A 0.6V 2.9µW mixed-signal front-end for ECG monitoring

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

<table>
<thead>
<tr>
<th>Citation</th>
<th>Yip, Marcus, Jose L. Bohorquez, and Anantha P. Chandrakasan. “A 0.6V 2.9µW Mixed-Signal Front-End for ECG Monitoring.” 2012 Symposium on VLSI Circuits (VLSIC) (June 2012).</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1109/VLSIC.2012.6243792">http://dx.doi.org/10.1109/VLSIC.2012.6243792</a></td>
</tr>
<tr>
<td>Publisher</td>
<td>Institute of Electrical and Electronics Engineers (IEEE)</td>
</tr>
<tr>
<td>Version</td>
<td>Author’s final manuscript</td>
</tr>
<tr>
<td>Accessed</td>
<td>Wed Aug 30 02:15:25 EDT 2017</td>
</tr>
<tr>
<td>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/95487">http://hdl.handle.net/1721.1/95487</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>Creative Commons Attribution-Noncommercial-Share Alike</td>
</tr>
<tr>
<td>Detailed Terms</td>
<td><a href="http://creativecommons.org/licenses/by-nc-sa/4.0/">http://creativecommons.org/licenses/by-nc-sa/4.0/</a></td>
</tr>
</tbody>
</table>
A 0.6V 2.9µW Mixed-Signal Front-End for ECG Monitoring

Marcus Yip\textsuperscript{1}, Jose L. Bohorquez\textsuperscript{2}, and Anantha P. Chandrakasan\textsuperscript{1} \textsuperscript{*}

\textsuperscript{1}Massachusetts Institute of Technology, Cambridge, MA, USA, \textsuperscript{2}Convergence Medical Devices, Woburn, MA, USA

Abstract

This paper presents a mixed-signal ECG front-end that uses aggressive voltage scaling to maximize power-efficiency and facilitate integration with low-voltage DSPs. 50/60Hz interference is canceled using mixed-signal feedback, enabling ultra-low-voltage operation by reducing dynamic range requirements. Analog circuits are optimized for ultra-low-voltage, and a SAR ADC with a dual-DAC architecture eliminates the need for a power-hungry ADC buffer. Oversampling and ΔΣ-modulation leveraging near-\(V_T\) digital processing are used to achieve ultra-low-power operation without sacrificing noise performance and dynamic range. The fully-integrated front-end is implemented in a 0.18µm CMOS process and consumes 2.9µW from 0.6V.

Introduction

Symptoms of cardiovascular disease are often very intermittent, necessitating ultra-low-power wearable ECG monitors with long lifetimes. In order to minimize system power, digital signal processing (DSP) can accomplish feature extraction and data compression which reduces the power burden of data transmission or storage. Recent biomedical DSPs leverage voltage scaling (down to 0.5V) to improve energy-efficiency [1]. Additional size and power benefits can be obtained by integrating the analog front-end (AFE) with the DSP back-end [2]. However, current AFES rely on high supply voltages [3, 4] to perform signal conditioning and accommodate aggressors like electrode offset (EO) and power-line interference (PLI), limiting their compatibility with low-voltage DSPs. Therefore, this paper presents a mixed-signal front-end (MSFE) that leverages a highly-digital architecture in order to operate from a 0.6V supply which improves power-efficiency through voltage scaling, and facilitates integration with low-voltage DSPs. This work focuses on the design of ultra-low-voltage front-end analog circuits aided by configurable and energy-efficient digital processing at near-\(V_T\) operation. A highly-integrated solution is presented to demonstrate feasibility of a 0.6V system.

System Description

Supply voltage scaling is an effective way to achieve linear and quadratic power reduction in analog and digital circuits respectively. However, for ECG acquisition, PLI can be a limiting factor for voltage scaling. For example, 5\(mV_{\text{p-p}}\) of PLI with 40dB of front-end gain could easily saturate a sub-1V system before digitization by the ADC. Therefore, the system architecture in this work is based on [4], but uses ΔΣ-modulation to simultaneously achieve a larger PLI cancellation range and low-noise performance as a key enabler for ultra-low-voltage operation. The burden of signal processing is shifted to the digital domain which is suitable for low-voltage systems. Compared to [4], this work reduces the supply voltage from 1.5V to 0.6V and optimizes analog circuits for ultra-low-voltage operation.

