A Wide-Band 2-Path Cross-Coupled Sigma Delta ADC

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Abstract— The performance of a sigma-delta ADC can be increased by increasing one or more of the main three parameters, over-sampling ratio, the order of the modulators and the number of bits used. Increasing each of these parameters presents a degree of challenge (i.e., the increase in the over-sampling ratio is limited by the technology and the power consumption requirement). This paper presents a new method to obtain 2nd order noise shaping from two 1st order, time interleaved modulators by applying cross-coupling of quantization noise between the two paths. The proposed sigma-delta ADC is implemented in 90nm CMOS technology.

I. INTRODUCTION

The portable semiconductor market demands high performance analog-to-digital converters (ADCs) in terms of resolution and signal bandwidth with stringent requirements on the power consumption, in order to maintain a longer battery life. Also, the analog circuitries are required to be integrated with the digital circuitries to provide system-on-chip solutions (SOCs). This leads to a need for analog circuitries to be implemented in digital technologies where analog friendly, high performance and precision devices do not exist. For the portable applications sigma-delta ADCs are preferred due to their high performance in the absence of precision components, and their low power consumption compared to their counterpart Nyquist rate converters.

The resolution of a sigma-delta ADC can be increased by increasing one or more of the three parameters; number of bits used for the flash, over-sampling ratio (OSR), and the order of the modulator [1]. The increase in the number of bits is limited due to the exponential increase in the area consumption as well as the complexity of the implementation of the digital-to-analog converter (DAC) in the feedback loop. OSR can be increased by increasing the sampling frequency; however, this increases the power consumption of the analog circuits. Higher order of modulators can be achieved by either cascading low order modulators or increasing the number of integration loops in single loop architectures. Beyond 2nd order, the single loop modulators exhibit stability problems. Due to this apparent trade-off, the system architecture and parameters have to be optimized to meet the desired system specifications.

Fig. 1. N-path ADC.

This paper presents a new sigma-delta modulator architecture that utilizes 1st order, two-path, time interleaved modulator to obtain a 2nd order noise shaping. The increase in the order of the modulator is achieved by cross-coupling of the quantization noise between two paths. The modulator architecture has the advantage of reducing the speed of the conversion by half, compared to traditional 2nd order modulators. Therefore, it enables low power implementations for low OSR, wide bandwidth applications. Furthermore, the proposed 2nd order modulator can be implemented with just one opamp. The reduction in active components enables further power savings. The sigma delta ADC is implemented and simulated using a 90nm CMOS technology.

Next section of the paper reviews the time-interleaved architectures and introduces the proposed cross-coupling two-path sigma delta ADC architecture. The system level verification of the proposed architecture via Simulink simulations is reported in Section III. Then, Section IV presents the circuit implementation and Spice simulation results. Finally, Section V summarizes the conclusions.

II. THE PROPOSED 2-PATH SIGMA-DELTA ADC ARCHITECTURE

A. Review of the multi-path ADC architectures

Multi-Path converters employ parallelism to increase the throughput of the conversion system. For this purpose arrays of converters are used in parallel [2], see Fig. 1. The effective rate of conversion increases by the number of parallel paths, which is equivalent to increasing the OSR of a single stage by the number of parallel paths. If sigma-delta modulators are

Fig. 2. The proposed sigma delta ADC architecture

Fig. 3. The proposed modulator after $z \rightarrow -z^2$.

simply placed in parallel to build multi-path architectures, overall improvement in the resolution is only 3dB for each doubling of the number of the paths, regardless of the order of the modulators used in the multi-paths. The improvement is due to the increase in the output data rate with the increase in the number of paths. The overall quantization noise of the system is not shaped. However, there are several reported multi-path sigma-delta modulator architectures that maintain the noise shaping characteristics as well, [3]-[17]. These architectures can be summarized under three groups:

- Multi-band sigma delta modulators are composed of parallel modulators that reject the quantization noise at a certain frequency band. The quantization noise out of the each band of each path is filtered out to allow reconstruction of the signal [3], [4].
- Modulation based sigma delta modulators modulate and demodulate the input and the output of each path, respectively, with a certain function, [5]-[9]. The output of each path is then filtered to generate the digitized signal.
- Time-interleaving sigma-delta modulators that apply block filtering principles to mutually cross-couple the paths [10]-[17].

