MASH ΣΔ modulator with highly reduced in-band quantisation noise

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A novel class of multi-stage noise-shaping ΣΔ modulators is presented. The proposed structure achieves a one-order higher noise-shaping than the modulator's order only by using two extra analogue paths. The noise transfer function zero optimisation is achieved by adjusting a single coefficient in the proposed modulator. Hence, with a minimal extra circuit, the signal-to-noise and distortion ratio is significantly increased compared with the conventional cascaded modulator. Analytical calculations and simulation results are provided to verify the usefulness of the proposed modulator.

Introduction: High speed and accurate ΣΔ A/D converters are often used in the next generation wired and wireless telecom systems [1]. High-order noise-shaping without any stability problems makes the multi-stage noise-shaping (MASH) modulator a good candidate for wideband applications with low oversampling ratios (OSRs). A novel class of MASH modulators is proposed in this Letter to significantly reduce the in-band quantisation noise. This is done by increasing the overall noise-shaping order by one along with optimising the zeros of the total noise transfer function (NTF), just by using two additional analogue paths.

MASH structure: As is known, in a conventional MASH modulator, the quantisation noise of the preceding stage is fed to the succeeding stage. Ideally, by assuming the high accuracy analogue circuits, the quantisation errors of all except the last single-stage modulator are cancelled by the subsequent digital signal processing logic. Thus, the ideal output of the overall modulator will only contain the quantisation error of the last stage modulator, attenuated by a noise-shaping function with the same order as the overall cascaded modulator [2].

Proposed structure: Fig. 1 shows the block diagram of the proposed MASH ΣΔ modulator where L_{s1} and L_{n1} denote the signal and the noise loop filters of the first stage, respectively. In this structure, the first-stage quantisation noise is used as the input of the second stage similar to the traditional two-stage MASH modulator. The structure used in the second stage is a unity signal transfer function (STF) modulator where the first integrator is separated from the others of the loop filter. Using a unity STF structure in the second stage of the proposed MASH modulator relaxes the analogue circuit requirements [3]. Furthermore, the output of the first integrator in this stage is as follows:

$$V(z) = -\frac{z^{-1}}{1-z^{-1}}\mathrm{NTF}_2(z)E_2(z) \tag{1}$$

where $\mathrm{NTF}_2(z)$ denotes the second-stage NTF and it is given by

$$\mathrm{NTF}_2(z) = \frac{1}{1 + H_2(z) \times z^{-1}/(1-z^{-1})} \tag{2}$$

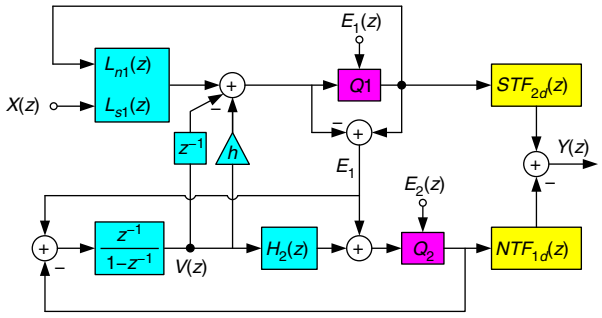

Fig. 1 *Block diagram of proposed MASH ΣΔ modulator*

A ratio of the $V(z)$ and its one-sample delayed version is injected into the most insensitive node of the first stage which is the input of the quantiser.

The overall output of the modulator shown in Fig. 1 is given by

$$\begin{aligned} Y(z) &= \mathrm{STF}_1(z)\mathrm{STF}_{2d}(z)X(z) \\ &+ \left[\mathrm{NTF}_1(z)\mathrm{STF}_{2d}(z) - \mathrm{STF}_2(z)\mathrm{NTF}_{1d}(z)\right]E_1(z) \\ &+ \left[\mathrm{NTF}_{1d}(z)\mathrm{NTF}_2(z) - \mathrm{STF}_{2d}(z)\mathrm{NTF}_1(z)\mathrm{NTF}_2(z)\frac{hz^{-1}-z^{-2}}{1-z^{-1}}\right]E_2(z) \end{aligned} \tag{3}$$

where STF_i and NTF_i and E_i denote the signal and the NTFs and the quantisation error of the ith stage, respectively. NTF_{id} and STF_{id} are the digital estimates of NTF_i and STF_i, respectively. Ideally with the well-matched analogue and digital filters and $\mathrm{STF}_2(z) = 1$, the modulator's output will be

$$\begin{aligned} Y(z) &= \mathrm{STF}_1(z)X(z) \\ &+ \frac{\mathrm{NTF}_1(z)\mathrm{NTF}_2(z)\left[1-(1+h)z^{-1}+z^{-2}\right]}{1-z^{-1}}E_2(z) \end{aligned} \tag{4}$$

