

# Interference Rejection in Delay Line Based Quadrature Band-Pass $\Sigma\Delta$ Modulators

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**Abstract**—This paper presents a new concept for an effective design of quadrature band-pass  $\Sigma\Delta$  modulators with built-in Signal Transfer Function (STF) filtering action and discusses the architectural level implementation issues for second and third order modulators based on delay line topologies. The methodology uses an architecture which locks the intermediate frequency (IF) to the sampling frequency for both STF and Noise Transfer Function (NTF). Robustness of the structure against the mismatch is analyzed with interference tones placed in different locations of the receiver spectrum, including the image band. Simulations at the behavioral level verify the architecture implementation and the effectiveness of the approach.

**Index Terms**—Analog-to-Digital conversion, band-pass  $\Sigma\Delta$  modulation, complex filters.

## I. INTRODUCTION

The research in the field of quadrature band-pass  $\Sigma\Delta$  modulators has become popular for their use in wireless receiver applications. Shifting the analog-to-digital converter (ADC) towards the antenna side in the receiver architecture relaxes the analog circuits requirements at the expense of a more complex digital circuit. This also allows more digital integration of analog functions on a single chip resulting in a cheaper system. However ADCs need to be designed with high linearity, large dynamic range, bandwidth and strong image rejection capabilities. Quadrature  $\Sigma\Delta$  modulators [1], [2], [3], [4], [5], are effective candidates for achieving such objectives. In the RF receiver of communication systems such as cellular phones and wireless LANs, low intermediate frequency (IF) receiver architecture is frequently used. This allows moving some receiver functions, such as compatibility with multiple standards and automatic gain control, to the digital part in order to provide more programmability. In conventional zero-IF receiver architectures, two real sigma-delta modulators are used for in-phase and quadrature paths. The main disadvantage of this approach is that not only input, but also image signals are converted by the ADCs. Furthermore, direct down conversion is prone to DC offset and  $1/f$  noise. On the other hand, Fig. 1 shows a low IF receiver architecture, [1], which includes a quadrature band-pass  $\Sigma\Delta$  modulator that can provide superior performance compared to a pair of real band-pass  $\Sigma\Delta$  modulators of the same order.

A well known problem of these kind of systems is the image rejection. Mathematically, the image part can be canceled by combining the two outputs as real and imaginary part,

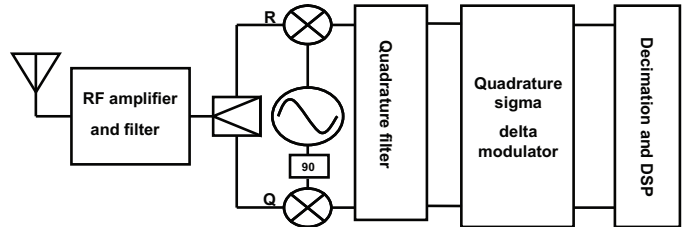


Fig. 1. Typical quadrature receiver architecture.

respectively. However, if there is any mismatch between the I and Q channels, the cancellation of the image contribution will be incomplete, as shown in Fig. 2. Fig. 2(a) shows the receiver spectrum operated by a non ideal mixer, where  $f_{LO}$  and  $f_o$  are the oscillator and the input signal. Non ideal mixer output spectrum based on the convolution of input spectrum with oscillator frequency is shown in Fig. 2(b). If the interference tones are stronger than the signal band then requirements of the quadrature filter would be stringent. Fig. 2(c) shows the non ideal operation of the quadrature modulator. The overall effect

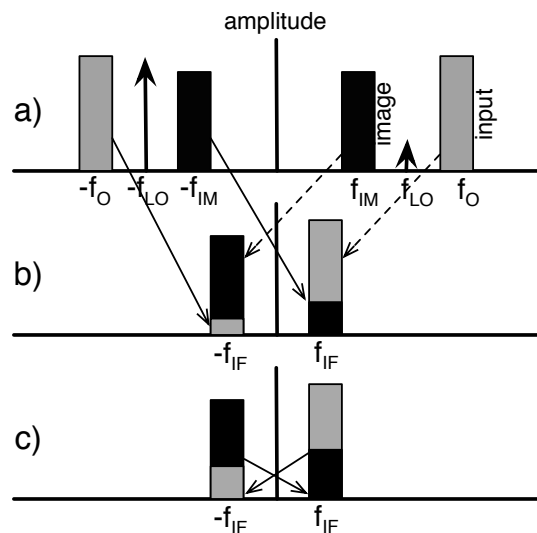


Fig. 2. Down-conversion in low IF receiver with a non-ideal mixer: a) mixer input spectrum, b) mixer output spectrum, c) path mismatch inside quadrature modulator.