Shown in Fig. 1, a low-noise amplifier (LNA) gains the input by 34.5dB, and ac-coupling achieves greater than ±300mV of EO rejection as required [5]. A sinc anti-aliasing filter (SAAF) provides an integrate-and-dump function at a sampling frequency of \(f_S=10kHz\), resulting in a sinc frequency response with notches placed at multiples of \(f_S\) which are precisely in the center of the aliasing bands. At the end of each integration period, the signal is digitized by a 9b dual-DAC SAR ADC.

\textsuperscript{*}The authors acknowledge the funding support of Texas Instruments and the NSERC Fellowship.
BNEF calculation based on 9.26µVrms input-referred noise integrated over 0.5Hz-50kHz, using a 2.93kHz 3dB bandwidth.

Peripheral blocks

Input-Referred Electrode offset tolerance

Maximum PLI tolerance

Channel

Technology and Vsupply voltage scaling, the LNA achieves a PEF of 17. By integrating the input capacitance of a conventional SAR ADC. Finally, the ADC full-scale is digitally tunable, providing up to 4.9dB of embedded gain.

Fig. 3 shows the block diagram of the programmable digital BPF based on [4], but optimized for area and integrated for near-Vref operation. The BPF takes the form of a frequency-translated accumulator, and its center frequency and width are tunable through ω0 and GPLL, respectively. In this work, the sinusoids required for frequency translation are generated on-chip using a direct-digital synthesizer (DDS) with 9b outputs, comprising a phase accumulator and a LUT as a phase to waveform generator. The number of bits in the LUT is reduced by over 5x when compared to [4] by storing only a quarter period and using the sine-phase difference technique [6], requiring only 4Kgates. The cosine phase is generated by adding an offset of π/2 and the LUT is used for both sine and cosine by time-multiplexing.

Measurement Results

A prototype was fabricated in a 0.18µm CMOS process. The closed-loop frequency response of the SAAF output shown in Fig. 4 demonstrates the digital programmability of the PLI notch frequency and width. The total gain of the system can be set between 34.5dB and 69.4dB by selecting one of the 60 SAAF and 4 ADC gain settings. At the lowest gain setting, the MSFE can accommodate PLI up to 12.6mVp-p and an input of 8mVp-p with 1% THD, meeting the requirement in [5]. The LNA alone achieves a noise-efficiency-factor (NEF) of 5.32 using a 3dB bandwidth of 2.93kHz and 9.26µVrms of noise integrated from 0.5Hz to 50kHz. Using the power-efficiency-factor (PEF) introduced in [7] to account for the impact of supply voltage scaling, the LNA achieves a PEF of 17. By including the entire signal chain (LNA/SAAF/ADC/decimator), the MSFE achieves an input-referred noise of 3.44µVrms in a 156Hz bandwidth, well within the 50µVp-p specification [5]. This corresponds to a signal dynamic range of 58dB despite 0.6V operation, made possible by oversampling and ∆Σ-modulation. The ADC INL/DNL, SNDR at Nyquist, and FOM are 0.55/0.48LSB, 50dB, and 37.3dB/conversion-step re-

Fig. 4. Measured frequency response at the output of the SAAF. Fig. 2. The ADC uses dual capacitave DACs, where switches S1 and S2 are complementary so that DAC1 and DAC2 alternate between bit cycling and sampling so that only one of them adds C5 to C6 during any given period. The interleaved dual-DAC architecture effectively merges the ADC sampling capacitance with the SAAF integrating capacitor, eliminating the need for a power-hungry ADC buffer which is usually needed to drive the input capacitance of a conventional SAR ADC. Finally, the ADC full-scale is digitally tunable, providing up to 4.9dB of embedded gain.

Fig. 6. Measured chip summary, die photo, and comparison table. Fig. 5a shows the input-referred spectrum with an 8mVp-p, 60Hz input. With the notch enabled, the tone is attenuated and the ∆Σ-modulator shapes the DAC quantization noise to higher frequencies, maintaining the in-band noise floor to achieve an interference dynamic range of 62dB using just an 8b DAC. Finally, Fig. 5b shows ECG measurements on a male subject using gel electrodes and unshielded wiring. The PLI is clearly canceled when the notch filter is enabled.

Conclusion

Fig. 6 shows the chip summary, die photo, and comparison table. At 0.6V, the single-channel MSFE consumes 1.15µW, and the integrated peripheral circuits consume 1.71µW. In comparison, the same implementation at a supply of 1.5V as in [4] would require greater than 5µW of additional power. The combination of a mixed-signal architecture and circuit optimizations at scaled voltages helps to achieve ultra-low-power operation at 0.6V, demonstrating compatibility with ultra-low-voltage DSPs.

References