Power Management for Portable Audio Applications

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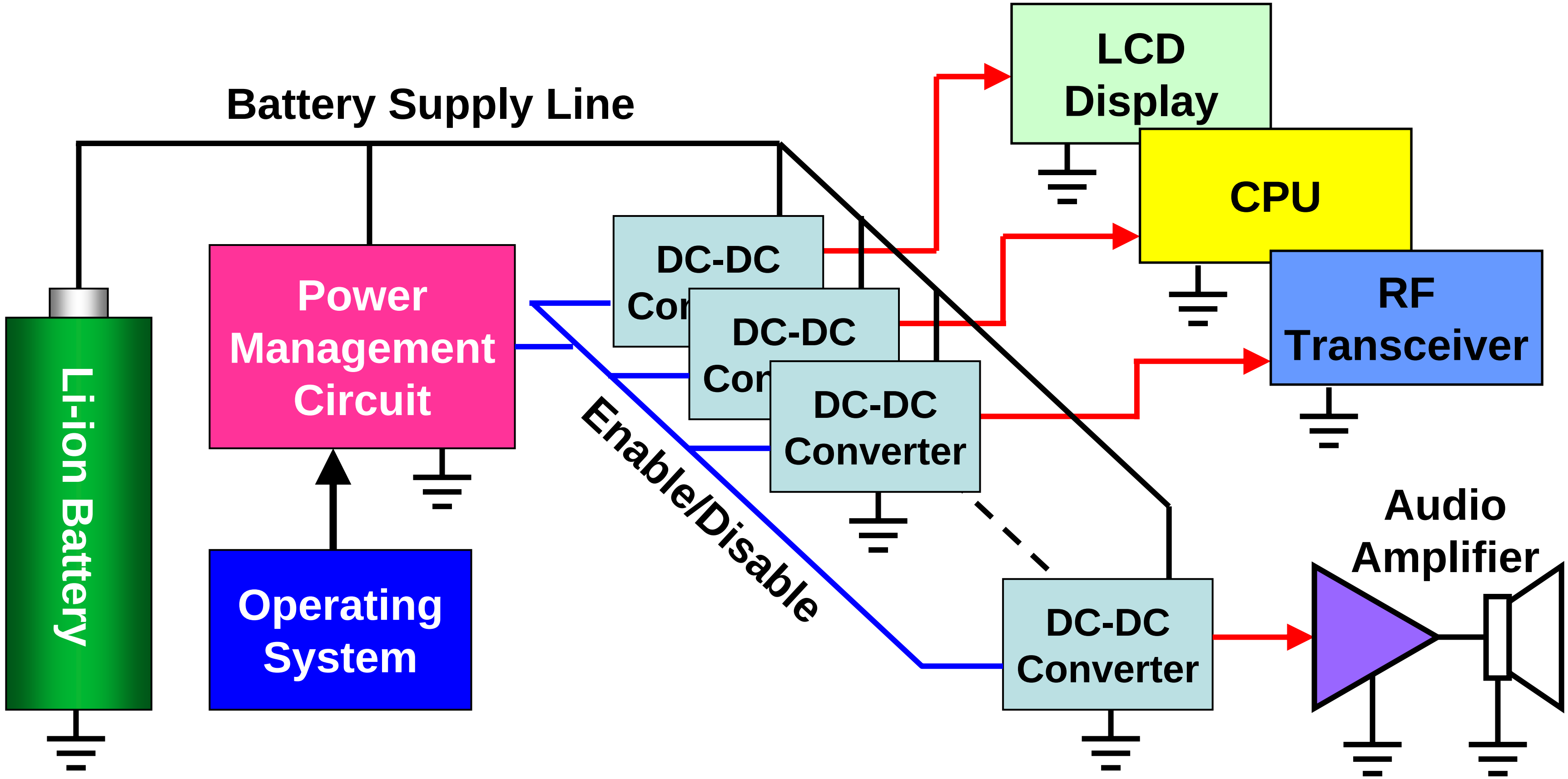
Outline

- Power Management for Portable Applications
- Self-Optimization in DC-DC Converters
- Optimized Efficiency Through SOS
- Application of Predictive Feedforward: Miniature Class-D Audio Amplifier
- Conclusions

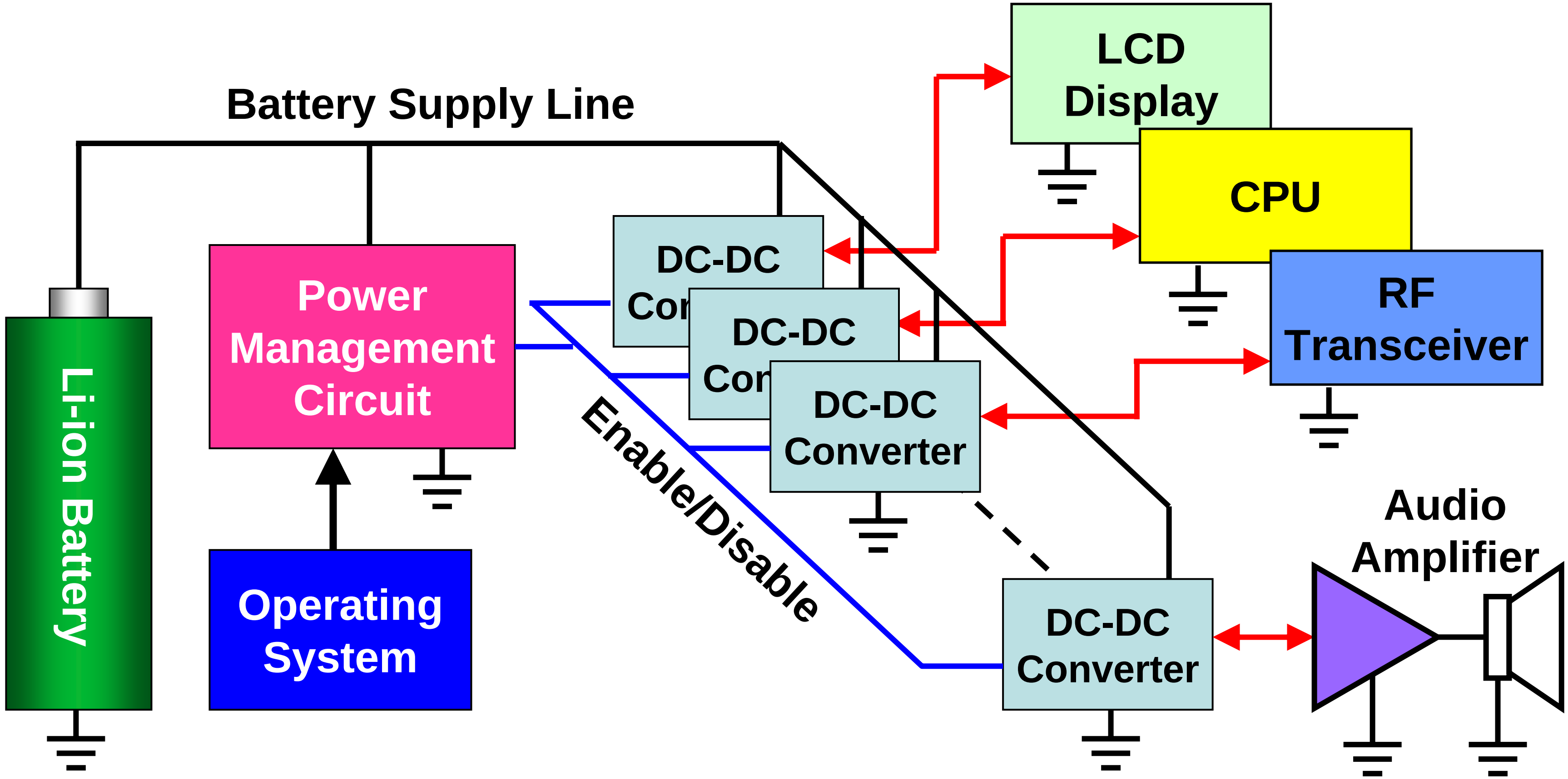
Power Management for Portable Applications

- Traditional Power Management (e.g. ACPI) is basically a **one-way** decision.



