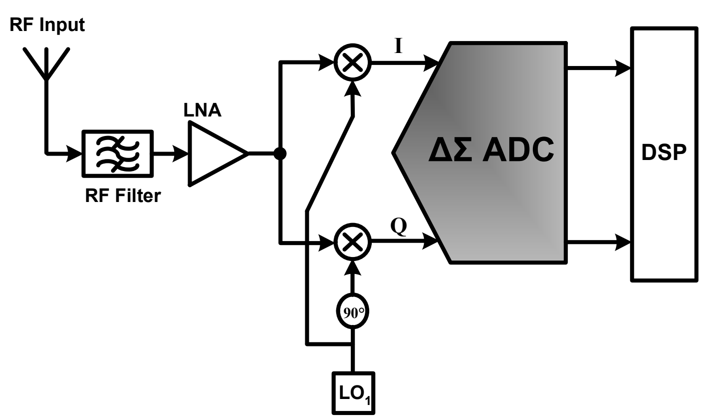


Figure 1. Low-IF receiver architecture using smart ADC.

## II. Continuous-Time Quadrature Bandpass ΔΣ Modulator

### A. Quadrature ΔΣ Noise Shaping

A lowpass ΔΣ modulator converts an analog input signal into a digital output bit stream and uses a lowpass noise transfer function (NTF) to suppress the quantization noise inside the band at low frequencies. In contrast to that, a quadrature, or complex, bandpass ΔΣ modulator converts a complex I/Q analog input signal into a complex I/Q digital output bit stream [3] and uses a complex NTF to suppress the quantization noise inside the band around the centre frequency $f_c$. This paper presents the CT implementation of a quadrature bandpass ΔΣ modulator.

A structure that realizes n$^{th}$-order quadrature ΔΣ modulator is shown in Figure 2. The structure is actually the extension, to complex form, of a similar structure used in higher-order real ΔΣ modulator [4]. It can be described as a chain of polyphase filters with feedback summation and local resonator feedbacks. The general structure shown makes easy the independent positioning of all transfer-function poles and zeros, which is advantageous since noise-shaping can then be performed at an arbitrary fraction of the sampling frequency and since noise-shaping zeros can be spread optimally across the band of interest.

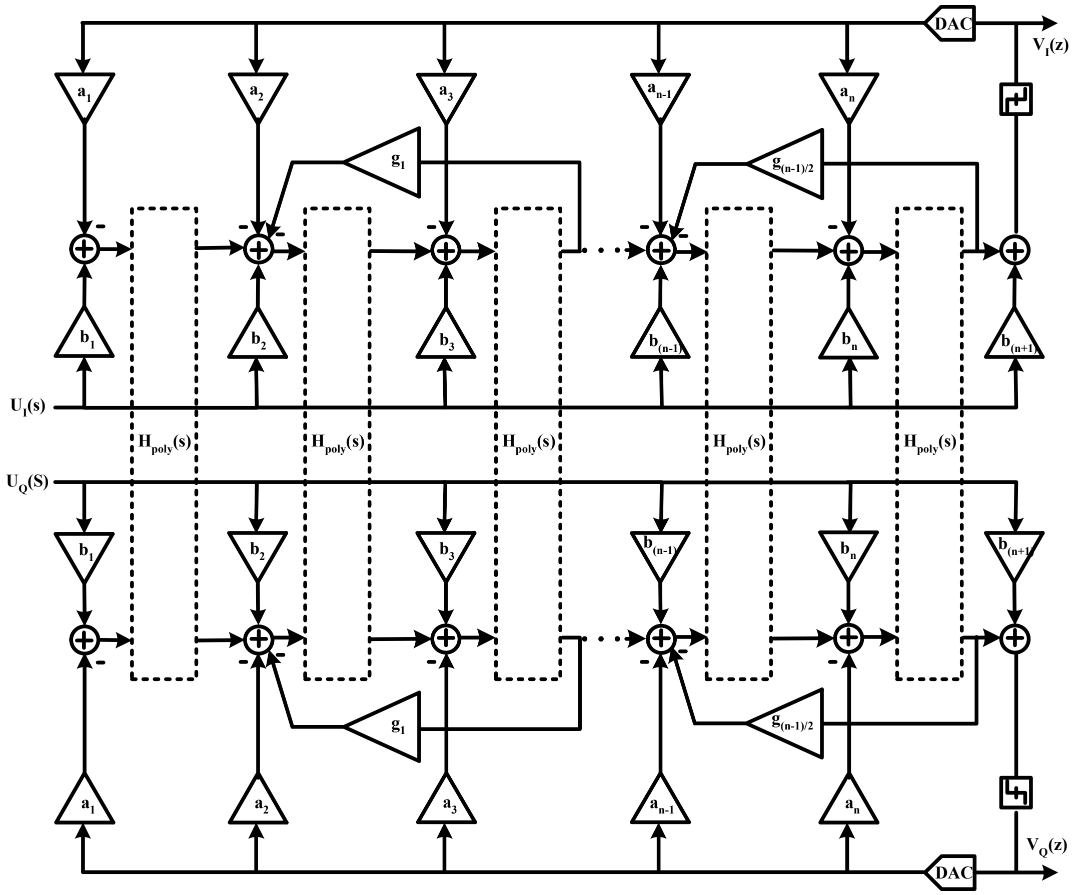


Figure 2. N$^{th}$-order QBP ΔΣ modulator with feedback compensation.