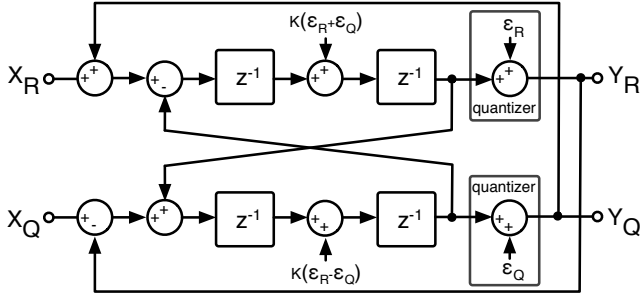


Fig. 3. Second order quadrature band-pass  $\Sigma\Delta$  architecture for  $NTF = 1 + z^{-1}k(1 - j) - jz^{-2}$  with  $IF = 3f_N/4$ .

is a noise leakage from image to signal band which results in reduced signal-to-noise and distortion ratio (SNDR). It would be desirable to remove the image band such that leakage of the noise injection into the signal band is minimized, as many of the current receiver architectures requires very high Image Rejection Ratio (IRR). A possible solution would be to place one of the zeros of quadrature NTF at image location, [1], or selecting signal band near to DC such that quantization noise at image location is still shaped [6]. It is worth noticing that placing a zero at image band helps only to reduce noise leakage into the signal band. Interference signal is independent of NTF zeros. Mismatches in the quadrature modulator also cause leakage of interference signal into signal band and especially interference signal in the image location.

This paper presents an architectural solution for interference cancelation in quadrature  $\Sigma\Delta$  modulators. The STF used in the architecture reduces the leakage of the interference into the signal band. The paper is organized as follows. Section II reviews the basic scheme for a delay based second order quadrature modulator and introduces STF and NTF constraints for the synthesis of quadrature modulators. In addition, robustness against mismatches with interference tones are analyzed. Section III describes the synthesis of third order NTF with second order STF. This Section also illustrates and discusses problems with interference tones at image band and proposes possible solutions. Finally, Section IV draws some conclusions.

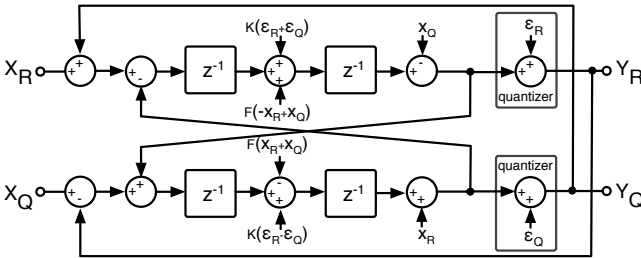


Fig. 4. Second order quadrature band-pass  $\Sigma\Delta$  architecture for STF and NTF design.

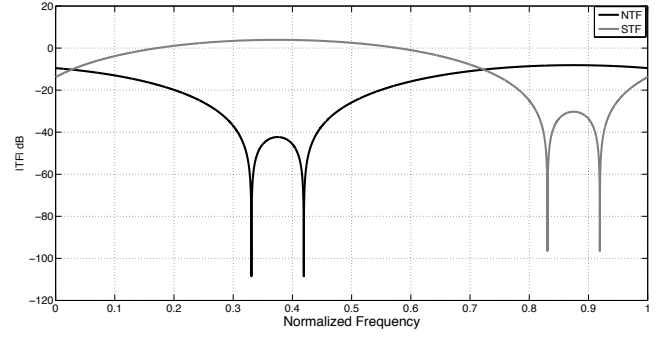


Fig. 5. STF and NTF plot of the architecture shown in Fig. 4.