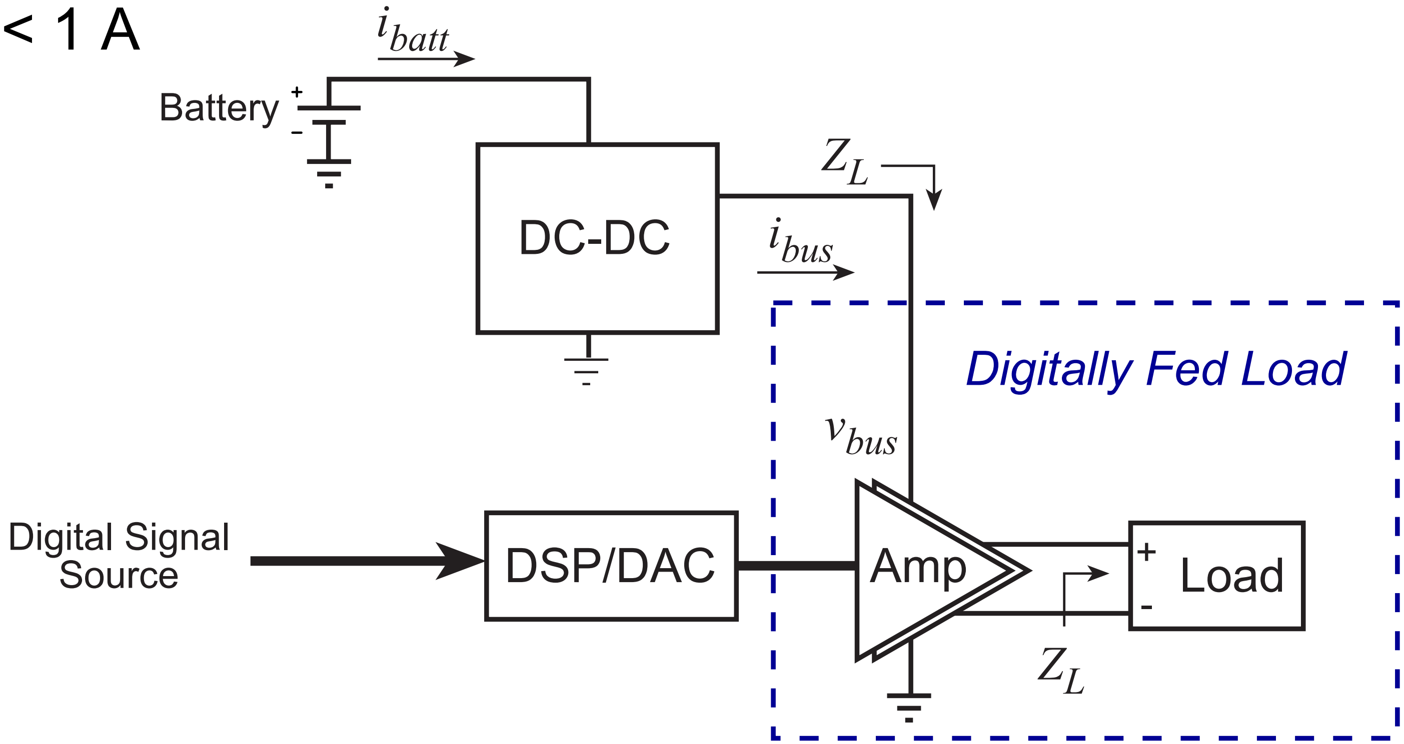
Power Management for Portable Applications

- The load must be able to **communicate** to the power supply and optimize power use.



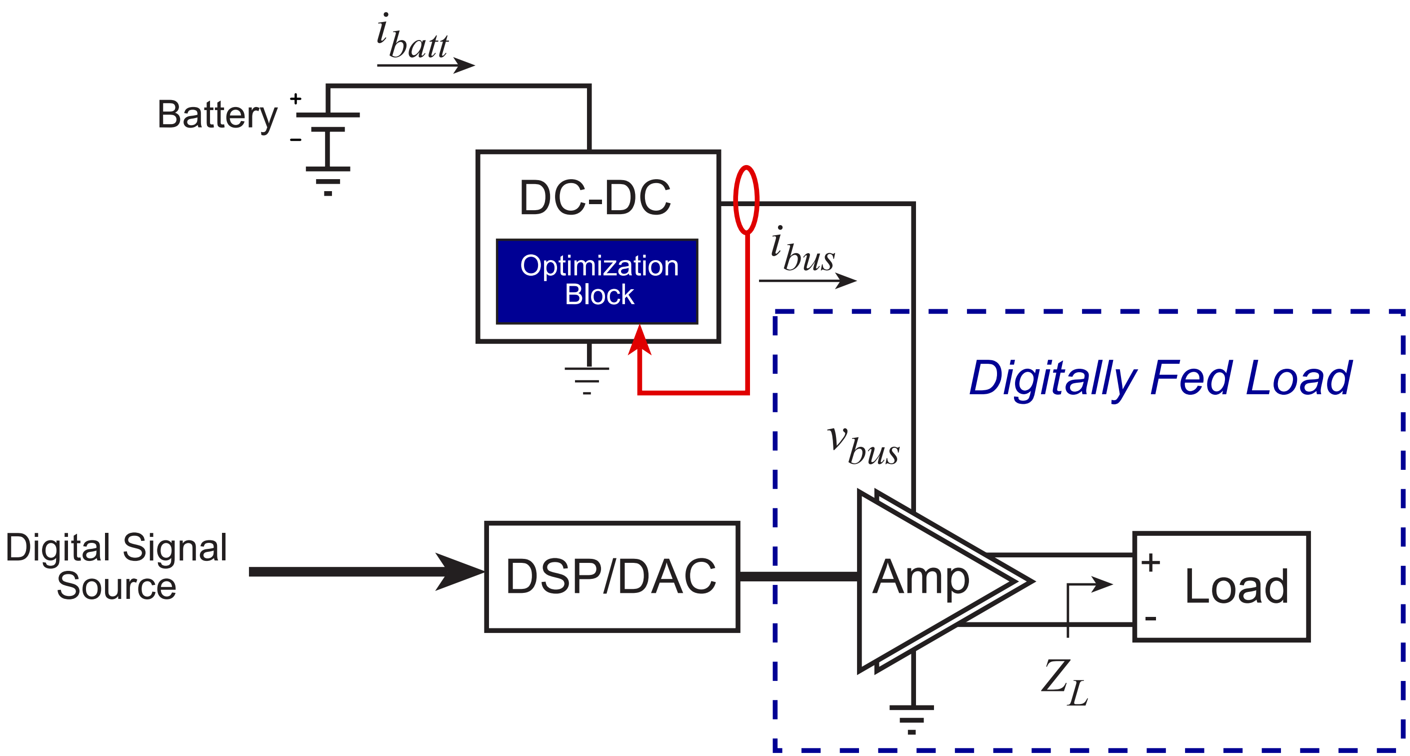
Target Application: Handheld Devices

- DC-DC converter provides a regulated bus voltage for digitally fed ***predictable*** load
- In general, the digitally fed load may be a speaker, display, ICs etc.
- Goal: on-the-fly optimization of DC-DC converter performance
- 2.6 V < V_{batt} < 4.2 V (single cell lithium Ion)
- I_{batt} < 1 A



Self-Optimization in DC-DC Converters

- There exists numerous digital/analog schemes for on-line optimization of :
  - Efficiency: R_{on}, Q_{gate}, dead-time, multi-mode (PFM, DCM etc.)
  - Dynamic response: compensator coefficients, auto-tuning etc.
- How is it achieved in current technology?



