A Complex Bandpass ΔΣ Converter for Digital Radio

S. A. Jantzi, K. W. Martin, W. M. Snelgrove and A. S. Sedra

Abstract — A new architecture is proposed for a single-chip digital radio receiver. This architecture has several advantages over the direct conversion architecture that has been gaining interest for use in single-chip designs. A non-zero quadrature IF reduces the image problem and eliminates concerns about self-EMI and 1/*f* noise. A "complex" bandpass filter embedded in a delta-sigma (ΔΣ) loop allows the A/D conversion to be performed directly on the pair of quadrature outputs from the mixer. Simulation results show potential SNR greater than 100dB for an ideal 4th-order complex modulator.

1 Introduction

Many applications require radio receivers that are small and have low power consumption, which requires a receiver that preferably can be integrated onto a single chip. Flexible demodulation and filtering capabilities are also important, so that implementing as much of the receiver digitally using a programmable digital signal processor (DSP) is desirable. Use of a DSP allows a change in function to be implemented by a simple software change.

The direct-conversion architecture, an example of which is shown in Fig.1, has been gaining much interest recently as a potential candidate for a single-chip digital radio receiver [1][2]. The direct-conversion architecture has many benefits over the super-heterodyne architecture when complete integration is desired, in that much of the RF front-end processing can transferred to the digital world. The receiver architecture ideally has no image response, and thus the narrowband image rejection filter in the RF stage, which tends to be bulky, can be replaced with a broadband one. Channel selectivity is performed by lowpass filters at baseband, rather than with a high-Q front-end bandpass filter.

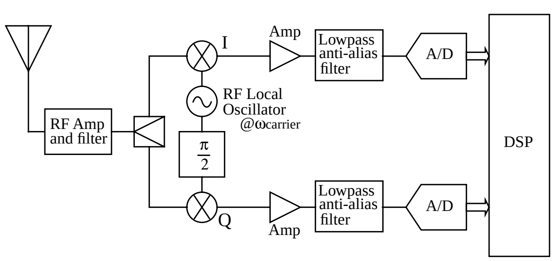

Fig.1 Direct-conversion architecture.

These direct-conversion receivers have considerable problems however. DC offset at the output of the two mixers can be much greater in magnitude than the desired baseband signal. AC coupling can be used, but this places a notch in the effective receiver passband which can adversely affect some modulation schemes. The zero-IF approach means that 1/*f* noise is a serious concern in the back-end blocks, and that the local oscillator radiates energy at the carrier frequency, which causes interference. Finally, mismatch between the I and Q channels causes an image to appear at baseband, thus degrading performance.

2 Proposed Architecture

A possible architecture to eliminate some problems of the direct-conversion architecture is shown in Fig.2.

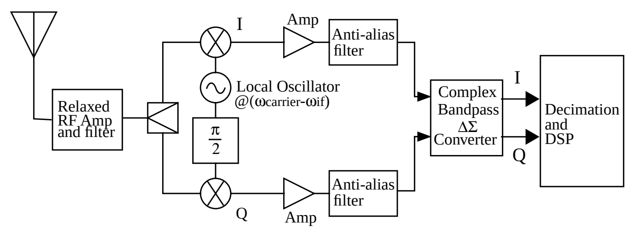

Fig.2 A quadrature-IF system using a complex bandpass delta-sigma modulator.

In this architecture, the input signal is shifted to a non-zero IF where 1/*f* noise and DC offsets cause no problems, and self-EMI is not a issue because the oscillator frequency is different than the carrier frequency. The non-zero IF also means that only odd-order distortion products have an effect, as is the case in any bandpass system. A quadrature-IF mix minimizes the image problem, so that the front-end filter can have relaxed specifications, and thus reduced size. The signal processing and narrowband channel-selectivity filtering is still performed in the digital domain due to the bandpass nature of the A/D conversion [3][4]. The use of a ΔΣ converter, as opposed to a flash converter for example*, is that the converter behaves much more like an analog circuit, having distortion products that fall at the 3dB per 1dB rate [5].

3 Complex Filters

A filter that has a transfer function with complex-valued coefficients (and thus is not limited to complex-conjugate pairs of poles or zeros) is known as a complex filter [6][7]. A complex filter is not restricted to having a symmetrical magnitude response around DC, which can be useful in the generation of single-sideband signals, for instance.

Although the filter takes a complex input signal and

* In a flash converter, distortion products tend to remain at a fixed level, regardless of signal strength.