## II. SECOND ORDER ARCHITECTURES

One of the possible NTFs [7] with zeros on the unity circle at the positions  $e^{j\phi_i}$ ,  $i = 1, n$  is

$$NTF = \prod_1^n \left[ 1 - \frac{e^{j\phi_i}}{z} \right] = 1 + \frac{a_1}{z} + \dots + \frac{e^{j\sum_i^n \phi_i}}{z^n} \quad (1)$$

With zeros on the unity circle, the last term has modulus one and phase that is the addition of the phase of all the zeros. The method developed in [7] and in this paper limits the zero positioning to situations for which  $\sum_i^n \phi_i = 0, \pi/2, \pi, 3\pi/2$  or, correspondingly, the last coefficient of (1) is  $1, j, -1$  or  $-j$ . For  $n = 2$ , it is possible to implement the following STF and NTF, as reported in [7]:

$$NTF = 1 + z^{-1}k(1 - j) - jz^{-2} \quad (2)$$

$$STF = z^{-2} \quad (3)$$

A possible architecture which implements the above NTF is shown in Fig. 3 with IF at  $3f_N/4$  (being  $f_N$  the Nyquist frequency). For stringent NTF constraints, normally it is difficult to achieve flexibility while designing STF. The methodology developed in this paper for the derivation of the STF is similar to what done for the NTF of (1) with similar constrains. One of the possible second order STFs for the interference cancelation is

$$STF = j - F(1 + j)z^{-1} + z^{-2} \quad (4)$$

Note that previously derived architecture has a built-in delay of  $z^{-2}$  so that additional missing terms can be derived using feed-forward paths. The synthesized architecture for the above STF is shown in Fig. 4. NTF is derived using conventional paths with injection of the quantization errors, whereas STF is implemented with feed-forward paths. The STF and NTF plots are shown in Fig. 5. The output spectrum of the modulator shown in Fig. 3 for exaggerated 5% (normally mismatches are less than 1%) mismatch in the feedback path is shown in Fig. 6. An additional interference tone is injected into the modulator at frequency  $7f_N/4$ . The tone at  $-3f_N/4$  is due to the leakage of signal band into the image band. Noise floor in the signal band is raised due to leakage of noise from image to signal band. Fig. 7 shows the output spectrum for

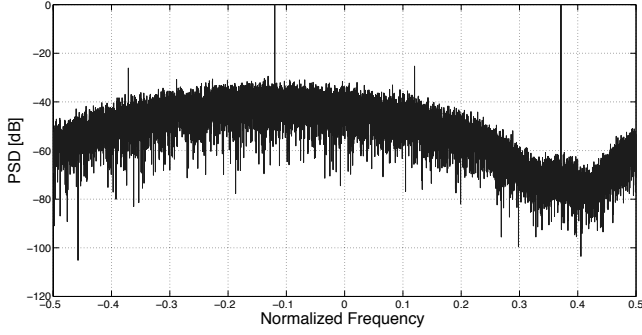


Fig. 6. PSD of the  $3f_N/4$ -IF second order quadrature band-pass modulator with 5% mismatch in the feedback path and interference band at  $7f_N/4$  for the architecture shown in Fig. 3.

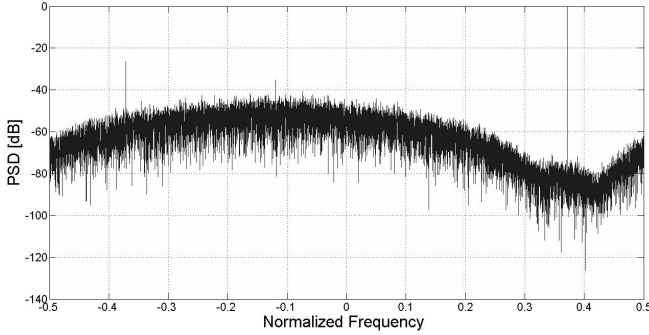


Fig. 7. PSD of the  $3f_N/4$ -IF second order quadrature band-pass modulator with STF filter.

the modulator shown in Fig. 4. The chosen coefficients are  $k = 1.36$  and  $F = 1.36$ . It can be noted that interference tones are reduced by nearly 40 dB thanks to the STF based filter. However STF filter does not process quantization noise and, for this reason, noise floor is still visible in the signal band.