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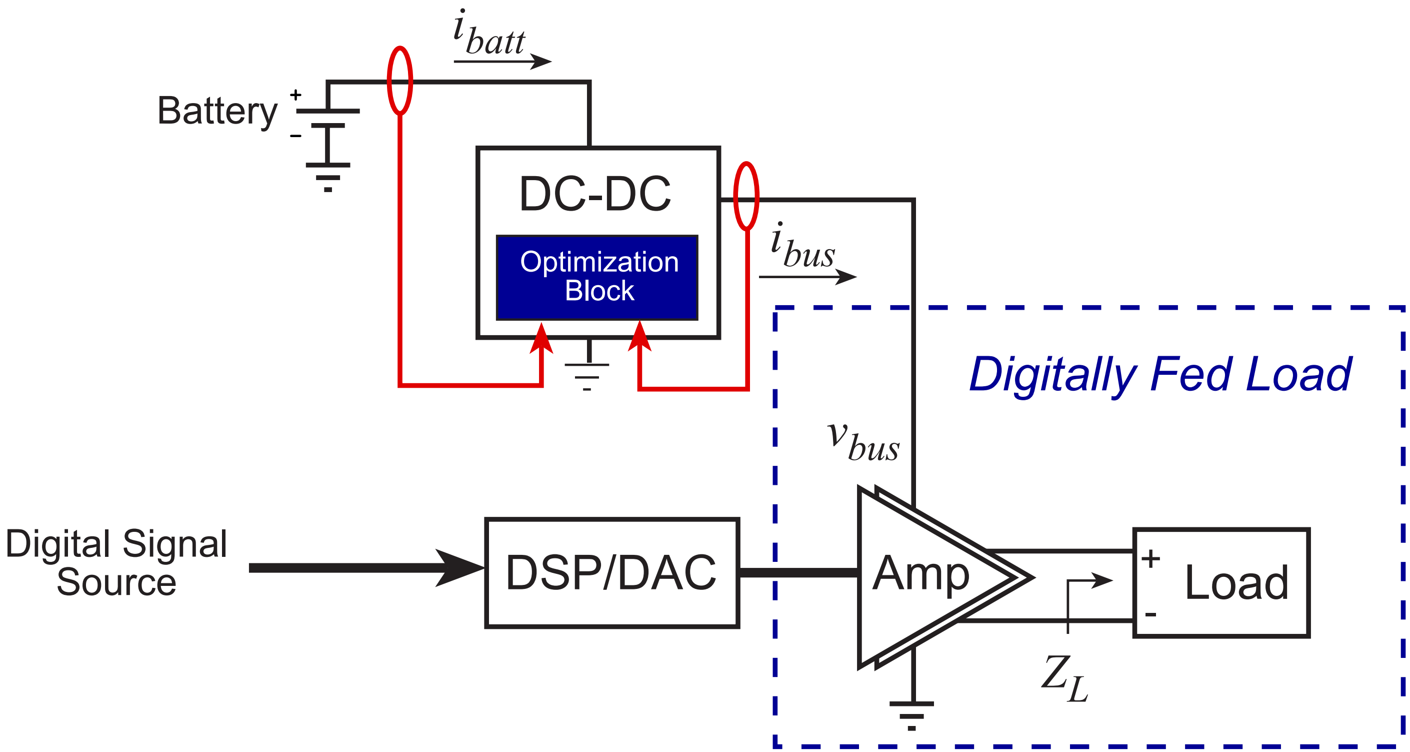

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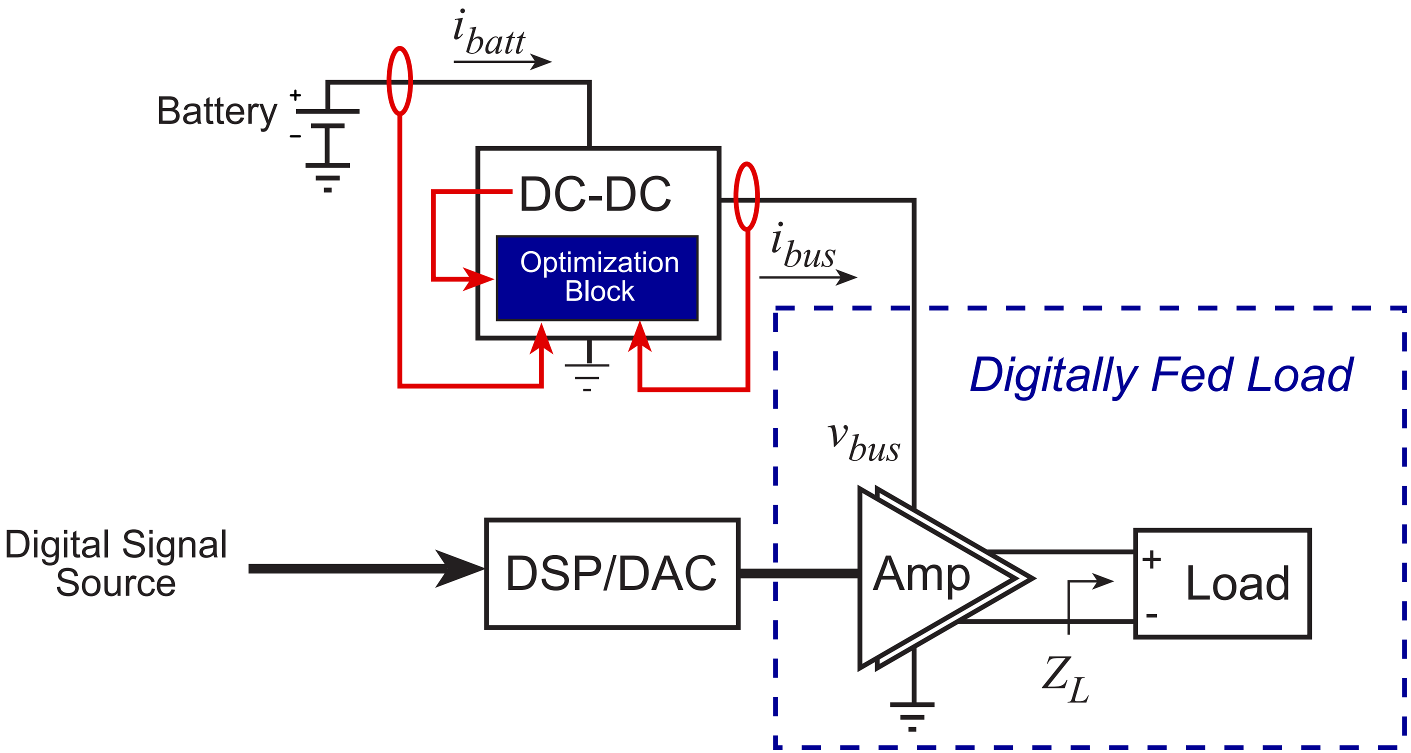

