A Low-Voltage Flexible Cascade $\Sigma\Delta$ Modulator for Beyond-3G Wireless Telecom

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Abstract – This paper presents a new adaptable cascade $\Sigma\Delta$ modulator architecture for low-voltage multi-standard applications. It uses two reconfiguration strategies: a programmable global resonance scheme and a variable loop-filter order. These techniques are properly combined in a novel topology that allows to increase the effective resolution in a given bandwidth, whereas keeping relaxed output swing requirements and high robustness to mismatch and to non-linearities of the amplifiers. Time-domain simulations including main circuit-level effects are shown to demonstrate the benefits of the presented modulator when it is configured to cope with the requirements of GSM, UMTS, WLAN and Wi-Max.^{†1}

I. INTRODUCTION

Sigma-Delta Modulators ($\Sigma\Delta$ Ms) are very suited for the implementation of reconfigurable Analog-to-Digital Converters (ADCs) required for the fourth generation (4G or Beyond-3G) of wireless hand-held devices [1]. Based on the combined use of oversampling and noise shaping, $\Sigma\Delta$ Ms adapt their dynamic ranges to different specifications with large hardware re-use, reduced power consumption and at the lowest cost [2]–[9].

Although changing the sampling frequency has been the reconfiguration strategy most commonly applied, the mandatory use of low OverSampling Ratios (OSRs) in wideband standards has forced $\Sigma\Delta$ Ms to achieve the required dynamic ranges by resorting to different strategies, including: high-order shaping [2][6][8][9], switchable cascade topologies [5][9]; programmable notches within the signal band [2][8]; multi-bit embedded quantizers [3][7][9]. However, the efficient implementation of these techniques requires to explore new $\Sigma\Delta$ M topologies capable of adapting their performance to as many specifications as possible while keeping high robustness to circuit errors.

The modulator presented in this paper is based on three strategies to adapt its functionality to different specifications. First, the modulator loop-filter order can be varied according to the required performance by connecting or disconnecting low-order stages in a cascade topology. Second, resonance is used to optimally distribute the zeroes of the Noise Transfer Function (NTF) within the required signal bandwidth. Third, unity Signal Transfer Function (STF) is employed in all stages of the cascade to reduce the amplifier output swing requirements [10]. The above-mentioned strategies are combined in a novel reconfigurable cascade $\Sigma\Delta$ M topology that maximizes the effective

resolution within a given bandwidth, with reduced circuit complexity, low sensitivity to element mismatches and high robustness with respect to opamp non-linearities.

II. PROPOSED MODULATOR ARCHITECTURE

Fig.1 shows the proposed modulator architecture. It consists of a reconfigurable cascade topology that makes use of two concepts, namely: unity STF [10] and global resonance [11]. The former is implemented by the feedforward paths that connect the input of each stage with the corresponding quantizer inputs, whereas global resonance is achieved thanks to the inter-stage paths (highlighted in Fig.1) that feeds back a delayed scaled version of the last-stage quantization error at the input of the first-stage quantizer. One important advantage of the proposed modulator is that, on the contrary to the one reported in [11], only Forward-Euler (FE) integrators are required, thus making its Switched-Capacitor (SC) implementation easier.

The modulator includes a number of switches to configure the NTF according to the required performance. On the one hand, by connecting the switchable error feedback paths from the last to the first stage—with switches S_r and S_L in ON mode—the global resonance effect is enabled. On the other hand, the order of the cascade is also reconfigurable. Both reconfiguration strategies, i.e. adaptive global resonance and NTF order, can be used independently, thus giving more flexibility to the $\Sigma\Delta$ M to adapt its functionality to the required performance. In a practical application, those components which are not used can be turned off (by using a power-down control) in order to save power consumption.

In case resonance is enabled and considering a linear model for the embedded quantizers, it can be shown that the NTF of the proposed architecture is given by:

Figure 1. Proposed reconfigurable $\Sigma\Delta$ M topology.

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$$NTF(z) = \frac{-(1-z^{-1})^2 \cdot [1 - (2-K) \cdot z^{-1} + z^{-2}]}{d} \quad (1)$$

where d stands for the inter-stage gain. Note that two of the NTF zeroes are a function of K , whose value can be optimally chosen to maximize the Signal-to-Noise+Distortion Ratio (SNDR).

