An Open-Loop Class-D Audio Amplifier with Increased Low-Distortion Output Power and PVT-Insensitive EMI Reduction

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Outline

- Background and Motivation
- System Overview
- Proposed Techniques
  - Adaptive-Coefficient Delta-Sigma Modulator
  - PVT-Insensitive Low-EMI Control Method
- Measurement Results
- Conclusions
Digital-Input Audio Amplifier

- **Class-AB amplifier with DAC**

- **Class-D amplifier with DAC**

- **Class-D amplifier with digital PWM (DPWM) gen.**
Class-D Amplifier with DPWM

- **Pros**
  - High efficiency
  - No need of high-resolution DAC

- **Cons**
  - Distortion from class-D amp. \(\rightarrow\) Degraded THD+N
  - Need of L-C low-pass filter for EMI suppression
Closed-Loop vs. Open-Loop

- **Closed-loop architecture**

- **Open-loop architecture** \( \rightarrow \) adopted in this work

- Lower complexity

- Smaller chip area

- Easier design porting to advanced processes
THD+N vs. Output Power

- Distortion and noise sources
  - Constant noise
  - Power stage distortion
  - Clip distortion

- Low-distortion $P_{\text{OUT}} = \max. P_{\text{OUT}}$ with $\text{THD+N}<1\%$
  - Dominated by clip distortion due to DSM instability
DSM Instability in Open-Loop

- When DSM input is large
  → DSM’s quantizer overload
  → clipping at DSM_{OUT} → clip distortion at amp. output
  → decreased low-distortion output power

Digital Input → Interpolator (gain k=1) → DSM → PCM-to-PWM Converter (gain 1/k=1) → Power Stage → Power Output

- SNDR @ DSM_{OUT}
- SNDR @ PWM_{OUT}
- THD+N vs. output power

SNDR(dB) vs. Input mag. (dBFS) for k=1

SNDR(dB) vs. Input mag. (dBFS) for k=1

THD+N(%) vs. Output power (W) for k=1, limited by power stage 1%
DSM Instability in Open-Loop

- To reduce DSM input: interpolator’s gain
- To increase gain after DSM: PCM-to-PWM’s gain

→ Clipping at PWM_{OUT}
→ DSM instability can **NOT** be prevented by scaling k
Common-Mode EMI Reduction

- Conventional BD modulation

- Common-Mode Free BD (CMFBD) modulation [1]

Targets of This Work

- Increase low-distortion output power for open-loop class-D amplifiers **without**
  - increasing supply voltage
  - increasing off-chip components
  - sacrificing THD+N at small output power

- Reduce common-mode EMI **without**
  - using expensive L-C filters
  - PVT-sensitive issue
System Overview

- Block diagram of this work

- Two selectable modes
  - BD-Modulation Mode
  - Low-EMI Mode [1]
Trade-Off in DSM Design

- **Two DSM Designs**
  - DSM\textsubscript{A}: high in-band noise suppression
  - DSM\textsubscript{B}: full-scale stable input range

- **NTF plot**

- **Root-locus plot**
Proposed ACDSM

- Adaptive-Coefficient Delta-Sigma Modulator (ACDSM)
  - Small $x[n]$ $\rightarrow$ coeff. with high in-band noise suppression
  - Large $x[n]$ $\rightarrow$ coeff. with full-scale stable input range

![Diagram of Proposed ACDSM](attachment:image.png)
Direct Coefficient Switching

- Coefficient is switched between
  - Small $x[n] \rightarrow Set_A$ (high in-band noise suppression)
  - Large $x[n] \rightarrow Set_B$ (full-scale stable input range)

$Set_A = [g_1A, \ldots, g_5A, a_1A, \ldots, a_5A, b_1A, \ldots, b_4A]$

$Set_B = [g_1B, \ldots, g_5B, a_1B, \ldots, a_5B, b_1B, \ldots, b_4B]$

→ large internal transient spike → DSM unstable
ACDSM Algorithm

- **Linear-interpolated coefficient changing**
  - operating coefficient set is changed with small $\Delta$
  - internal transient spike is reduced
Dynamic Range (DR) Plots

- The ACDSM simultaneously achieves
  - a wide stable input range
  - high in-band noise suppression
CMFBD Realization

- Previous low-EMI control method [1]

Previous Low-EMI Control (1/3)

- In state $S_0$

![Diagram showing MOSFETs and speaker load](image-url)
Previous Low-EMI Control (2/3)

- In transition from $S_0$ into $S_1$
Previous Low-EMI Control (3/3)

- In state $S_1$

![Diagram of electronic circuit with labels and timing graphs](image_url)
PVT Variation Effect (1/2)

- Significant shoot-through current

![Diagram of a circuit with M1 to M6 transistors and speaker load](image)

- **M1**, **M4** turn-on: $V_{G1}$, $V_{G5}$
- **M5**, **M6** turn-on: $V_{G4}$, $V_{G6}$

**Shoot-through**

- **OUTP**
- **OUTN**

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PVT Variation Effect (2/2)

- Additional output voltage transition
CMFBD Realization

- Proposed low-EMI control method

![Circuit Diagram]

-\( M_1 \rightarrow M_4 \rightarrow M_5 \) (turn-on:)
-\( M_2 \rightarrow M_6 \) (turn-on:)
-\( M_5 \rightarrow M_6 \) (turn-on:)
-\( M_5 \rightarrow M_6 \) (turn-on:)
-\( M_2 \rightarrow M_3 \rightarrow M_6 \) (turn-on:)