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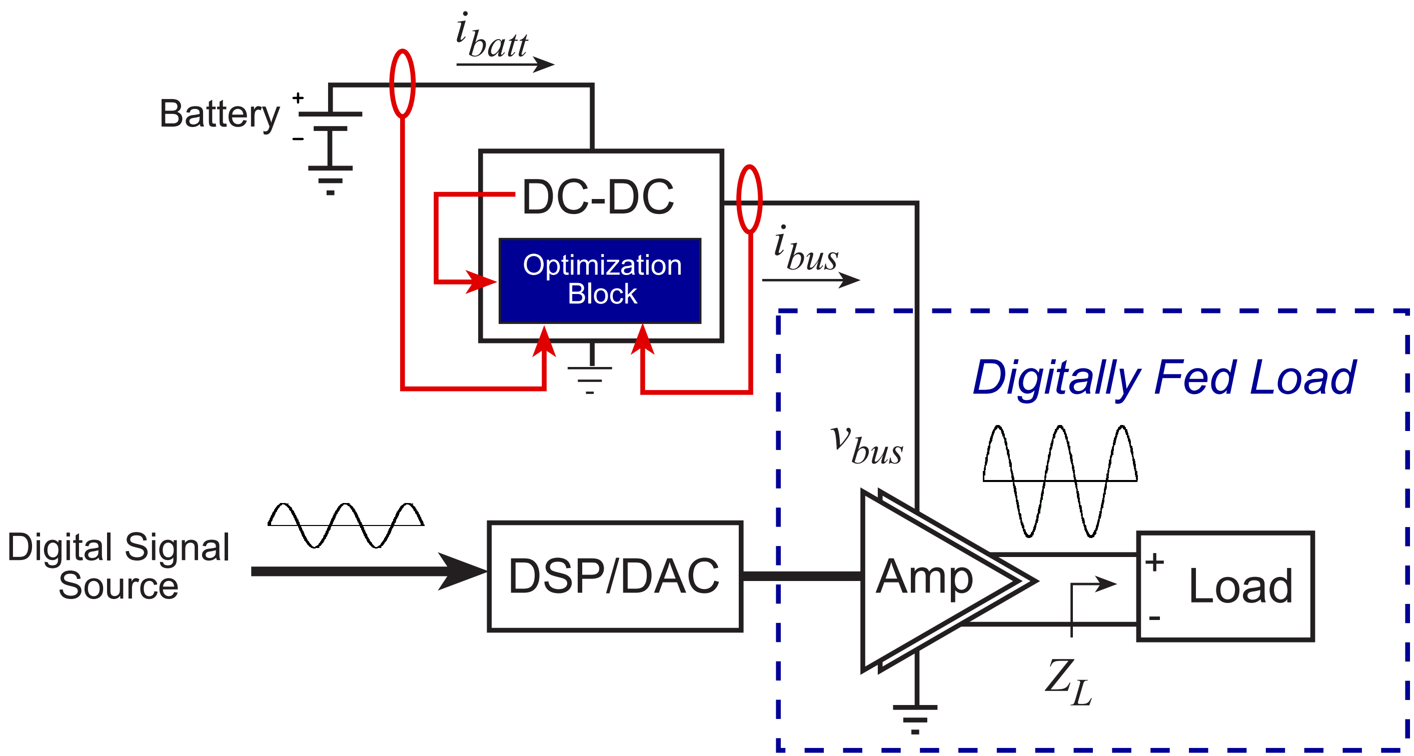
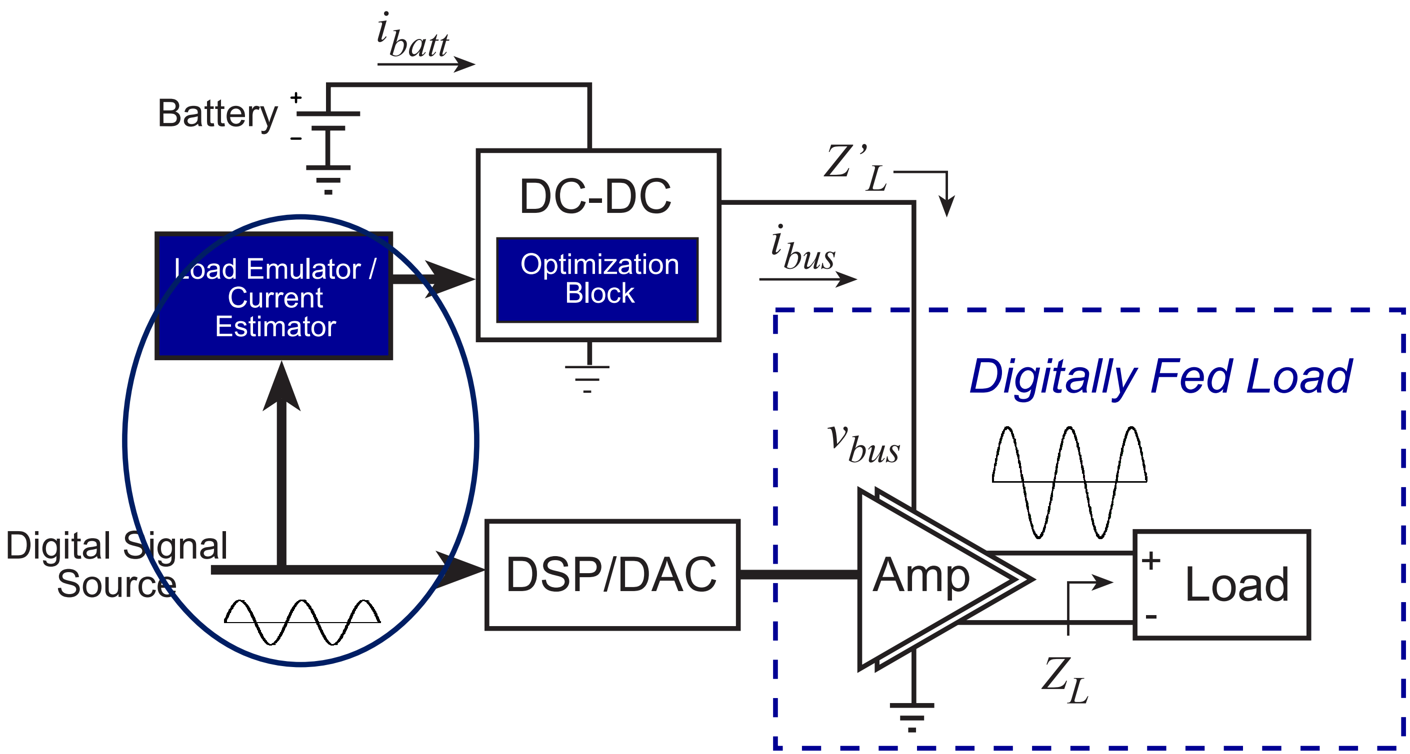


This Work: Load Prediction Concept

- Premise: *digitally fed load has predictable load impedance*
- Sensor-less approach:
  - Data stream is used to optimize DC-DC converter efficiency in real-time

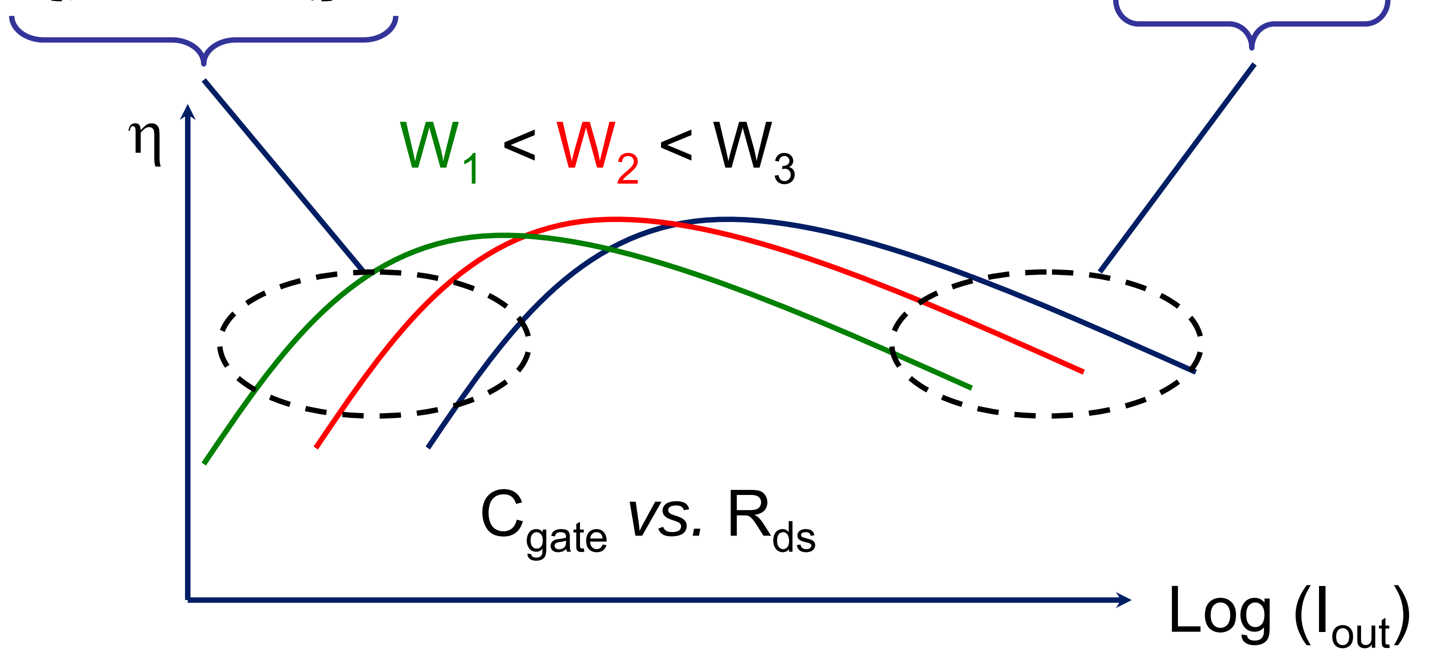


Optimized Efficiency Through SOS

- Optimum gate width varies with load power: $W_{opt} \propto \frac{P_{out}}{\sqrt{f_s}}$