The performances of all of these three groups are similar but the time-interleaving architectures offer area efficient implementations [12].

B. Proposed cross-coupled sigma delta ADC

The proposed sigma-delta ADC architecture is composed of two time-interleaved low-pass sigma delta modulators, as shown in Fig. 2. The quantizers are represented by their linear models and the quantization noises of the each path are cross-coupled with a gain of two between these two modulators. The interleaved paths operate at half of the output data rate, F_s and the input signal is sub-sampled in alternating polarities in order to modulate the sampled signal with ± 1 pulse train. Therefore, if it is referred back to the highest clock frequency, this is equivalent to applying $z \rightarrow -z^2$ transform to the system [18], [19]. The system architecture after $z \rightarrow -z^2$ transform is depicted in Fig. 3. The negative sign that appears for the input after the transformation is arbitrary, hence it is ignored.

The transfer function of the system can be obtained by writing the outputs of each path, $y_1(n)$ and $y_2(n)$ in z-domain as below

$$\begin{aligned} Y_1(z) &= z^{-2}X_1(z) - 2E_2(z) + (1 + z^{-2})E_1(z) \\ Y_2(z) &= z^{-2}X_2(z) - 2z^{-2}E_1(z) + (1 + z^{-2})E_2(z) \end{aligned} \quad (1)$$

The input, $X(z)$ and the output $Y(z)$ of the system are equal to the summations of the input and the output of the two paths, respectively:

$$X(z) = z^{-1}X_1(z) + X_2(z) \quad (2)$$

$$Y(z) = z^{-1}Y_1(z) + Y_2(z) \quad (3)$$

Also, we can define a quantization noise, $e(n)$ for the overall system as

$$E(z) = z^{-1}E_1(z) + E_2(z). \quad (4)$$

Substituting (1), in (3) and rearranging according to (2) and (4) yield the systems transfer function

$$Y(z) = z^{-2}X(z) + (1 - z^{-1})^2 E(z). \quad (5)$$

The system equation in (5) reveals that by cross-coupling the quantization noises of the two paths with a gain of -2, a low pass sigma-delta modulator with a 2nd order noise shaping is obtained from 1st order time-interleaved modulators. The proposed architecture offers 15dB improvement in the SNR of the sigma delta modulator per each doubling of the OSR, while a traditional two-path modulator built with the same 1st order modulators can offer only 9dB improvement per each doubling of the OSR. Also, compared to a traditional second order sigma delta modulator, the proposed architecture has the advantage of having the analog circuits operate at the half of the output data rate while providing the same performance. As a result of this, the constraints on the analog circuitries are relaxed. Besides, traditional 2nd order sigma-delta modulator requires two integrators. But, with the proposed architecture, the number of integrators can be reduced by sharing one integrator between the two paths. Consequently, the power and area consumption are improved.

Fig. 4. Simulink model of (a) the top level and (b) the modulator architecture of each path.

TABLE I. THE SIMULINK MODEL PARAMETERS

Signal Bandwidth	2 MHz
Output Data Rate	60 MHz
OSR	15
Input Signal Frequency	622 KHz

Fig. 5. The power spectral density of the Simulink model with -1dB input.