This effect is illustrated in Fig.2 for an OSR of 4 and embedded quantizers with 4-bit resolution. The optimum values of K/d for an inter-stage gain of 1 and 4 are roughly 0.4 and 0.1, respectively implemented by capacitor ratios of 2/5 and 1/10. If there is no signal scaling along the cascade ($d = 1$), the resolution is increased in 11dB, whereas if $d = 4$, an increment of 23dB is achieved.

For the sake of completeness, Fig.3(a) shows the optimal location of the NTF zeroes in the unity-circle for oversampling ratios of 4, 8 and 16. The effect on the noise shaping is depicted in Fig.3(b) by representing the NTF for the different cases together with their corresponding signal BandWidths (BW s).

Note that an increase of d (to reduce the quantization noise) yields a reduction of the feedback coefficient K/d . In practice, this results in a smaller capacitor ratio, which makes the electrical implementation more difficult and prone to circuit non-idealities. However, the value of K/d can be easily implemented if

the oversampling ratio is low enough because—as Fig.3(a) illustrates—a reduction of the OSR means an increase of K . Therefore, the resonance provided by the proposed architecture is specially suited for wideband applications with low OSR .

III. CASE STUDY: APPLICATION TO 4G WIRELESS TELECOM

In order to show the reconfigurability of the proposed $\Sigma\Delta M$ architecture, a case study is presented considering the specifications and standards listed in Table I. Global resonance is used only in WLAN mode. In this case, the rounded optimal feedback coefficient is $K/d = 0.1$, resulting in a shift of two zeroes of the NTF from 0 to $0.8 \pm j \cdot 0.6$. Note that thanks to this optimum distribution of the NTF zeroes—together with the employment of an inter-stage scaling $d = 4$ —, the in-band noise has already been minimized, as shown in Fig. 2(b).

TABLE I.
SPECIFICATIONS OF THE CASE STUDY

Standard	GSM	UMTS ^a	Wi-Max	WLAN
SNDR (bit)	14	12	8	10
BW (MHz)	0.2	4	20	20

a. Although the bandwidth of UMTS is 3.84 MHz, it has been expanded to 4MHz in order to easily implement the sampling frequency.

Figure 2. Variation of the in-band quantization noise with K/d for: (a) $d = 1$, (b) $d = 4$ ($OSR = 4$ and $B_1 = B_2 = 4$).

Figure 3. Optimum distribution of NTF zeroes in the proposed resonance-based $\Sigma\Delta M$ for different oversampling ratios: (a) Location of zeroes in the unit circle, (b) NTF vs. frequency ($d = 1$).

Table II shows the values of the modulator design parameters that are reconfigured for the different operation modes, namely: NTF order (L), resonance coefficient (K/d) and OSR . Note that in those operation modes in which no resonance is used (GSM, UMTS and Wi-Max), the switches responsible for the last-stage error feedback (S_r in Fig. 1) are disconnected. Additionally, in GSM mode only the first stage is working—with switches S_r and S_L disconnected—whereas all the integrators and comparators of the second stage are turned off. Note that different oversampling ratios—and their corresponding sampling frequencies (f_s)—are employed in order to cope with the required resolution of each signal bandwidth.

IV. SIMULATION RESULTS

Several behavioral simulations have been performed using SIMSIDES, a Simulink-based time-domain simulator for $\Sigma\Delta$ modulators [12]. In all operation modes, 4-bit internal quantizers and a 1-V reference voltage were considered. Additionally, kT/C noise, sampled by 0.25-pF sampling capacitors, is introduced at the first integrator in all simulations. The embedded Digital-to-Analog Converters (DACs) are assumed linear, although dynamic element matching will be required in practice at least in the first stage of the cascade.