The implementation of the above derived architecture using switched capacitor circuits will be difficult due to the summing block before the quantizer. One of the possible solutions is to use first order STF instead of a second order STF: however, in this way, the effectiveness of the approach will be reduced. Alternatively, it is possible to provide additional delay at the input stage, as shown in Fig. 8. Though the architecture looks like a third order modulator, the order of the modulator is still two with second order STF and NTF. A third order modulator with second order STF is much more attractive, as will be discussed in the next Section.

### III. THIRD ORDER ARCHITECTURES

One of the main concerns in the receiver block is the image interference tones. Big image interference tones can completely mask the signal band in case of a mismatch. Consider the following third order quadrature NTF with second order STF

$$NTF = 1 - z^{-1}k_2(j) + k_1z^{-2} - jz^{-3} \quad (5)$$

$$STF = -1 - F(j)z^{-1} + z^{-2} \quad (6)$$

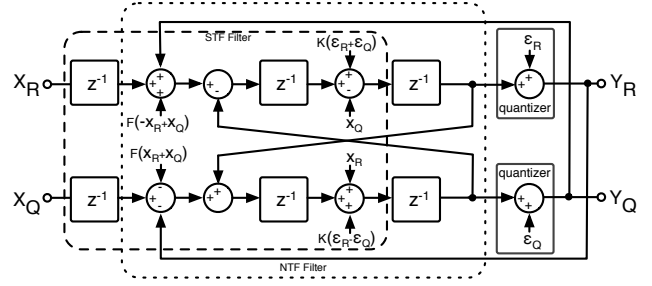


Fig. 8. Modified second order quadrature band-pass  $\Sigma\Delta$  architecture for implementation.

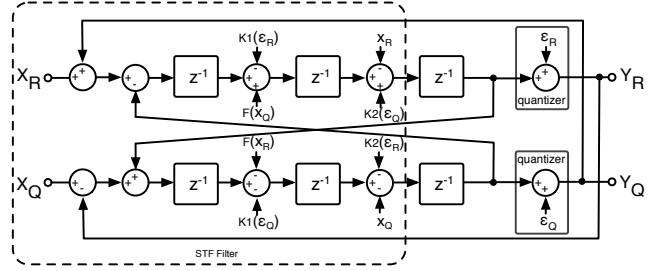


Fig. 9. Third order quadrature band-pass  $\Sigma\Delta$  architecture with second order STF.

A possible implementation of the above third order  $\Sigma\Delta$  modulator with IF at  $f_N/2$  is shown in the Fig. 9. Without feed-forward paths, the architecture realizes a STF equal to  $z^{-3}$ . Hence, implemented STF of the architecture is given by

$$STF = z^{-1}[-1 - F(j)z^{-1} + z^{-2}] \quad (7)$$

The STF and NTF plots for  $k_2 = 2.9$ ,  $k_1 = 2.9$  and  $F = 1.97$  are shown in Fig. 10.

Fig. 11 shows the output spectrum with 1% mismatches in the feedback path for the modulator without STF filter. Image interference tone of magnitude -10 dB is added to the modulator at frequency equal to  $-f_N/2$ . Quadrature input signal is applied to the modulator at IF= $f_N/2 + \delta$ . Noise floor in the signal band raises due to injection of the quantization noise from image band to signal band. Tone at  $f_N/2$  is due

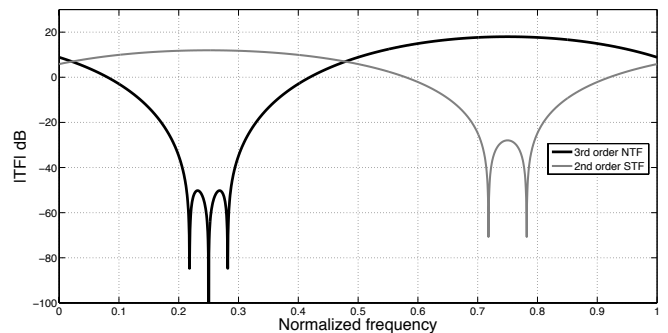


Fig. 10. STF and NTF plots of the architecture shown in Fig. 9.