$$P_{gate} = f_s\left(C_{gate,N}V_{in}^2 + C_{gate,P}V_{in}^2\right)$$

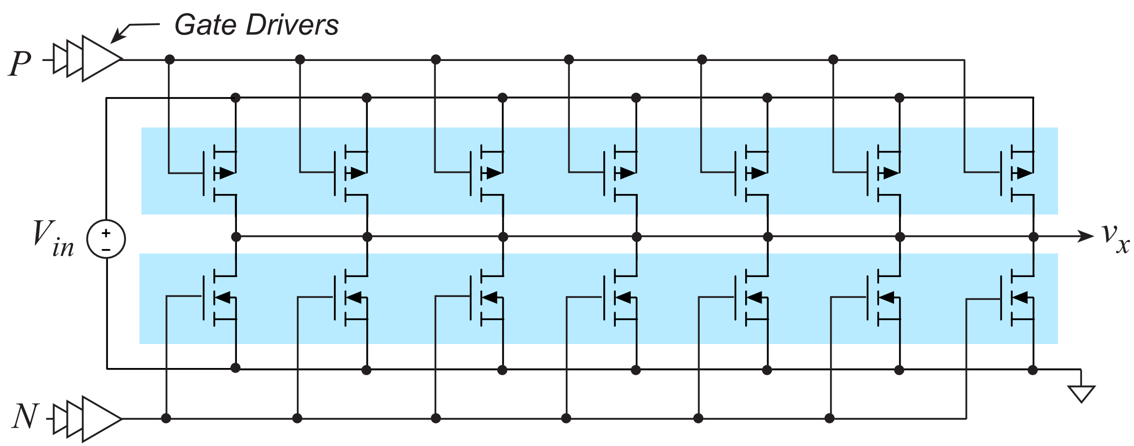
$$P_{cond} = \left(I_{out}^2 + \frac{\Delta i_L^2}{12}\right)\left(DR_{ds,P} + D'R_{ds,N}\right)$$



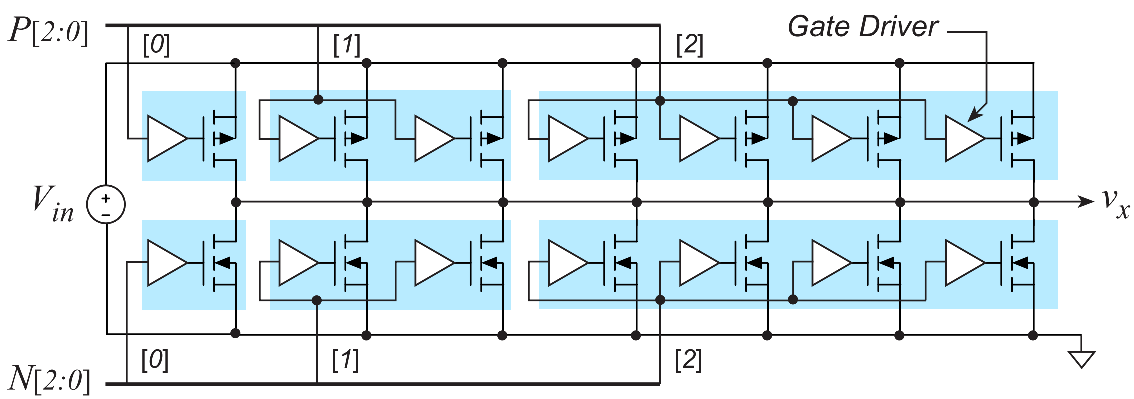
SOS Implementation

- "Switched-W" concept can be expanded to multi-gate *binary-weighted* (segmented) output stage:
- Active area is identical to traditional output stage

Traditional Output Stage:

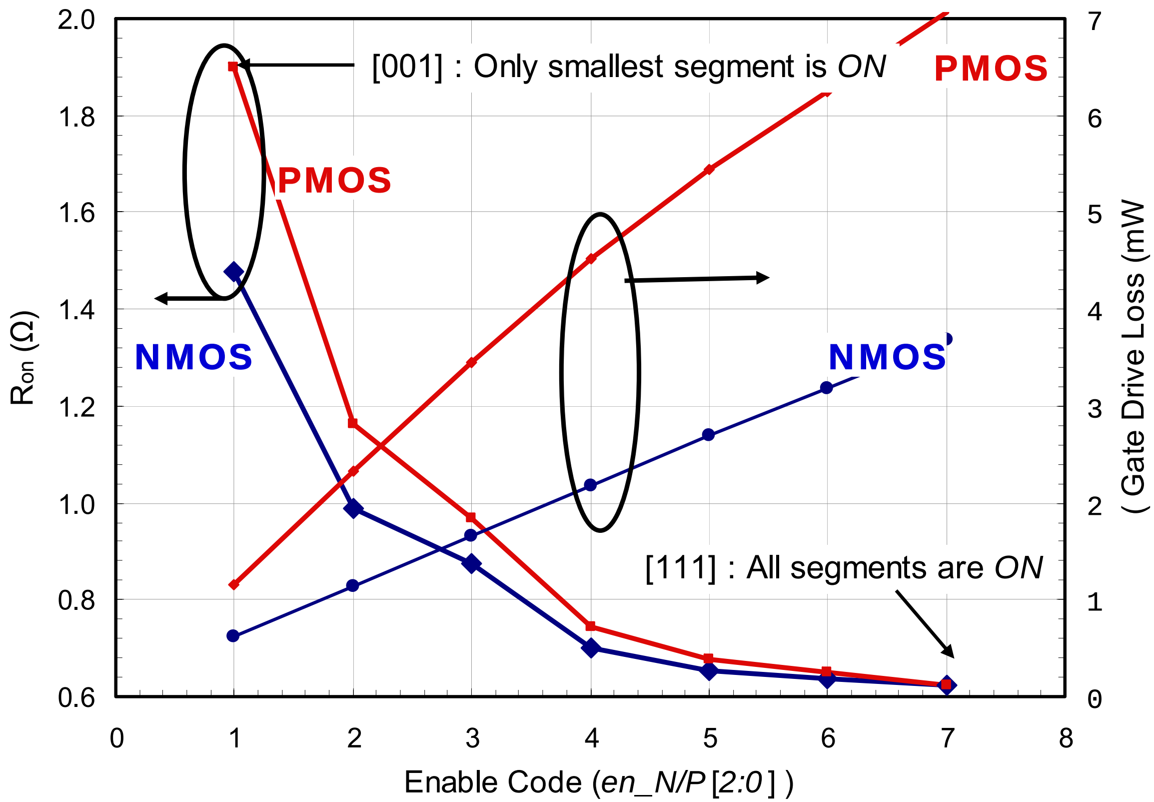


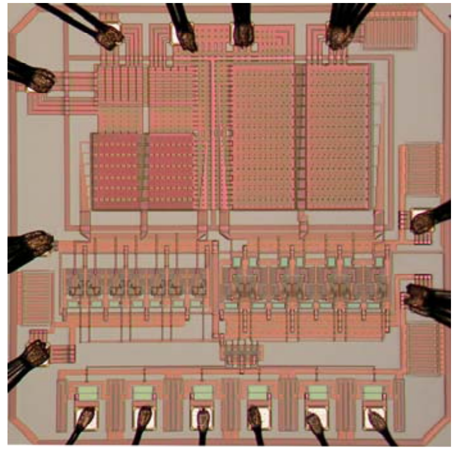
Segmented Output Stage:



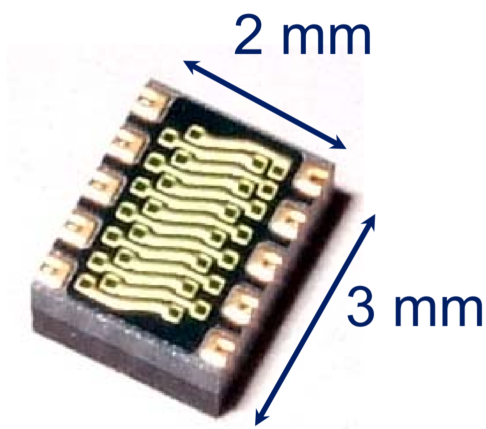
Trade-off Between R_{on} and P_{gate}

- When changing from [111] to [001]:
  - P_{gate} is reduced by 6.3×
  - $R_{on,N}$ increased by 2.4×, $R_{on,P}$ increased by 3.1×