Fig. 4 shows the modulator output spectra for all the operation modes. In GSM [Fig. 4(a)], the in-band error is dominated by thermal noise, whereas in UMTS [Fig. 4(b)] the larger error term is not clearly defined between thermal or quantization noise. The effect of resonance can be clearly distinguished by comparing Fig. 4(c) and (d), corresponding to Wi-Max and WLAN, respectively. Note that in WLAN, resonance reduces the in-band quantization error power as compared to Wi-Max. This is illustrated in Fig. 5 where the $SNDR$ is represented versus the input signal amplitude. Note that the effective resolution for WLAN is approximately 9dB larger than that for Wi-Max.

The sensitivity to noise leakages due to capacitor mismatch has been studied on the basis of Monte Carlo simulation. Fig. 6 shows the $SNDR$ at -6dBFS obtained for a 50-run Monte Carlo simulation considering a standard deviation of 0.1% in all capacitors. The average $[m \text{ (bits)}]$ and standard deviation (σ) of the resulting effective modulator resolutions are also shown for each operation mode. Note that the use of resonance in the WLAN mode introduces no appreciable performance degradation when compared to the rest of operation modes.

TABLE II.
RESONANCE COEFFICIENT, MODULATOR ORDER, OSR AND d

Standard	GSM	UMTS	Wi-Max ^a	WLAN
Order (L)	2	4		
Inter-stage gain (d)	----	4		
K	0 (No resonance)			0.4
K/d	0 (No resonance)			0.1
OSR	100	10	4	
f_s (MHz)	40	80	160	

a. Note that resonance could also be employed in this case if a larger resolution is demanded.

Figure 4. Modulator spectra of the different modes: (a) GSM, (b) UMTS, (c) Wi-Max, (d) WLAN (-6dBFS input level, 64k-point FFTs).

Fig. 7 shows the effect of the amplifiers finite DC gain on the modulator effective resolution for all the operation modes. Note that the impact of the amplifiers gain on the modulator performance is considerably lower in GSM when compared to the rest of standards. This is due to the topology used for the $\Sigma\Delta$ in the former case (single-loop), which does not present the sensitivity to noise leakages inherent to cascade topologies (used in

Figure 5. $SNDR$ versus input level.

the remaining standards). In the case of UMTS and Wi-Max, there is no appreciable degradation for amplifiers gains above 40dB. This value raises to 50dB for WLAN, which is still not a demanding requirement in practice.

An appealing advantage that comes from the use of unity STF is the subsequent reduction of the amplifiers output swing. This is illustrated in Fig. 8 by plotting the histogram of the integrator outputs obtained from the operation of the proposed modulator in all operation modes. Note that the required output swing is only $\pm 0.15V$ for the 1st and 3rd operational amplifiers (OA_1 and OA_3), whereas it reduces to $\pm 0.10V$ for the 2nd and 4th ones (OA_2 and OA_4). This translates into an excellent linearity behavior for the proposed architecture.

The latter is illustrated in Fig.9 by plotting the effect of the opamp gain non-linearity on the modulator SNDR. In this simulation, a finite gain of 55dB is considered for all amplifiers,

Figure 6. SNDR variation considering a 0.1% capacitor mismatch (-6dBFS input level, 50-run Monte Carlo simulation).

Figure 7. SNDR vs. amplifiers finite gain (-6dBFS input level).

Figure 8. Output swing requirements.

Figure 9. SNDR vs. non-linearity of the amplifier gain (-6dBFS input level, 55-dB amplifier gain).

while varying the second-order non-linearity of the amplifier gain in the first stage amplifiers. Note that the robustness of the proposed $\Sigma\Delta$ to non-linearities is quite high, even if resonance is used to increase the effective modulator resolution.

CONCLUSIONS

A new multi-functional cascade $\Sigma\Delta$ architecture has been presented. This architecture is capable to reconfigure the order of the quantization noise filtering and to resonate through switchable feedback inter-stage paths. Additionally, it achieves high linearity with reduced output swing requirements by using unity STF. These characteristics make the proposed modulator very appropriate for the implementation of low-voltage multi-mode A/D conversion, where the resolution of wideband standards can be easily increased by means of adaptive global resonance. A case study covering GSM, UMTS, Wi-Max and WLAN standards has been discussed in order to show the capabilities of the proposed modulator to perform the A/D conversion in future 4G wireless multi-standard hand-held devices.

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