Time-interleaved noise-shaping integrating quantisers

Y. Hu, N. Maghari, T. Musah and U. Moon

A new time-interleaved noise-shaping quantiser architecture is proposed. By employing a time-interleaving technique with a new path-coupling scheme, higher order of noise shaping and increased bandwidth are achieved. This general topology can be employed to synthesise any noise transfer function without the need for dedicated digital-to-analogue converters to extract the quantisation noise. Simulation results are provided to verify the effectiveness of this structure.

Introduction: Single-slope and dual-slope analogue-to-digital converters (ADCs) are known for high linearity and guaranteed monotonicity, but they are slow in nature. A similarly natured integrating quantiser based on modified discharging phase [1] could introduce a first-order quantisation noise-shaping. Despite the advantageous quantisation noise-shaping, these structures are still limited to low-to-medium bandwidth.

To increase the effective bandwidth of these ADCs, an approach based on time-interleaving of multiple channels of the integrating quantisers is presented. In addition, to employ more aggressive quantisation noise-shaping, time-based quantisation noise-coupling is proposed. Hence not only is the effective sampling rate is increased, but also a higher order of noise shaping is achieved.

Noise-shaped integrating quantiser (NSIQ): In these ADCs, the input signal is sampled onto the integrator capacitor of the opamp in the sampling phase. In the discharging phase, the integrating capacitor is discharged with a fixed rate until zero-crossing which is detected by a comparator. Meanwhile, this discharging time period is measured by a fixed clock reference. However, unlike traditional single-dual-slope ADCs where the discharging phase will be terminated at the zero-crossing instance, in the modified integrating structure it will be terminated at the *next rising edge after* zero-crossing occurs, as shown in Fig. 1. As a result, the quantisation error (E_{qv}) is stored on the integrating capacitor at the end of discharging phase (S_2). This voltage will then be subtracted from the input signal in the next sampling phase (S_1), resulting in a first-order highpass quantisation noise shaping

$$Y = X + (1 - z^{-1})E_{qv}$$

Time domain inter-channel noise-coupling: To achieve higher signal bandwidth without increasing the sampling speed, several NSIQ modulators could be time-interleaved. However, the traditional time-interleaving technique will modify the overall noise transfer function (NTF) (assuming each has the NTF of (1)) to

$$Y = X + (1 - z^{-N})E_{qv}$$

where N is the number of time-interleaved channels. As a result, N zeros will be spread in the whole band [2]. For a simple lowpass modulator, this means $N - 1$ zeros are outside the desired signal band, hence the effective quantisation noise order is still one. To move these out of band zeros into the desired band, time-based inter-channel quantisation noise-coupling is proposed.

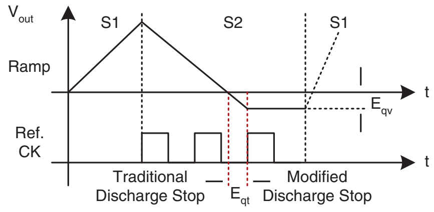

Fig. 1 *Timing diagram of noise-shaping integrated quantiser*

One interesting property of the modified NSIQ structure is that the quantisation error is not only ready and accessible in the voltage domain (E_{qv}) at the end of S_2, but it is also available in the time domain (E_{qt}), shown in Fig. 1. This pulse is the time interval between the comparator zero-crossing and the end of the discharging pulse. Hence, if multiple channels are parallelised, their sampling and discharging phases are time-interleaved and the quantisation error could be fed from one to another as a time domain pulse E_{qt}, triggered asynchronously by comparator zero-crossing and next edge of the reference clock.

Fig. 2*a* shows a two-channel example of this time-interleaved noise-shaping quantiser. During the input sampling of the first channel, the second channel is being discharged. By the end of the discharging of the second channel, the pulse $e_{qt}[n-1]$ will be available and used to asynchronously discharge the integrator of the first channel via a resistor. This results in the subtraction of the quantisation error of the channel 2 from channel 1, and vice versa, as shown in Fig. 2*b*. The value of the coupling resistors can be modified to obtain the desired coefficient, i.e. inter-channel coupling gain.

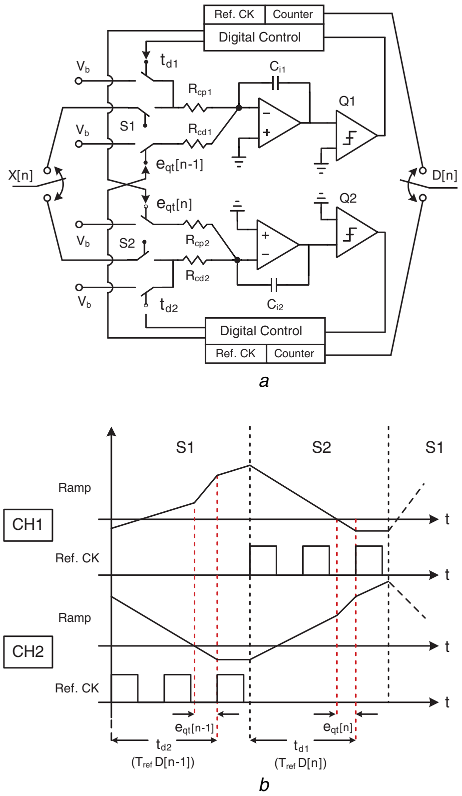

Fig. 2 *Two channel example of time-interleaved noise-coupling, and timing diagram of time-based quantisation noise-coupling*

a Two channel example of time-interleaved noise-coupling
b Timing diagram of time-based quantisation noise-coupling