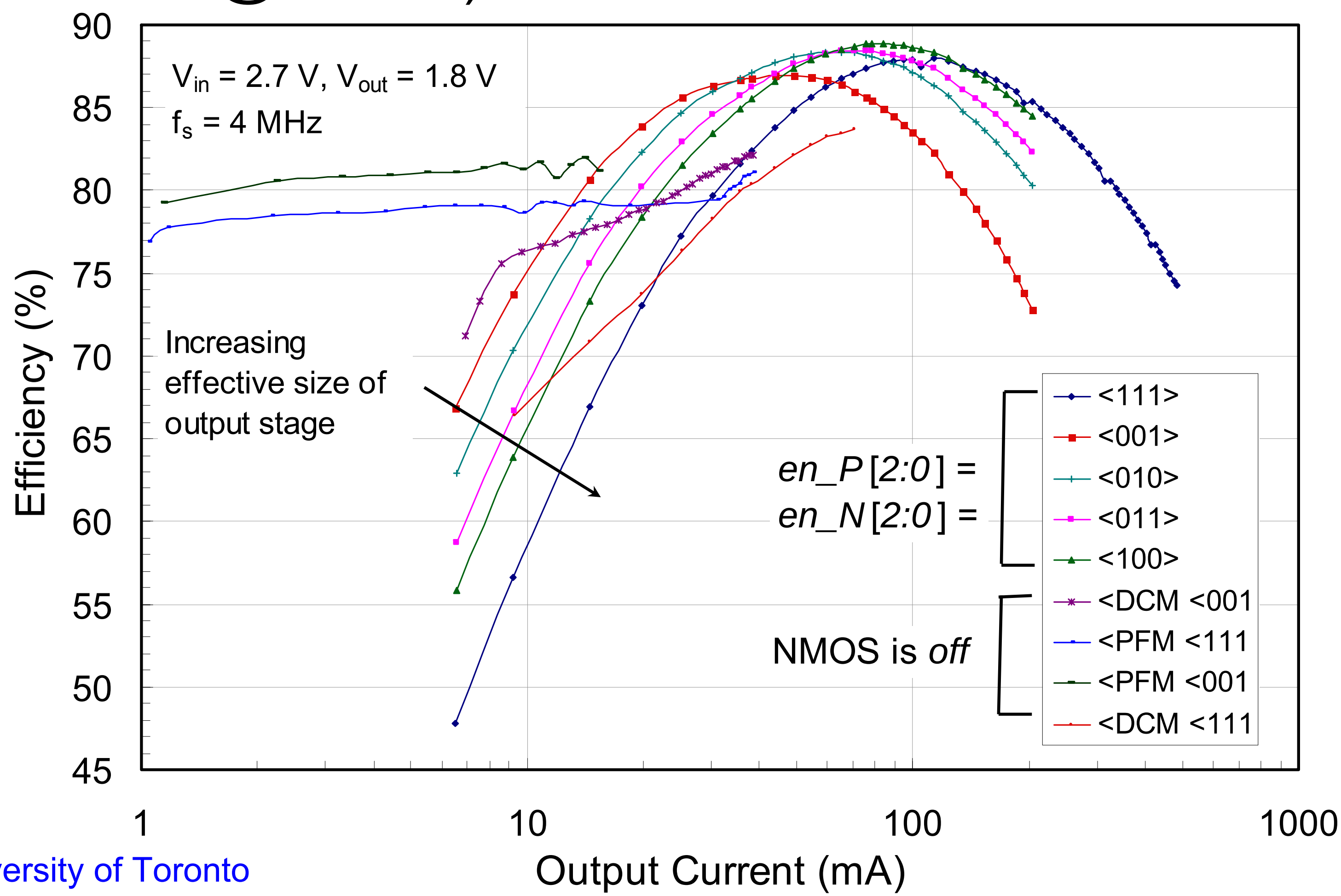


Trescases et al., ISPSD'06



Efficiency Measurements @ 4 MHz, V_{in} = 2.7 V

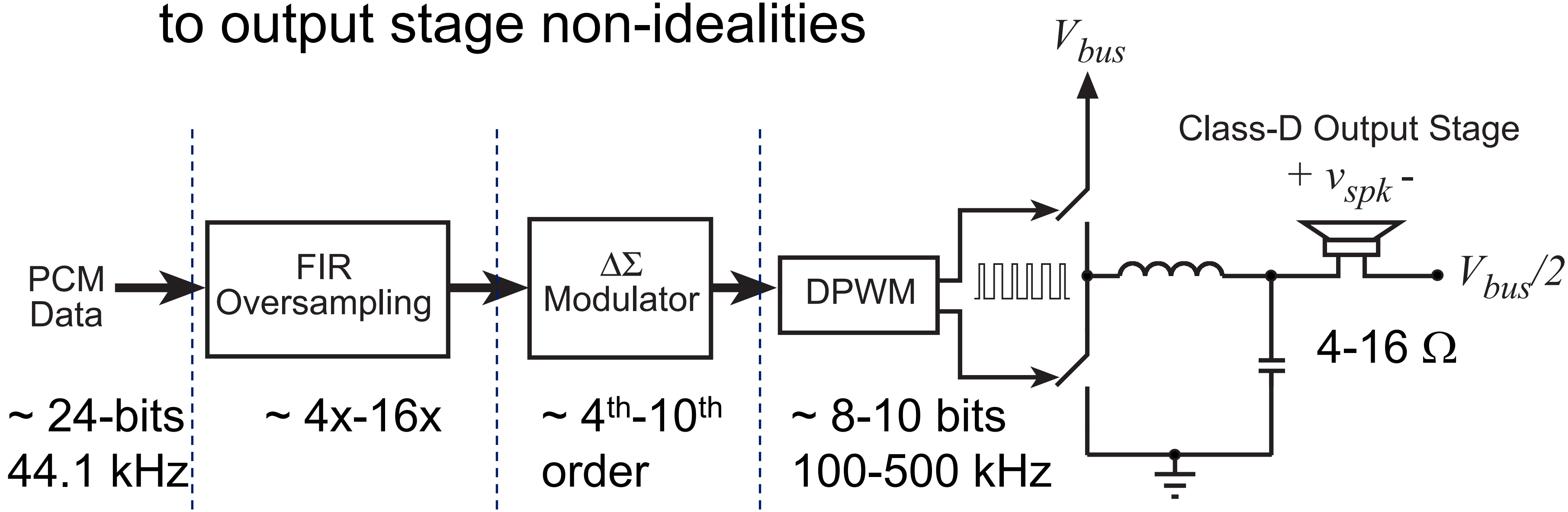
- Peak efficiency at 4 MHz is limited by high switching losses in the output stage + inductor conduction losses (> 90 % @ 2 MHz)



Application of Predictive Feedforward: Miniature Class-D Audio Amplifier

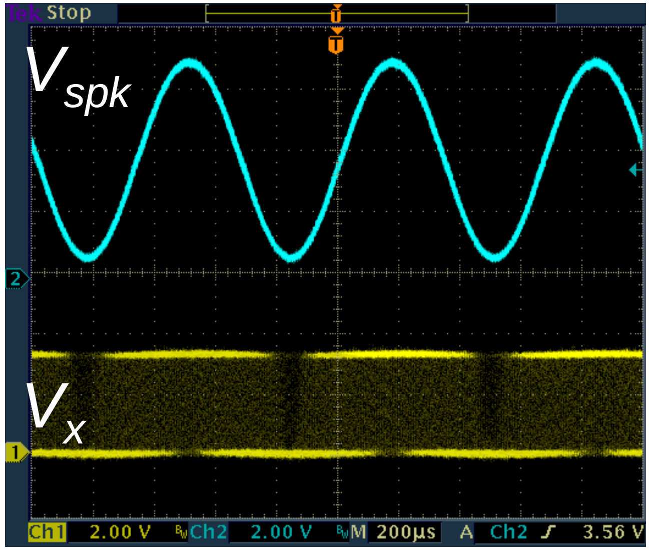
All-Digital Hi-Fi Open Loop Class-D Amplifier

