The Effect of Correlated Level Shifting on Noise Performance in Switched Capacitor Circuits

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(Presented by Taehwan Oh)

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Presentation Outline

• Background
  – CLS (Correlated Level-Shifting)
  – Split-CLS

• Theoretical Noise Analysis

• Numerical and Simulation Results

• Conclusion
Background
Correlated Level Shifting (CLS)

- Finite opamp gain error becomes $1/A^2$
- Opamp output tied to different nodes in $\Phi_1$ and $\Phi_2$

[Gregoire, JSSC 2008]
CLS Basic Operation

\[ \Phi_1 : \]
- opamp charges output directly
- processes full signal

Opamp Design Requirements

<table>
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<tr>
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CLS Basic Operation

Φ₂:
• opamp is level shifted to mid-rail
• processes error only

Opamp Design Requirements

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Observation: Split-CLS

- Use separate charging devices for $\Phi_1$ and $\Phi_2$
- Optimized design for each phase
  - Increase overall accuracy & efficiency

### Opamp Design Requirements

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Split-CLS (Correlated Level Shifting)

- Generalized form of Correlated Level Shifting (CLS)
- Finite opamp gain error approx. $1 / (A_1 * A_2)$

[Hershberg, JSSC 2010]
**Split-CLS (Correlated Level Shifting)**

**Φ₁:**
- amp charges output directly
- processes full signal

<table>
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<th>Amplifier Design Requirements</th>
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Split-CLS (Correlated Level Shifting)

\[ V_{\text{IN}} \rightarrow \Phi_S \rightarrow V_x \rightarrow A_{\Phi_1} \rightarrow V_{\text{CMO}} \rightarrow V_{\text{CLS}} \]

\[ (\pm V_r, 0) \rightarrow V_{\text{CLS}} \rightarrow C_{\text{CLS}} \rightarrow V_{\text{OUT}} \]

\[ \Phi_2: \]
- \text{opamp is level-shifted to mid-rail}
- \text{processes error only}

### Amplifier Design Requirements

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Split-CLS (Correlated Level Shifting)

- Many options for coarse amp / fine amp...
  - ISSCC 2010: ZCBC (coarse) + Telescopic opamp (fine)
  - ISSCC 2012: Ring Amplifier (coarse) + Telescopic opamp (fine)

[Hershberg, ISSCC 2010], [Hershberg, ISSCC 2012]
Split-CLS: ISSCC 2010

- Coarse Amp: Zero-crossing based circuit (ZCBC)
- Fine Amp: Double-cascoded telescopic opamp

[Hershberg, ISSCC 2010]
Split-CLS: ISSCC 2012

- Coarse Amp: Pseudo-differential Ring Amplifier (ringamp)
- Fine Amp: Double-cascoded telescopic opamp
- Best FoM of any high-resolution ADC ever reported
  - 76.8dB SNDR, 95.4dB SFDR, 5.1mW, 20Msps, 45fJ/c-step FoM

[Hershberg, ISSCC 2012]
Noise Analysis
Noise Analysis: Split-CLS

• The size of $C_{CLS}$ affects:
  – Accuracy - feedback factor
  – Speed - total load capacitance seem by fine amp
  – Opamp requirements - fine amp output swing requirement

• How does level-shifting affect noise performance
  – Help? Hurt?
Noise Analysis: Split-CLS

- Noise due to AMP1 is suppressed by gain of AMP2
  - Final noise determined by AMP2
- Only fine phase configuration must be considered
Noise Analysis: Split-CLS

\[ C_1 \quad C_2 \quad \text{C}_{\text{CLS}} \quad \text{C}_{\text{LOAD}} \]

\[ - a_0 \quad \text{opamp} \quad \beta \quad A_{\text{OTA}}(s) \quad H_{\text{CLS}}(s) \quad S_i \quad S_n \quad S_0 \]
Noise Analysis: Split-CLS

\[ C_{LOAD} = \alpha (C_1 + C_2) \]  \hspace{1cm} (1)

\[ \beta = \frac{C_2}{C_1 + C_2} \]  \hspace{1cm} (2)
Noise Analysis: Split-CLS

\[ H_{CLS}(s) = \frac{C_{CLS}}{C_{CLS} + C_{LD}} \]  \hspace{1cm} (3)

\[ C_{LD} = C_{LOAD} + \frac{C_1 \cdot C_2}{C_1 + C_2}. \]  \hspace{1cm} (4)
Noise Analysis: Split-CLS

Single-stage opamp (as is commonly used in Split-CLS) has one dominant pole:

\[ C_{OTA} = C_P + \frac{C_{CLS} \cdot C_{LD}}{C_{CLS} + C_{LD}} \]  

\[ A_{OTA}(s) = \frac{a_o}{1 + \frac{s}{p_1}} \bigg|_{p_1 = \frac{1}{R_O C_{OTA}}} \]
Noise Analysis: Split-CLS

\[ Af_p(s) = A_{OTA}(s) \cdot H_{CLS}(s) \]  

(7)

\[ H_n(s) = \frac{A_{OTA}(s) \cdot H_{CLS}(s)}{1 + \beta \cdot A_{OTA}(s) \cdot H_{CLS}(s)} \].  