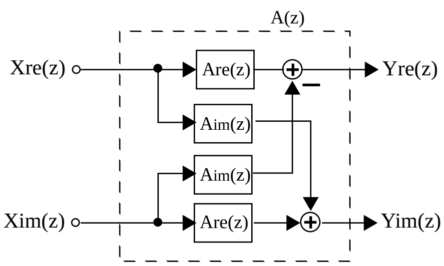

Fig.3 Realising a complex filter with real filter blocks.

produces a complex output signal, the actual filter is constructed from several cross-coupled real filters, as seen in Fig.3. If we have a complex input signal $X(z) = X_{re}(z) + jX_{im}(z)$ exciting a complex transfer function $A(z) = A_{re}(z) + jA_{im}(z)$, then the complex output signal is:

$Y(z) = Y_{re}(z) + jY_{im}(z) = A(z)X(z)$, where

$Y_{re}(z) = A_{re}(z)X_{re}(z) - X_{im}(z)A_{im}(z)$, and

$Y_{im}(z) = A_{re}(z)X_{im}(z) + X_{re}(z)A_{im}(z)$.

4 A Complex Bandpass ΔΣ Modulator

Bandpass ΔΣ modulators have recently been gaining popularity as a means of performing narrow-band A/D conversion on IF signals (signals with small bandwidths relative to their centre frequencies) [4][5][8]. Bandpass filtering and feedback around a low-resolution quantizer has the effect of shaping noise away from a narrow band at some IF frequency. The traditional bandpass ΔΣ modulator accepts a single, real input, and gives a high-speed single-bit-stream output that is representative of the input in a narrow frequency band.

By placing a complex bandpass filter in a ΔΣ loop, as shown in Fig.4, we obtain a system that can take a pair of analog inputs that are in phase-quadrature (I/Q signals) and perform an accurate A/D conversion directly on the "complex" input. The output is now a pair of high-speed bit streams, one of which represents the real output and the other the imaginary output. The complex output signal is again accurate in a narrow band, but the overall response can be asymmetric about DC. This architecture has the advantage that, with a single converter, it can directly perform an A/D conversion on the I and Q outputs provided by a quadrature mixer — and the overall receiver gains the image rejection properties from the quadrature front-end.

The block marked as $A(z)$ is a complex bandpass switched-C filter (although it could be replaced with a continuous-time complex filter) that forms complex poles on the unit circle. These poles become the zeros of the noise-shaping function when placed in the overall feedback loop. The $D(z)$ block, also a complex switched-C filter, allows the input to see an arbitrary transfer function to the output. If desired, this transfer function can provide out-of-band attenuation (providing suppression of adjacent channels). By giving the signal transfer function and the noise transfer function the same poles, some hardware can be shared.

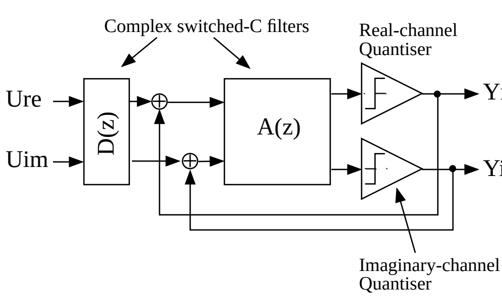

Fig.4 A complex ΔΣ modulator structure.

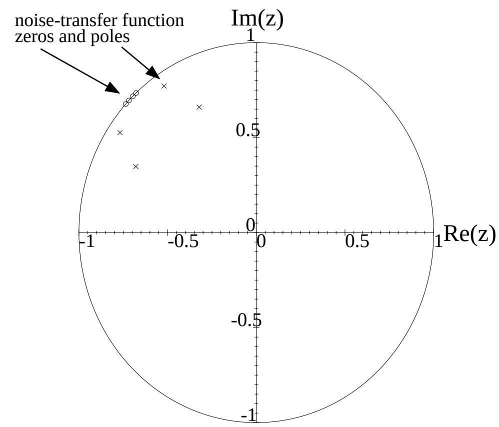

Fig.5 Pole-zero constellation for the complex noise transfer function (NTF).

5 Design of the Complex Filter

A generalised least-pth optimiser [9] was used to design a fourth-order complex noise shaping transfer function (NTF) — the transfer function from the quantization noise "input" to the modulator output. The band-centre was placed at $3\pi/4$, with a bandwidth of $\pi/32$ (giving an oversampling ratio of 32). These specifications would be suitable, for example, for a centre-frequency of 6 MHz and a bandwidth of 250 kHz at a sampling rate of 16 MHz.

The transfer function was optimized under the standard constraints of ΔΣ modulator design: maximum in-band attenuation for quantization-noise suppression; small out-of-band gain (less than 4 dB) to help modulator stability; and a first (NTF) impulse-response coefficient of unity to avoid any delay-free loops involving the quantiser (i.e. for causality).

The resulting NTF pole-zero plot is shown in Fig.5 (note that the poles and zeros have no complex-conjugates) and the associated full-band magnitude response is shown in Fig.6, which includes an expanded view of the in-band region (note that the magnitude response is not symmetric about DC).