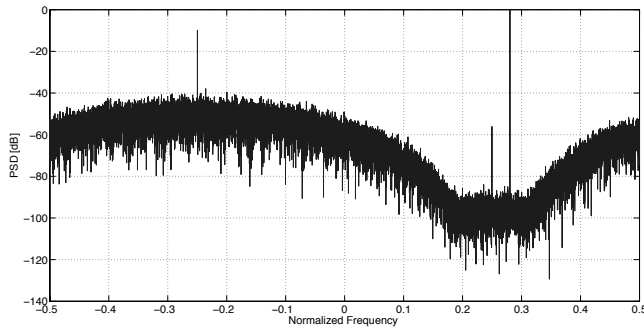


Fig. 11. PSD of the  $f_N/2$ -IF third order quadrature band-pass modulator with 1% mismatch in the feedback path and interference band at  $3f_N/2$ .

to the leakage of the image interference band into the signal band. For low-IF receivers, image bands are closer to the signal band; for this, in order to reduce the interference image tones stringent quadrature filter are typically required. The requirements can be relaxed when using built-in STF filter. Fig. 12 shows the output spectrum of the modulator with built-in STF filter. As expected, there is no interference image tone in the signal band.

Improved results can be achieved by placing one of the NTF zeros in the image band with built-in STF filter. Thus, the output spectrum of the third order modulator with effective second order NTF and STF is shown in Fig. 13. The undesired tone is located -80 dB below the input tone, which is satisfiable for most of the stringent applications. Switched capacitor circuits are used for the realization of the architecture, which provides better matching than a continuous time modulator. Notice that the above derived architecture does not require additional amplifiers for implementation of the built-in STF filtering. Similar schemes can be derived for the implementation of higher order modulators for better performance. The proposed architectural solution has been simulated at the behavioral level in Matlab-Simulink<sup>TM</sup>. Simulations include mismatches and op-amps non idealities (finite gain, bandwidth and slew-rate).

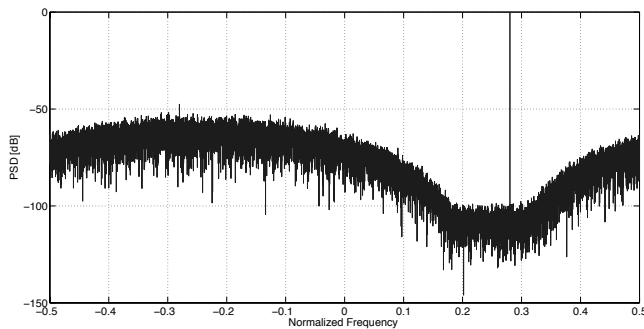


Fig. 12. PSD of the  $f_N/2$ -IF third order quadrature band-pass modulator with second order STF filter.

#### IV. CONCLUSION

This work extensively studied delay line based interference rejection quadrature band-pass  $\Sigma\Delta$  modulators. Potential noise leakage problems due to interference tones at different location including worst conditions at image location have been analyzed. STF filters are derived for above locations including image band. Case studies are verified by implementing architectures for second and higher order quadrature band-pass  $\Sigma\Delta$  modulators. Synthesized STF filters hold the advantage of locking the IF to sampling frequency  $f_s$ . The effectiveness of the proposed scheme was proved by simulations at the behavioral level.

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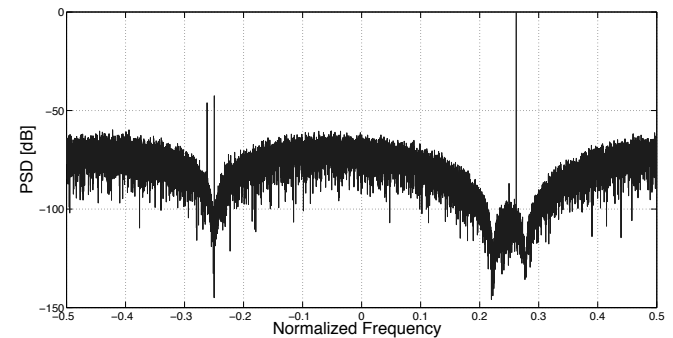


Fig. 13. PSD of the  $f_N/2$ -IF third order quadrature band-pass modulator with second order STF filter and one NTF zero at image band.