**B. Polyphase Filters**

A polyphase filter can be realized by frequency shifting of a lowpass filter. The transfer function of the polyphase filter ($H_{poly}$) can be obtained from the lowpass filter ($H_{lp}$) as shown in [1]:

$$H_{poly}(j\omega) = H_{lp}(j\omega - j\omega_c). \qquad (1)$$

with: $f_c = \omega_c / 2\pi$ as the center (shifting) frequency. The frequency shift in the transfer function is done by cross-coupling of two real filters, which is shown in Figure 3. Then a single pole complex bandpass filter can be derived from the two lowpass filters, where:

$$H_{lp}(j\omega) = \frac{1}{1 + j\omega T}. \qquad (2)$$

becomes

$$H_{poly}(j\omega) = \frac{1}{1 + j(\omega - \omega_c)T}. \qquad (3)$$

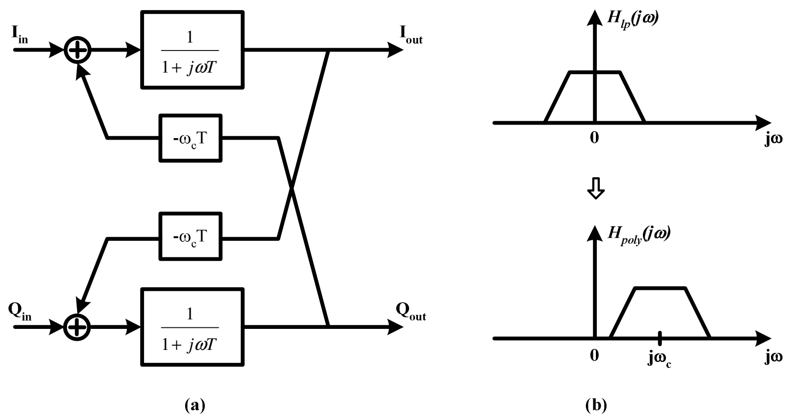


Figure 3. (a) Block diagram of a polyphase filter stage obtained from two cross-coupled lowpass filters. (b) Transfer function shifting illustration.

### C. Complex Noise Transfer Function

Based on lowpass NTF prototype, a complex NTF can be designed in two steps. First, the poles and zeros of the lowpass NTF are calculated with a standard filter program. The second step is that this lowpass NTF is shifted to a centre frequency $f_c$ (Figure 4). This is done by the multiplication of all lowpass NTF poles and zeros with a complex exponential function which describes the frequency shifting on the unit circle in the plane. Fifth-order CT QBP ΔΣM, is designed under design specification given in table 1.

Table 1. Design specifications

| | | |
|---|---|---|
| Sampling Frequency | 160 MHz | |
| Center Frequency | 20 MHz | |
| Standard | Bluetooth | WiMAX |
| Signal Bandwidth | 1 MHz | 20 MHz |
| Oversampling Ratio (OSR) | 160 | 8 |

The complex NTF (Figure 4) has complex poles and zeros and is asymmetrical around DC. The quantization noise is suppressed inside the band around the centre frequency $f_c$. Furthermore, the in-band region of the complex NTF is twice as wide as the in-band region of the shifted lowpass NTF, because of the complex characteristic of this NTF.

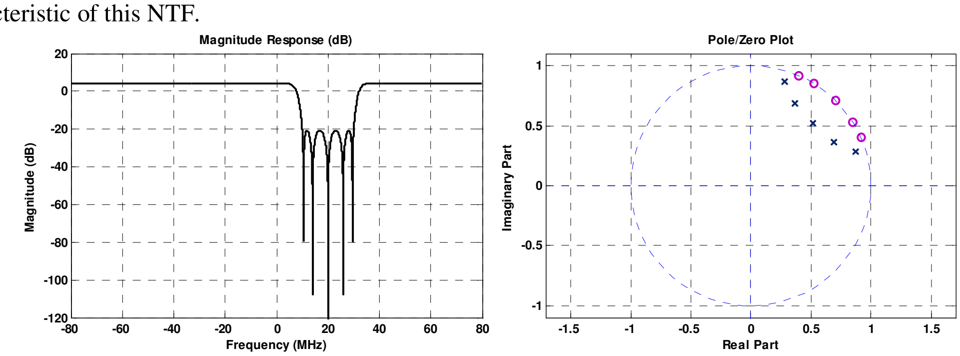


Figure 4. (a) Complex NTF frequency response plot. (b) Pole/zero constellation.