\( V_D D \)

Speaker Load

\( V_{G1} \rightarrow V_{G5} \rightarrow V_{G6} \)
Proposed Low-EMI Control (1/4)

- In state $S_A$

In the diagram, the states and their corresponding switches are shown:

- **$S_A$**
  - Turn-on: $M_1, M_4, M_5$

- **$S_B$**
  - Turn-on: $M_5$

- **$S_C$**
  - Turn-on: $M_5, M_6$

- **$S_D$**
  - Turn-on: $M_6$

- **$S_E$**
  - Turn-on: $M_2, M_3, M_6$

The diagram illustrates the electrical connections and control states for minimizing electromagnetic interference (EMI) in the system.
Proposed Low-EMI Control (2/4)

- In transition from $S_A$ into $S_B$

![Diagram showing the transition from $S_A$ to $S_B$ and corresponding signal levels and switch activations.

- $V_{G1}$
- $V_{G4}$
- $V_{G5}$
- $V_{G6}$
- $VDD$
- $OUT_P$
- $OUT_N$
- $M1$, $M2$, $M3$, $M4$, $M5$, $M6$
Proposed Low-EMI Control (3/4)

- In state $S_B$

![Diagram of Proposed Low-EMI Control with transistor symbols M1, M2, M3, M4, M5, and M6, and voltage labels $V_{G1}$, $V_{G4}$, $V_{G5}$, and $V_{G6}$, with speaker load.]
Proposed Low-EMI Control (4/4)

- In state $S_C$

![Diagram of circuit with labels and states]

- $V_G1, V_G4$
- $V_G5$
- $V_G6$
- OUTP, OUTN
- $S_A, S_B, S_C, S_D, S_E$

Turn-on:
- $M_1, M_4, M_5$
- $M_5$
- $M_5, M_6$
- $M_5$
- $M_1, M_4, M_5$

Scan of states:
- $S_A$
- $S_B$
- $S_C$
- $S_D$
- $S_E$
Chip Micrograph

Digital Audio Processor

Gate Driver

M₁ of L_{CH}
M₂,₄ of L_{CH}
M₃ of L_{CH}
M₃ of R_{CH}
M₂,₄ of R_{CH}
M₁ of R_{CH}
M₅,₆ of L_{CH}
M₅,₆ of R_{CH}

Dimensions:
- 2.45 mm length
- 1.5 mm width
- 0.3 mm height
- 0.2 mm height
THD+N vs. Output Power

- Measurement condition: 24-V<sub>DD</sub>, 8-Ω, BD modulation
- 30-W low-distortion output power → 20% increase by ACDSM
EMI Measurement

- **Conducted EMI**
  - BD-modulation mode
  - low-EMI mode
  - Frequency (MHz)
  - Level (dBμV/m)
  - 60
  - 40
  - 20
  - 0.15 0.5 1 5 10 20 30
  - 8 dBμV/m

- **Radiated EMI**
  - BD-modulation mode
  - low-EMI mode
  - Frequency (MHz)
  - Level (dBμV/m)
  - 50
  - 30
  - 10
  - 30 64 98 132 166 200 360 520 680 840 1000
  - FCC class-B standard
  - 24 dBμV/m
  - 24 dBμV/m
  - 30
## Comparison

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<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Supply Voltage $V_{DD}$ (V)</td>
<td>24</td>
<td>18</td>
<td>3</td>
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<tr>
<td>Nominal Load $R_L$ (Ω)</td>
<td>8</td>
<td>8</td>
<td>8</td>
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<tr>
<td>Peak Efficiency $\eta$ (%)</td>
<td>90</td>
<td>88</td>
<td>88</td>
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<tr>
<td>Output Power $P_{OUT}$ (W)</td>
<td>30</td>
<td>13</td>
<td>0.4</td>
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<td>@ 1%THD+N</td>
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<tr>
<td>Normalized Output Power$^{(1)}$</td>
<td>1.03</td>
<td>0.83</td>
<td>0.92</td>
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<tr>
<td>@ 1%THD+N</td>
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<tr>
<td>DSM Max. Stable Input (dBFS)</td>
<td>+0.2</td>
<td>-1.2</td>
<td>-0.7</td>
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<td>EMI Reduction ($dB\mu V/m$)</td>
<td>8 (conducted)</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>24 (radiated)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Chip Area (mm$^2$)</td>
<td>3.74 (stereo)</td>
<td>23.9 (5.1-ch)</td>
<td>0.76 (stereo)</td>
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<tr>
<td>Process</td>
<td>0.18µm BCDMOS</td>
<td>0.35µm HVCMOS</td>
<td>65nm CMOS</td>
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</tbody>
</table>

$^{(1)}$ Normalized Output Power = \[
\frac{P_{OUT}}{(\eta \cdot V_{DD})^2 / (2 \cdot R_L)}
\]
Conclusion

- A 30-W open-loop class-D amplifier is implemented for a 24-V supply voltage and 8-Ω load

- The ACDSM simultaneously achieves
  - high in-band noise suppression
  - wide stable input range
  - 20% low-distortion $P_{\text{OUT}}$ increase

- The proposed low-EMI control method
  - PVT-insensitive common-mode EMI reduction