As is seen, the effect of the first-stage quantisation error is cancelled similar to the traditional MASH modulator, whereas by choosing $h = 1$ the quantisation noise of the second stage is shaped one-order higher than the modulator's order. Moreover, by adjusting the coefficient h, depending on the OSR, the optimisation of one pair of the NTF zeros is achieved without affecting the digital cancellation filters. In fact, with an optimal h, one of the overall NTF zeros on the dc is cancelled and instead two zeros are added inside the desirable bandwidth. Another advantage of the proposed structure over the conventional MASH modulator is that since the second-stage quantisation noise is uncorrelated to all the other signals in the first stage, it operates as a dither signal there.

The proposed modulator needs just two simple extra analogue inter-stage paths along with an adder to combine the signals at the input of the first-stage quantiser. This combination can be achieved by the same adder required in a low-distortion structure that is used in the first-stage modulator, as shown in Fig. 2. This adder can be realised either with a passive or an active circuit as discussed in [3, 4]. For example, a MASH 2–1 modulator based on the proposed structure is shown in Fig. 2. Using a low-distortion structure to realise the modulator of both stages reduces the effect of the analogue circuit non-idealities [3].

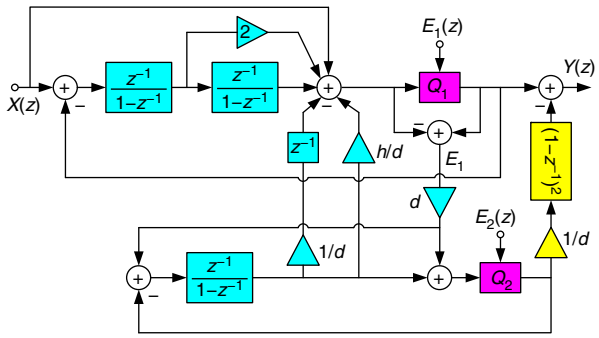

Fig. 2 *Proposed MASH 2–1 ΣΔ modulator*

The ideal output of the proposed MASH 2–1 modulator is given by

$$Y(z) = X(z) + \frac{1}{d}\left(1-z^{-1}\right)^2\left[1-(1+h)z^{-1}+z^{-2}\right]E_2(z) \tag{5}$$

This corresponds to the fourth-order noise-shaping with one pair optimisation of NTF zeros. Fig. 3 shows another implementation of the proposed MASH 2–1 modulator. In this structure, the inter-stage path with one sample delay is transferred to the input of the second integrator. Hence, the passive realisation of the adder before the first-stage quantiser is much simpler than the one shown in Fig. 2.

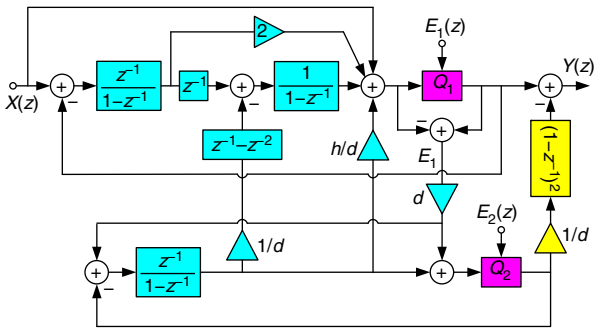

Fig. 3 *Another implementation of proposed MASH 2–1 ΣΔ modulator*

Besides a similar noise-shaping order while having one less integrator, the proposed MASH 2–1 modulator has another advantage over the MASH 2–2 modulator presented in [1]. To verify this superiority, consider the relations (5), mentioned above, and (6) which remarks the overall output of the MASH 2–2 modulator presented in [1]

$$Y_{[1]}(z) = X(z) + \frac{1}{d}(1 - z^{-1})^2\left[1 - (2 - k)z^{-1} + z^{-2}\right]E_2(z) \qquad (6)$$

As is clear, for the special places of the optimised NTF in-band zeros, the optimal value of k (k_{opt}) is much less than that of h (h_{opt}). Thus, in the proposed structure, the switched capacitor realisation of this inter-stage feedback path is simpler than the one presented in [1]. As shown in Fig. 4, by increasing the OSR, k_{opt} becomes smaller, whereas the value of h_{opt} is increased. Accordingly, this feature of the proposed modulator becomes more important for high OSR applications especially when $d > 1$ is used in the cascaded modulator.