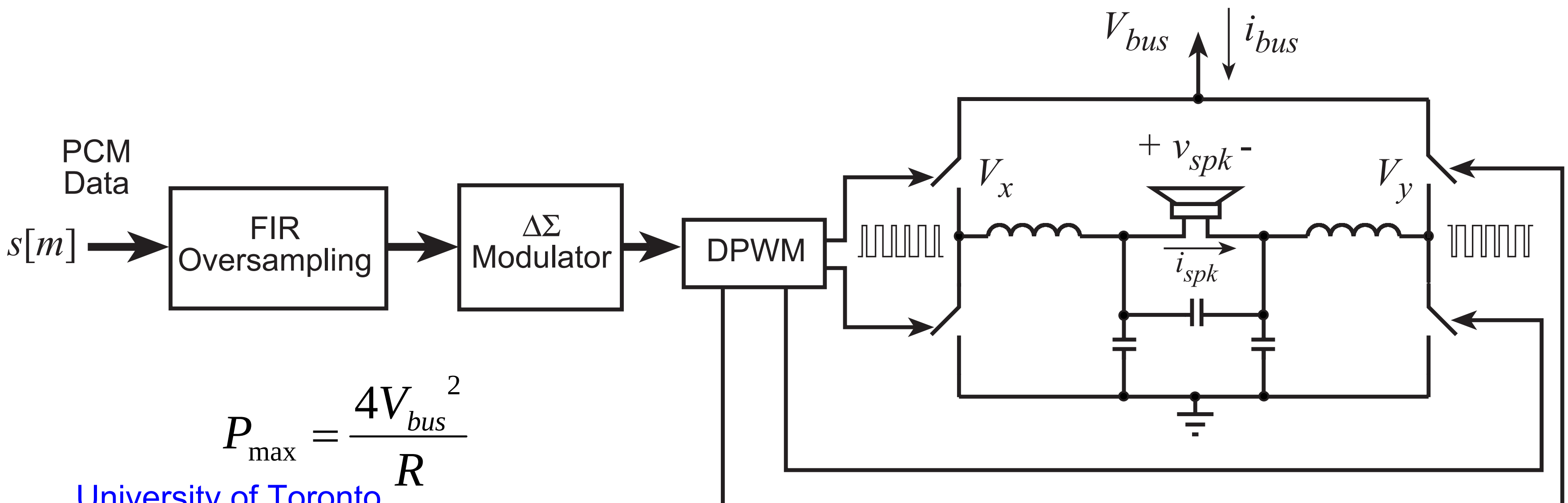
- Why class-D? Efficiency, Size, Cost
- Operates as a high-bandwidth *open-loop* DC-DC converter with variable V_{out}
- Open-loop class-D amplifier:
  - All digital
  - Well suited to digital audio sources
- Local feedback may be added to suppress distortion due to output stage non-idealities



All-Digital Hi-Fi Open Loop Class-D Amplifier

- H-bridge class-D amp is preferred
  - Improve PSRR
  - Eliminate need for negative rail or AC coupling cap





$$P_{\max} = \frac{4V_{bus}^2}{R}$$

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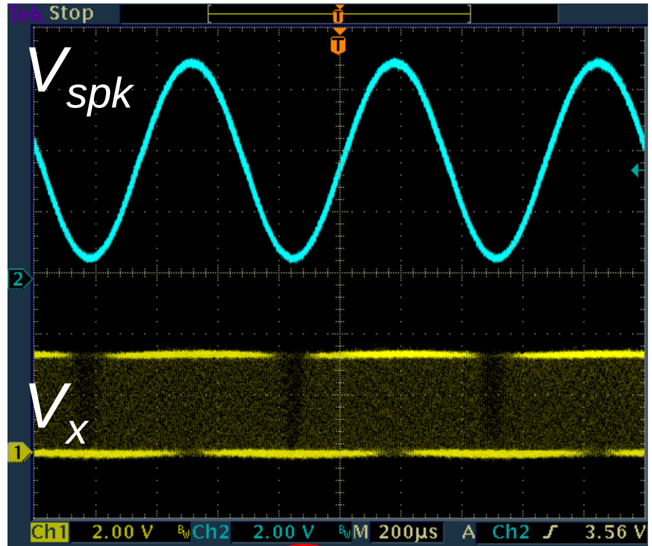

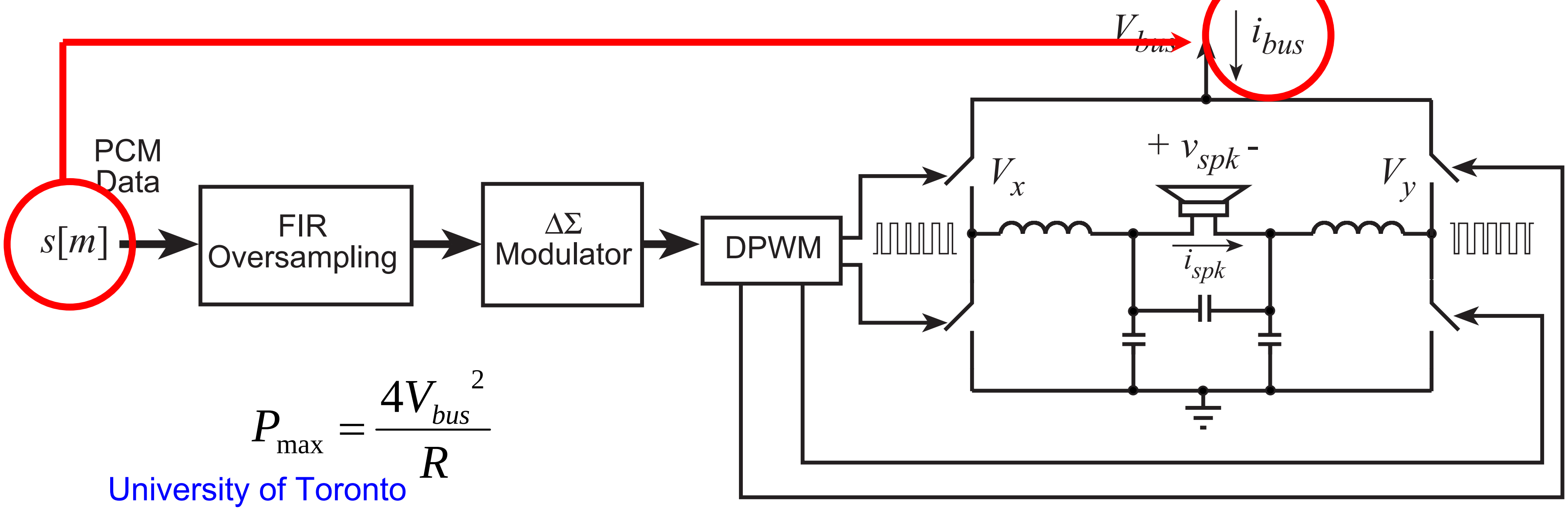

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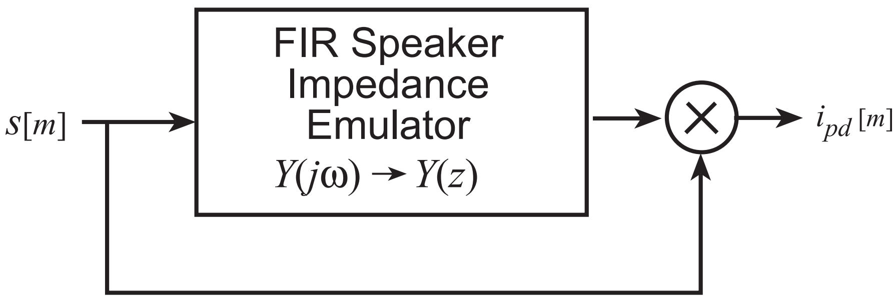
Estimating The Class-D Amplifier Load Current

- Class-D input current is proportional to output power (non-linear):

$$i_{bus}(t) = \frac{\overbrace{i_{spk}(t)v_{spk}(t)}^{P_{out}}}{V_{bus}\eta} = \frac{I_{spk}V_{spk}}{2V_{bus}\eta}\left(\cos\phi - \underbrace{\cos(2\omega t + \phi)}_{\text{Component at 2f}}\right)$$