(8)
Noise Analysis: Split-CLS

Forward Path Gain

- $C_{CLS} = 12.5\, \text{fF}$
- $C_{CLS} = 400\, \text{fF}$

Gain-Bandwidth Spreading

$A_{OTA}(s) \cdot H_{CLS}(s)$

$S_i \rightarrow S_n \rightarrow A_{OTA}(s) \rightarrow H_{CLS}(s) \rightarrow S_o$
Noise Analysis: Split-CLS

\[ A_f(s) = A_{OTA}(s) \cdot H_{CLS}(s) \]

\[ C_{OTA} = C_P + \frac{C_{CLS}}{C_{CLS} + C_{LD}} \]

\[ H_{CLS}(s) = \frac{C_{CLS}}{C_{CLS} + C_{LD}} \]

Normally, factors cancel & gain-bandwidth product is constant
Noise Analysis: Split-CLS

\[ A_{fp}(s) = A_{OTA}(s) \cdot H_{CLS}(s) \]

\[ C_{OTA} = C_P + \frac{C_{CLS}}{C_{CLS} + C_{LD}} \]

\[ H_{CLS}(s) = \frac{C_{CLS}}{C_{CLS} + C_{LD}} \]

Presence of \( C_P \) causes gain-bandwidth spreading when \( C_{CLS} \) is varied
Noise Analysis: Split-CLS

Noise Transfer Function

Frequency (Hz)

$A_{OTA}(s)$

$H_{CLS}(s)$

$\beta$

$S_i$ $S_o$

$S_n$
Noise Analysis: Split-CLS

Total integrated noise power for noise source $S_n(f)$:

$$\tilde{\nu}^2_{no} = \int_0^\infty S_n(f) \cdot |H_n(2\pi f)|^2 df.$$  (10)
Noise Analysis: Split-CLS

- Telescopic opamp used as noise source
- $M_1, M_2, M_3, M_4$ are the dominant noise contributors
  - Can be modeled as single input-referred noise contributor
When $1/f$ noise is entirely in passband of $A_{OTA}(s)$, noise sources can be treated as frequency-independent constants:

$$\tilde{v}_{n_o}^2 = v_{n(1/f)}^2 + \int_0^\infty S_{n(\text{white})} \cdot |H_n(2\pi f)|^2 \, df \quad (11)$$
Noise Analysis: Split-CLS

![Graph showing Output Noise vs Frequency (Hz)]

- $C_{CLS} = 12.5 fF$
- $C_{CLS} = 400 fF$

$A_{OTA}(s) \cdot H_{CLS}(s)$

$S_n$ $S_i$ $+\rightarrow$ $-\rightarrow$ $S_o$

$\beta$
Noise Analysis: Split-CLS

\[ \nu_n^2 \text{ vs. } C_{CLS} \text{ for various } C_P \]

\[ C_P \gg \frac{C_{CLS} \cdot C_{LD}}{C_{CLS} + C_{LD}} \rightarrow C_{CLS} \text{ and noise are heavily correlated.} \]

\[ C_P \ll \frac{C_{CLS} \cdot C_{LD}}{C_{CLS} + C_{LD}} \rightarrow C_{CLS} \text{ and noise are weakly correlated.} \]

(Mostly likely case in practical designs.)
Comparison with Simulation
Comparison with Simulation

- Extracted values
  - $C_P = 45\, \text{fF}$
  - $a_o = 58.4\, \text{dB}$
  - $C_1 = C_2 = 400\, \text{fF}$
  - $C_{LOAD} = 640\, \text{fF}$
  - $v^2n(1/f) = 6.31 \times 10^{-10} \, \text{V}^2$
  - $S_n(\text{white}) = 6.17 \times 10^{-17} \, \text{V}^2/\text{Hz}$
Comparison with Simulation

- Simulation and Theoretical model found to be in good agreement.
Comparison with Simulation

- Simulation and Theoretical model found to be in good agreement.

Integrated Noise Power (V^2) vs C_{CLS} (fF)

- Theoretical Model
- Cadence Simulation

C_P=45fF
C_P=145fF
C_P=245fF

\[ V_{bn}, V_{bp}, V_{bt}, V_i^+, V_i^-, V_{CMFB}, V_{DD}, V_{SS}, M_1, M_2, M_3, M_4 \]
Conclusion
Conclusion

• CLS and Split-CLS reduce finite-opamp gain error by approximately $1/A^2$

• Addition of $C_{CLS}$ network to MDAC structure introduces bandwidth spreading dependent on $C_{CLS} \leftrightarrow C_P$ relation.

• For most practical Split-CLS designs, $C_{CLS} >> C_P$
  – $C_{CLS}$ should be large enough to minimize swing requirement, maintain sufficient loop gain.
  – $C_P$ is only intrinsic parasitic capacitances of opamp

• In practical cases, total integrated opamp noise is not significantly affected by Split-CLS.
Thank You For Your Attention