6 Simulation Results

Discrete-time simulations were performed on the modulator system described by Fig.5 for a variety of input signals. An output spectrum is shown in Fig.7 for a half-scale tone input. Note that the figure shows the full spectrum from DC to the sampling frequency, f_s, and that the "complex" frequency response is not symmetric about $f_s/2$. Fig.8 shows an expanded view of the in-band region.

64K-long simulations were performed for varying amplitudes of a fixed-frequency complex-sinusoidal input. Hann-windowed fft's of the output data allowed calculation of

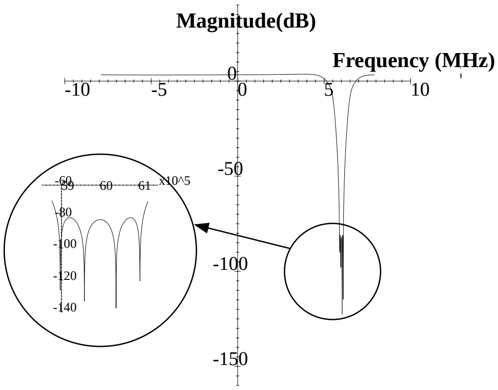

Fig.6 Magnitude response of the complex noise transfer function. An expanded view of the in-band region is shown in the bubble.

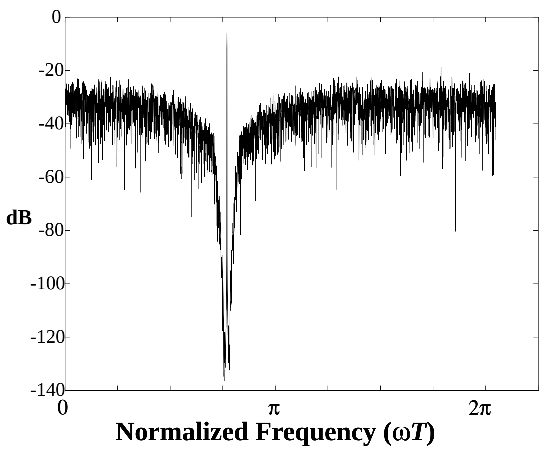

Fig.7 Output spectrum of the complex bandpass ΔΣ modulator. Note that the output spectrum is not symmetrical about the half-sampling rate ($\omega T=\pi$).

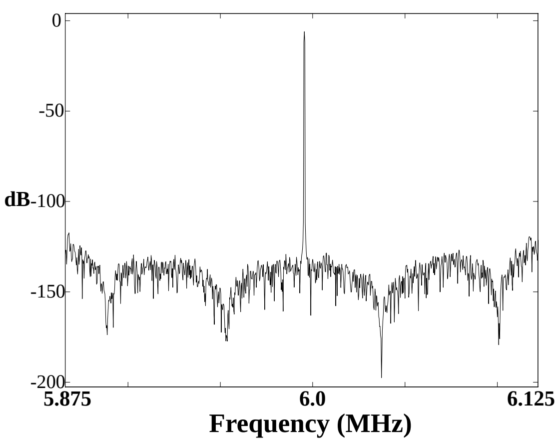

Fig.8 In-band view of the output spectrum shown in Fig. 7.

the signal-to-noise ratio by comparing the ratio of power in the signal bins to the in-band noise power of the output

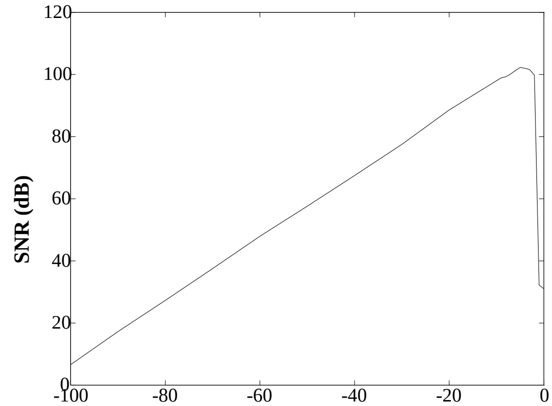

Fig.9 A plot of signal-to-noise ratio versus input amplitude. The input is a tone, centered slightly above band-centre.

spectrum. A plot of SNR versus input amplitude is shown in Fig.9. A maximum SNR of 102dB is realized for a -4dB input signal (relative to full scale) in the ideal modulator.