Although similar in nature, it is of critical importance to distinguish between the proposed technique and the noise-coupled time-interleaved modulators [3] where noise-coupling is employed to result in an extra zero in the band without modifying the rest of the NTF zero placements. The traditional path coupling technique also requires extra DACs to extract the quantisation error to realise the required coupling coefficients in order to achieve higher order of noise shaping, thus having a significant thermal noise contribution. For a simple illustration, assuming the inter-channel coupling gain is unity, the DAC coupling capacitance should be equal to the sampling/integrating capacitance, doubling the thermal noise power and adding to circuit complexity. On the other hand, in the time domain coupling, the coupling resistor should be equal to the sampling resistor. However, this resistor is only connected for a short period of time, i.e. E_{qt}, which in the worst case would be equal to the total discharging time divided by number of the quantisation levels (LSB in time-domain), making it negligible to the input signal sampling thermal noise. As it will be discussed shortly, for a higher order of noise shaping, the coupling coefficients will become larger and hence the advantage of time-based coupling will become more apparent.

Generalised time-interleaved noise-shaping quantiser: The two-channel time-interleaved NSIQ discussed above can be generalised to an N-channel modulator with maximum achievable order of N, as shown in Fig. 3. The inter-channel coupling gain $a_{i,j}$ for quantisation error, which indicates the quantisation noise-coupling from channel i to channel j, is related to the overall NTF as follows (i,j = 1,2...N):

$$a_{i,j} = \begin{cases} c_{(j-i)}, & \text{for } i < j \\ c_{(N-i+j)}, & \text{for } i \geq j \end{cases}$$

$$NTF(z) = 1 + \sum_{k=1}^{N} c_k \, z^{-k}$$

These coefficients are always rotationally symmetric. For example, to realise a third-order lowpass modulator with all zeros at DC, three-channel architecture would be required with inter-channel coupling gain:

$$a_{1,2},\ a_{2,3},\ a_{3,1} = -3;\ a_{1,3},\ a_{2,1},\ a_{3,2} = 3;\ a_{1,1},\ a_{2,2},\ a_{3,3} = -1$$

All the noise-coupled paths can be implemented in time-based quantisation noise-coupling as discussed above, eliminating the need for large sampling, loading capacitors, and dedicated DACs compared to traditional noise-coupling techniques. However, owing to the added phases for the noise-coupling, for an N channel system with effective sampling rate of N.fs, each channel should operate at N.fs$/2$ which sets a trade-off between speed and available noise-shaping.

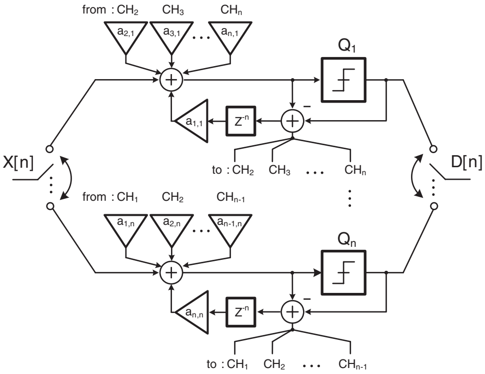

Fig. 3 *Generalised time-interleaved noise-shaping integrating quantiser*

Simulation results: The proposed structure is employed to realise a third-order three-channel time-interleaved LP noise-shaping quantiser and its performance is compared to that of a first-order single channel, operating at three times the sampling rate of the proposed structure. Both structures are simulated using Matlab. The oversampling ratio is 16, and the number of quantisation levels is assumed to be nine for both structures. The output spectra of these two are shown in Fig. 4, which clearly shows that a third-order noise-shaping is achieved by the proposed structure. This higher order of noise shaping results in an extra 30 dB signal-to-quantisation noise ratio improvement. It should be also noted that although the proposed structures has almost three times the hardware of that of the single channel modulator, it is operating two times slower than the single channel.

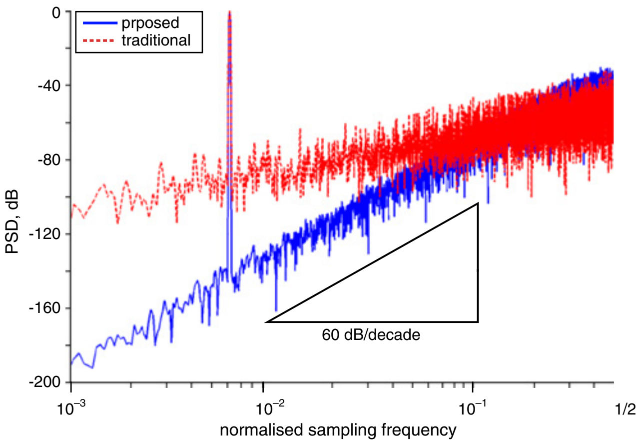

Fig. 4 *Output spectra of proposed and traditional structures*

Conclusion: A time-interleaved noise-coupled delta-sigma modulator based on a noise-shaping integrating quantiser is presented. The proposed time-based noise-coupling technique allows moving the extra zeros to the desired signal band and hence improving the performance of the modulator. Furthermore, the time-based operation allows simple coupling, without the need for extra sampling capacitors, minimising the thermal noise contributions of the extra paths. The proposed structure combines the effective sampling speed enhancement with more aggressive and versatile quantisation noise-shaping, resulting in wide signal bandwidth and high resolution conversion.

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

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