III. SYSTEM LEVEL SIMULATIONS WITH SIMULINK

In order to verify the proposed sigma-delta modulator architecture, a Simulink model is developed, see Fig. 4. The quantization noises are cross-coupled with a gain of two and a negative polarity is used for the first channel, as shown in Fig. 4(a). The modulators in each path are 1st order low-pass sigma delta ADCs with nine level quantizers, Fig. 4(b). The commutator in the model modulate the input signal with sequence of $\{+1, -1, +1, \dots\}$. The commutator can be eliminated by simply applying the $z \rightarrow -z^2$ transform to the modulator model. But, it is kept just because the model is built to closely represent all the elements of the actual circuit implementation of the modulator. Also, a 2nd order sigma-

TABLE II. SIMULINK SIMULATION SNDR RESULTS FOR PROPOSED ARCHITECTURE AND THE REFERENCE SYSTEM

Input Signal Level [dB]	Proposed Modulator [dB]	2 nd Order Reference [dB]
-48	13	17
-24	39	42
-12	54	55
-6	59	59.6
-3	62	60

Fig. 6. The implementation of the integrator for both of the paths.

delta modulator model is used as a reference system to benchmark the results obtained. The parameters used for the Simulink simulations for both of the models are summarized in Table I.

The Simulink simulations of the proposed modulator show exactly the same spectral density for the quantization noise as the 2nd order sigma delta modulator (see Fig. 5). This result is also inline with the theoretical result given in (5). The Simulink simulations were also performed with analog circuit non-idealities such as finite amplifier gain, gain-bandwidth and slew-rate [20]. The SNDR performance of proposed modulator closely follows the reference modulator's performance for signals with input levels higher than -12dB as shown in Table II. But the SNDR of proposed modulator degrades more than the SNDR of reference modulator for input levels lower than -12dB.

IV. CIRCUIT IMPLEMENTATION

The 1st order sigma delta ADCs used in each path is composed of an integrator, a quantizer and a feedback DAC. Since, the integrator and the quantizer of each path are active during only one phase of the clock, the opamp of the integrator and the quantizer are shared between the two paths. But, two separate sets of capacitors, one for each path, are used to implement the integrator and the DAC as shown in Fig. 6. The DAC is implemented using switched capacitors.

Fig. 7. The power spectral density obtained from Spice simulation.

The quantization noises, $e_1(n)$ and $e_2(n)$ are equal to the difference between the output voltage of the integrator and the DAC. Therefore, the output voltage of the integrator is sampled on C_{Q1} during ϕ_1 and on C_{Q2} during ϕ_2 , for the 1st and 2nd path, respectively. At the following phases of the clocks, ϕ_1 for the 1st path and ϕ_2 for the 2nd path, these capacitors are connected between the input of the opamp and the appropriate DAC voltage in order to integrate the cross-coupled quantization noise on the integrating capacitors C_{F1} and C_{F2} . The capacitances of these capacitors are twice of the integrating capacitors C_{F1} and C_{F2} . Therefore a gain of two is achieved for the cross-coupling quantization noise. The input sampling capacitors, C_{S1} and C_{S1} are also used for the feedback DAC. The parameters, given in Table I, are also used for the transistor level simulations, except the input signal is chosen to have a frequency of 1MHz and amplitude of -12dB.

The power spectral density of the proposed ADC from Spice simulation is presented in Fig. 7. The noise shaping is 2nd order and the SNDR obtained from Spice simulation is 53dB for 2MHz signal bandwidth. This SNDR value closely matches with the result obtained from Simulink simulations for the same input signal level of -12dB, given in Table II. The ADC consumes only 1.56mW from a 1.2V power supply and provides 9-bit performance for -6dB input level. This corresponds to a figure of merit of 0.75pJ, as defined in [21].

V. CONCLUSIONS

Time-interleaved sigma delta ADC architecture with cross-coupled quantization noise is presented. This architecture is composed of 1st order modulators, but the order of the noise shaping is raised to 2nd order by cross-coupling of the quantization noise between stages. Since time-interleaving is used, the 1st order modulators run at half of the output data rate. Therefore, the design constraints on the analog circuitries are relaxed. This enables low power sigma delta ADC designs for the low OSR and wide bandwidth applications. Compared to a traditional 2nd modulator, the proposed sigma delta modulator offers further power and area saving by allowing implementations with just one opamp. The proposed architecture is verified through the spice simulations of the low-power ADC designed in 90nm CMOS technology.

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