A 2.9-mW 11-b 20-MS/s Pipelined ADC with Dual-Mode Based Digital Background Calibration

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Conventional Pipelined ADC: High-gain Op-amp
Low Power Design Approach with Digital Background Calibration

Murmann, Boser, JSSC 38, 2040 (03)

\[ G = G_1 - G_3 V_E^2 \]
Dual-Mode-Based Background Calibration (1)
--- Basic Idea ---

\[
\frac{D_{out} \times R}{2} = \frac{1}{2} (D_{out,A} - D_{out,B}) = f(G_1, G_3)
\]
Dual-Mode-Based Background Calibration (2)

--- Sampling Phase ---

![Diagram of 6 Input Regions and Conventional Circuit](image)
Dual-Mode-Based Background Calibration (3)

--- Charge Transfer Phase ---

Mode A

Mode B
Dual-Mode-Based Background Calibration (4)

--- Transfer Curves ---

Mode A

Mode B
Dual-Mode-Based Background Calibration (5)

--- Output Differences ---

\[
\begin{align*}
\frac{1}{2}G_1 + \frac{G_3}{16}G_1 &= \delta_1 \\
\frac{1}{2}G_1 + \frac{G_3}{4}G_1 &= \delta_2
\end{align*}
\]

Solve for \( G_1 \) & \( G_3 \)
Dual-Mode-Based Background Calibration (6)
--- Correlation Architecture ---

ADC with background calibration

- Pseudo-random number generator
- ADC core
- 1st stage two modes
- Backend ADC
- Correction
- Gap length & curvature
- Coeff. Est.
- DEMUX
- LPF
- \( \delta_1 \), \( \delta_2 \), \( \delta_3 \), \( \delta_4 \), \( \delta_5 \), \( \delta_6 \)
A 11-b 2.9-mW 20-MS/s Pipelined ADC

--- Design Scheme ---

Calibration Technique Applied

\[ V_{in} \rightarrow 1.5b \quad 1.5b \quad 1.5b \quad 1.5b \quad 1.5b \quad 1.5b \times 6 \rightarrow 3b \]

High-Gain Op Amp (Gain ~ 100000)

Low-Gain Op Amp (Gain: 300)
Additional Low Power Techniques (1)

- Input transistors biased in weak inversion to maximize $g_m$ efficiency
- Opamp shut off during sampling phase
- Almost ideal 50% power saving due to short turn-on time of 200 ps
Additional Low Power Techniques (2)

--- Stage Scaling ---

<table>
<thead>
<tr>
<th>Cap Value</th>
<th>C</th>
<th>C/2</th>
<th>C/4</th>
<th>C/8</th>
<th>C/16</th>
</tr>
</thead>
<tbody>
<tr>
<td>I&lt;sub&gt;D&lt;/sub&gt;</td>
<td>180uA</td>
<td>90uA</td>
<td>52uA</td>
<td>39uA</td>
<td>25uA</td>
</tr>
</tbody>
</table>
Additional Low Power Techniques (3)
--- No Sample-and-hold ---

- Sampling mismatch removed by moving comparators to the opamp output and adding a quantization phase between sampling and charge transfer phase. Shorten quantization phase by not loading $C_L$.

Practical Design Issue (1)

Sampling Phase

Charge Transfer Phase

Mode A

Mode B
Practical Design Issue (2)
--- Sub-Capacitor Mismatch Calibration ---

Diagram of a circuit with mode selection, scrambling, and calibration components.
A 11-b 2.9-mW 20-MS/s Pipelined ADC
--- Architecture ---
A 11-b 2.9-mW 20-MS/s Pipelined ADC
--- Die Photo and PCB ---

Printed Circuit Board

Die Photo

Active area
1st Stage
2nd Stage
6th to 12th to 5th

Output Driver

1.3 mm
Measurements (1)

--- Before Calibration ---

(a) INL

(b) DNL

(c) Spectrum

SNDR: 45 dB
SFDR: 50 dB
Measurements (2)
--- After $G_1$ Calibration ---

(a) INL
(b) DNL
(c) Spectrum

+0.6/−0.7
+0.4/−0.4

SNDR: 59 dB
SFDR: 74 dB
Measurements (3)

--- After G₁ and G₃ Calibration ---

(a) INL

(b) DNL

(c) Spectrum

SNDR: 60 dB
SFDR: 86 dB
Measurements (5)

--- Convergence Time ---

- Cancelling correlation noise by performing
  \[(D_{out} - V_{in}^*) \times R\]
  where

  \[V_{in^*} = \begin{cases} 
  -\frac{3}{4} & \text{Region } 1 \\
  -\frac{3}{8} & \text{Region } 2 \\
  -\frac{1}{8} & \text{Region } 3 \\
  +\frac{1}{8} & \text{Region } 4 \\
  +\frac{3}{8} & \text{Region } 5 \\
  +\frac{3}{4} & \text{Region } 6 
  \end{cases}\]

- Short convergence time of 5 ms (10^5 samples at 20MS/s)
Measurements (6)

--- Power Breakdown ---

Analog (Amplifiers & Biasing): 0.7 mW

Digital Computations (Estimated): 0.6 mW

Digital (Switch Drivers & Comparators): 1.6 mW

Total Power: 2.9 mW
## Comparison to Recent Works on Digital Background Calibration in JSSC

<table>
<thead>
<tr>
<th>Technology</th>
<th>SNDR (dB)</th>
<th>SFDR (dB)</th>
<th>Speed (MHz)</th>
<th>Power (mW)</th>
<th>FOM (pJ/conv-step)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.18 um</td>
<td>73</td>
<td>98</td>
<td>20</td>
<td>285</td>
<td>3.90</td>
</tr>
<tr>
<td>0.18 um</td>
<td>60</td>
<td>70</td>
<td>45</td>
<td>81</td>
<td>2.20</td>
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<tr>
<td>90 nm</td>
<td>69.8</td>
<td>85</td>
<td>100</td>
<td>130</td>
<td>0.51</td>
</tr>
<tr>
<td>90 nm</td>
<td>73</td>
<td>90</td>
<td>100</td>
<td>200</td>
<td>0.55</td>
</tr>
<tr>
<td>90 nm</td>
<td>61.5</td>
<td>N/A</td>
<td>200</td>
<td>186</td>
<td>0.96</td>
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<tr>
<td>0.35 um</td>
<td>70.2</td>
<td>80.9</td>
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<td>231</td>
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<tr>
<td>90 nm</td>
<td>64.5</td>
<td>78.1</td>
<td>30</td>
<td>2.95</td>
<td>0.07</td>
</tr>
<tr>
<td>90 nm</td>
<td>58.2</td>
<td>75</td>
<td>100</td>
<td>6</td>
<td>0.10</td>
</tr>
<tr>
<td>0.18 um</td>
<td>77.8</td>
<td>90</td>
<td>250</td>
<td>850</td>
<td>0.51</td>
</tr>
<tr>
<td><strong>This Work</strong></td>
<td><strong>0.18 um</strong></td>
<td><strong>60</strong></td>
<td><strong>86</strong></td>
<td><strong>20</strong></td>
<td><strong>2.9</strong></td>
</tr>
</tbody>
</table>
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