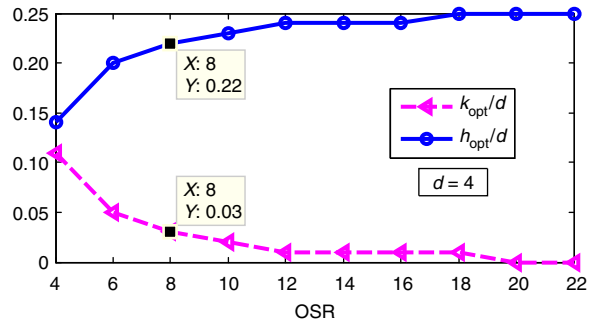

Fig. 4 *Values of h_{opt}/d and k_{opt}/d coefficients against OSR*

Simulation results: The proposed MASH 2–1 ΣΔ modulator shown in Fig. 2 along with the traditional unity STF MASH 2–1 and the resonation-based MASH 2–2 modulator presented in [1] are simulated using MATLAB and Simulink. Circuit non-idealities including amplifier finite dc gain and amplifier limited output swing were included in the Simulink, based on the models proposed in [5]. The assumed OSR and the number of quantisation bits in both stages were 8 and 4, respectively. The inter-stage gain (d) was 4. The simulated signal-to-noise and distortion ratio (SNDR) is 96.3 dB for the proposed MASH 2–1 architecture with $h_{opt} = 0.9$, whereas 77.6 and 96.4 dB are obtained for the conventional MASH 2–1 and the resonation-based MASH 2–2 modulators, respectively, where a −2.5 dBFS sinusoidal input signal was employed. Thus, an SNDR enhancement of about 18.7 dB is achieved with respect to the conventional MASH 2–1 modulator. Fig. 5 shows the simulated SNDR against the input signal amplitude. As seen, the proposed MASH 2–1 has an overload level factor about 2 dB lower than the conventional MASH 2–1. This is because in the proposed MASH 2–1, the first-stage quantiser should also process the shaped quantisation error of the second stage, and hence it is overloaded with a lower input signal amplitude than the conventional MASH structures. This condition is also established for the modulator presented in [1], but it has an overload level factor about 0.5 dB higher than the proposed modulator. This is because of its smaller optimised inter-stage coefficients making the first-stage quantiser process a smaller ratio of the second-stage quantisation error compared with the proposed MASH 2–1. Monte Carlo simulations with 200 iterations and considering a standard deviation of 0.2% mismatch in all the capacitors show that the sensitivity of the proposed MASH structure is the same as the conventional MASH topology.

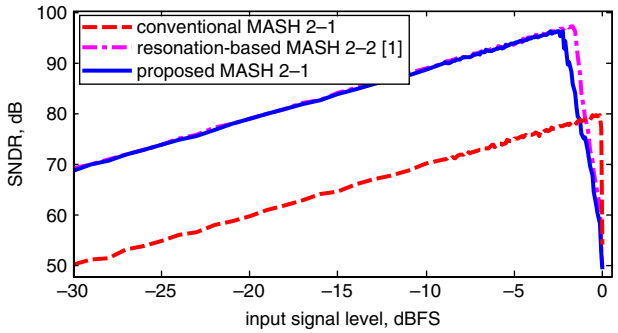

Fig. 5 *SNDR against input signal amplitude*

Conclusion: A novel topology of the MASH ΣΔ modulator has been presented. By using only two extra simple analogue paths between the two stages of the cascaded modulator, both the NTF zero optimisation and the one-order higher noise-shaping ability over the modulator's order are simultaneously achieved. This makes the proposed architecture most suitable for the low power and the broadband A/D converters realisation.

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One or more of the Figures in this Letter are available in colour online.

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