### C. Signal Transfer Function Design for Image-Rejection

The STF spectrally shapes the input signal, and is normally required to have unity gain in-band. Modified STF can allow the nulling of certain portions of the input spectrum, to help minimize specific interferers prior to conversion, and image rejection via strategic placement of IF.

The STF has only feed-forward inputs into the main structure shown in Figure 2, so it shares poles with the NTF; this saves on hardware and presents no significant limitations. The fifth inputs to the structure in the I and Q path allow fifth STF zeros to be positioned. The STF magnitude response is shown in Figure 5(a), and its pole-zero plot in Figure 5(b). It has an in-band gain of 0 dB and out-of-band rejection of more than 57 dB. One STF zero is placed in the center of the image-band (20 MHz), as a technique to help minimize SNR and image-rejection degradation due to component mismatch. leaving fourth zeros available to effect shaping of the input spectrum. In this case, a complex bandpass filtering function is achieved.

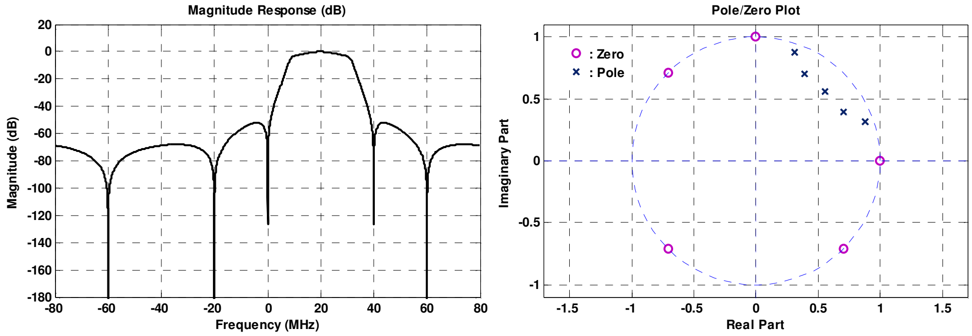


Figure 5. STF (a) Magnitude response. (b) Pole/zero constellation.

## III. Simulation Results

Full system-level simulations were performed on the fifth-order modulator just described. The spectrum in Figure 6 presents a detail of the measured output spectrum at 160-MHz clock frequency. This spectrum shows the fifth notches of the complex noise transfer function inside the 20-MHz bandwidth, centered at 20-MHz IF. Furthermore, this spectrum shows the measured image rejection of 24 dB for flat STF with 20 % disparity between I and Q path (Figure 6(a)). The functionality of the tailored STF is also apparent from Figure 6(b) where there is no image generation.

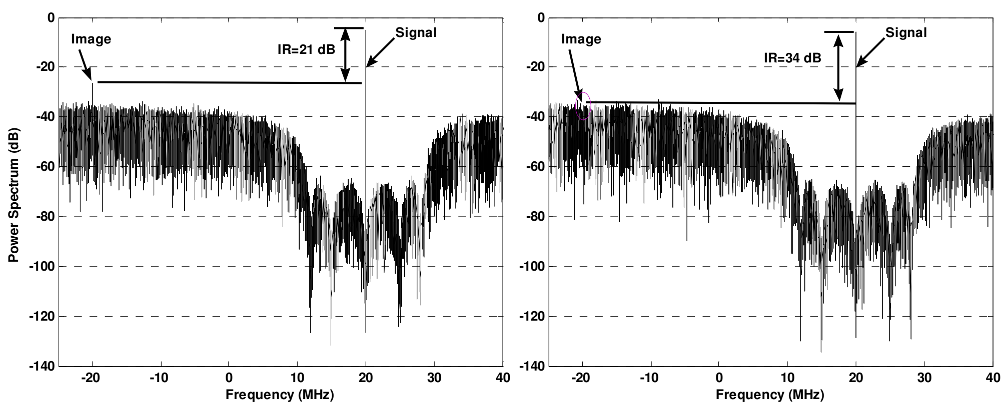


Figure 6. Measured image rejection with (a) Flat STF, (b) Tailored STF.

## IV. Conclusions

This paper has presented the design of built-in image rejection in CT QBP ΔΣ modulators. The quadrature delta-sigma noise shaping character and polyphase filter implementations was presented. The image rejection was improved via tailored STF design and strategic IF placement. The strong mismatch applied between the I and Q path has no effect in the designed $5^{th}$-order CT QBP ΔΣ modulator. Thus, illustrating clearly the totally elimination of image generation and the correctly signal process.

## References


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