7 Implementation

The complex modulator can be implemented with standard switched-capacitor circuit techniques. Some of the required coefficients will turn out to have negative values, which can be realized with fully-differential circuitry by reversing the polarity of connections to differential op amp outputs. A possible switched-C cascade structure is shown in Fig.10. This structure produces a 4th-order complex NTF and a 3rd-order complex signal transfer function (the transfer function from modulator input to output). An LDI-structure would be a useful improvement on this structure [7], in that it would ensure that all of the complex filter $A(z)$'s poles (and thus the NTF zeros) would remain on the unit circle even with capacitor mismatch. With the cascade structure, mismatch alters both the real and imaginary components of the NTF zeros, moving them from their ideal locations and lowering modulator SNR.

8 Channel Mismatch

A quadrature mix (i.e. a mix with two oscillator signals that are in phase quadrature) ideally means that there are no images of the desired channel. Any gain or phase mismatch between the real and imaginary (or I and Q) channels of our system mean that this is no longer the case. Mismatch in the quadrature oscillator channels, the multipliers, or the ΔΣ modulator will create an image.

Capacitor (coefficient) mismatch in the two channels of a complex filter can be a serious problem. Whereas in a real filter, mismatch simply alters the expected pole-zero locations, in a complex filter mismatch may mean that the filter no longer simply realizes a complex transfer function. It has been shown [10] that any common-mode error in a coefficient (i.e. when the error in a coefficient is equal in both the real and imaginary paths of the complex filter) simply affects the desired response of the filter, $A(z)$, to the input signal, $X(z)$. Differential error, on the other hand — when a coefficient changes by a certain amount in the real channel, and the same coefficient changes by an opposite amount in the imaginary channel — has the effect of giving the filter, $A(z)$, a response to the conjugate of the input signal, $\overline{X(z)}$. This

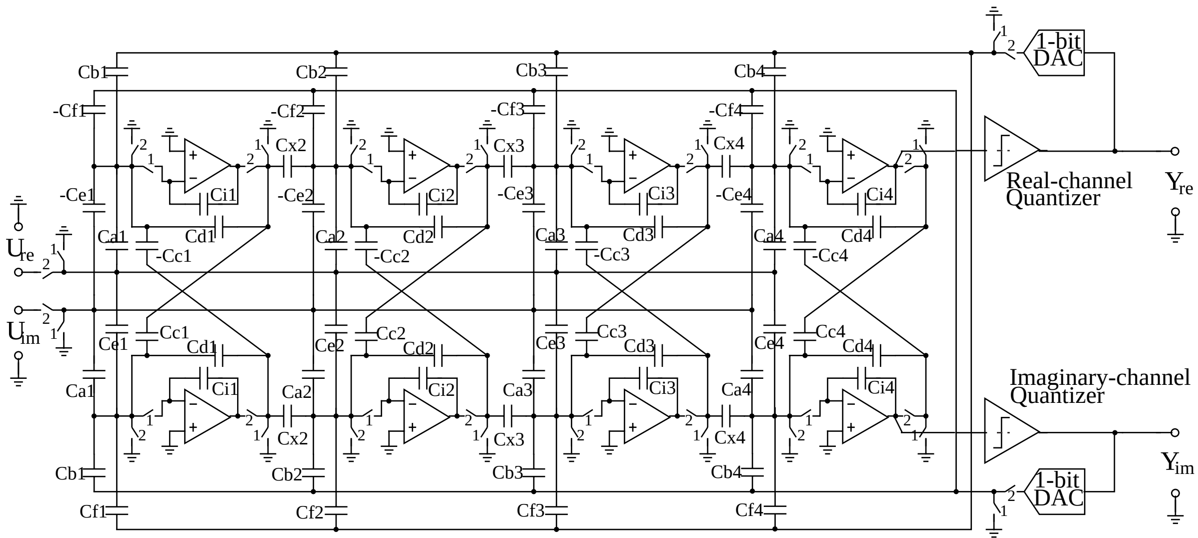

Fig. 10 A single-ended representation of the complex switched-capacitor modulator architecture.

implies that for a complex-sinusoidal input at ω_x, the filter output will have energy at two frequencies, ω_x and $-\omega_x$. If the filter has a real input, differential error would be seen as a loss of stopband attenuation.

Channel mismatch is being investigated for the switched-capacitor structure of Fig.10, and development of a suitable LDI structure is underway. Some confidence is gained from the knowledge that a discrete-component complex analog filter (eight-order bandpass) achieved greater than 70dB of stopband attenuation [6][10]. In an integrated switched-C version of the filter, great care should be taken in the IC layout to ensure a strong correlation between corresponding coefficients in the real and imaginary paths. Further work on mismatch will be presented in the final version of this paper.

9 Conclusions

A new architecture for a digital radio receiver has been presented. This structure contains a new “complex” version of a bandpass ΔΣ modulator, and allows a single modulator to perform A/D conversion on the I/Q outputs of a front-end quadrature mixer. Bandpass ΔΣ conversion means that a zero-IF is not necessary, eliminating many of the problems with the direct-conversion architecture.

10 Acknowledgements

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