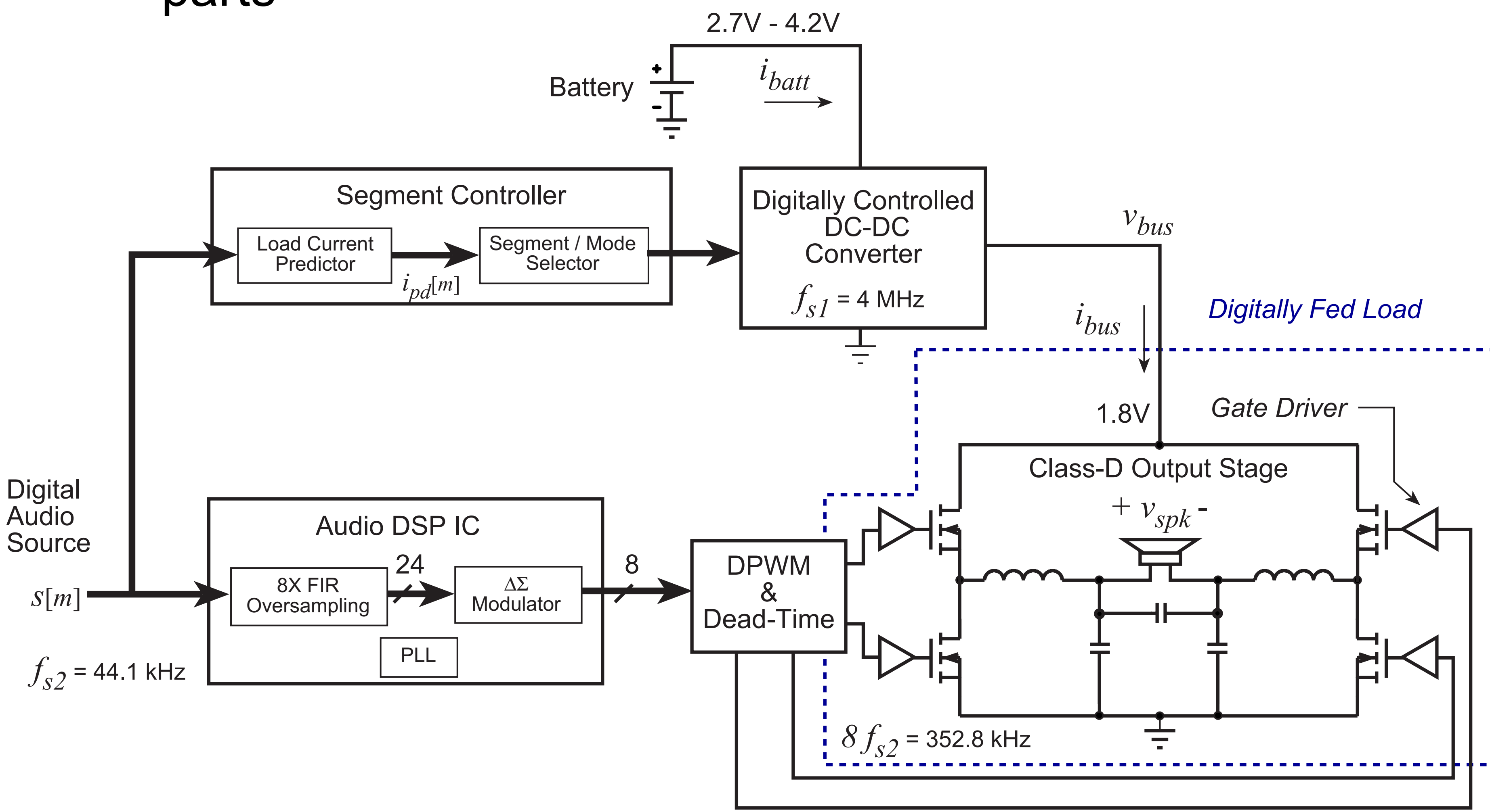
- Crude resistive speaker approximation: $Y(j\omega) \approx 1/R$

$$i_{bus}(t) = \frac{V_{spk}{}^2(t)}{V_{bus}\eta R} \propto V_{spk}{}^2(t) \propto s[m]^2(t)$$

Speaker voltage can be obtained directly from audio data stream !

DC-DC Converter + Class-D Amplifier

- Prototype system includes 2 custom ICs + off-the-shelf parts



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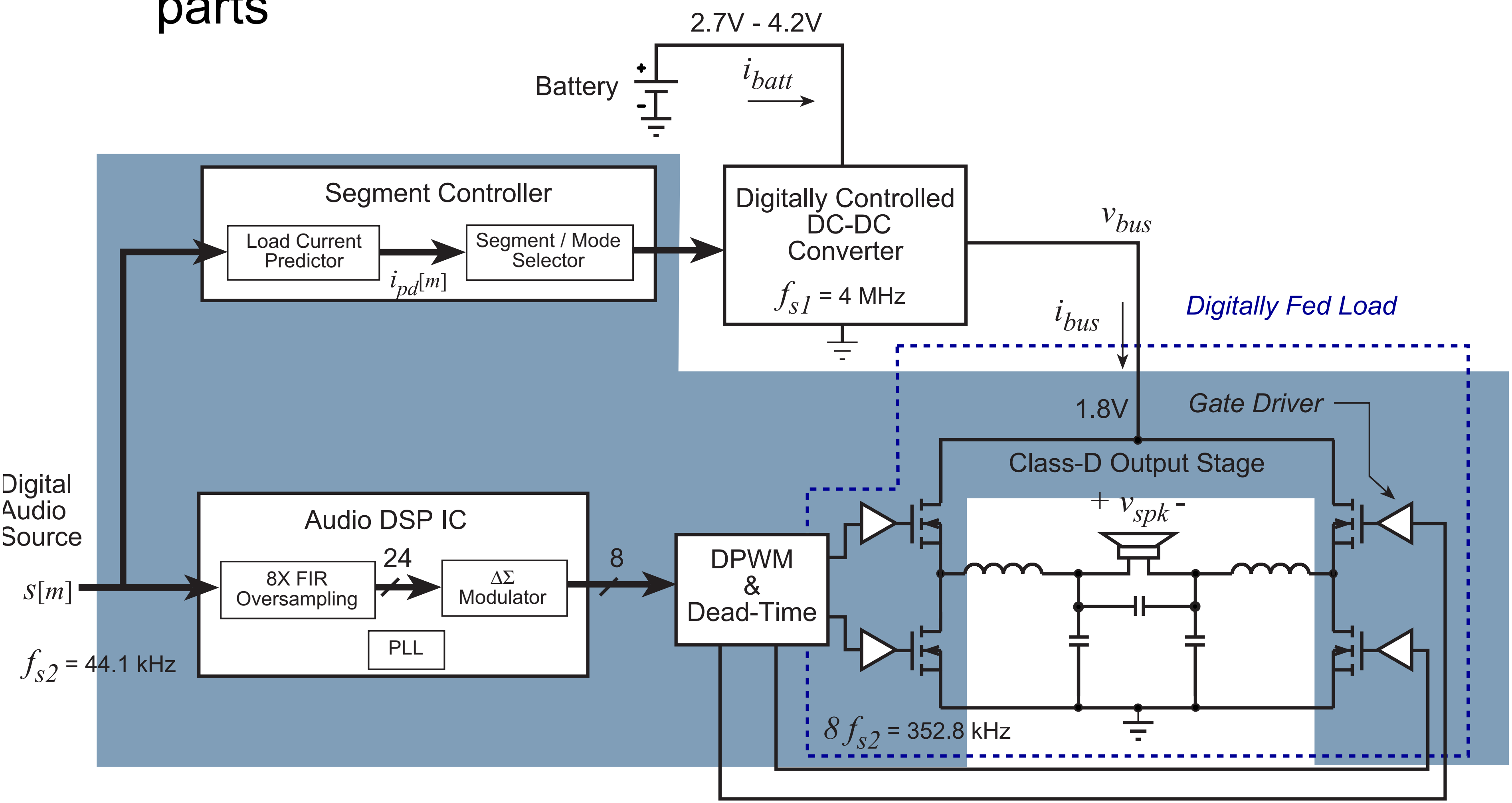

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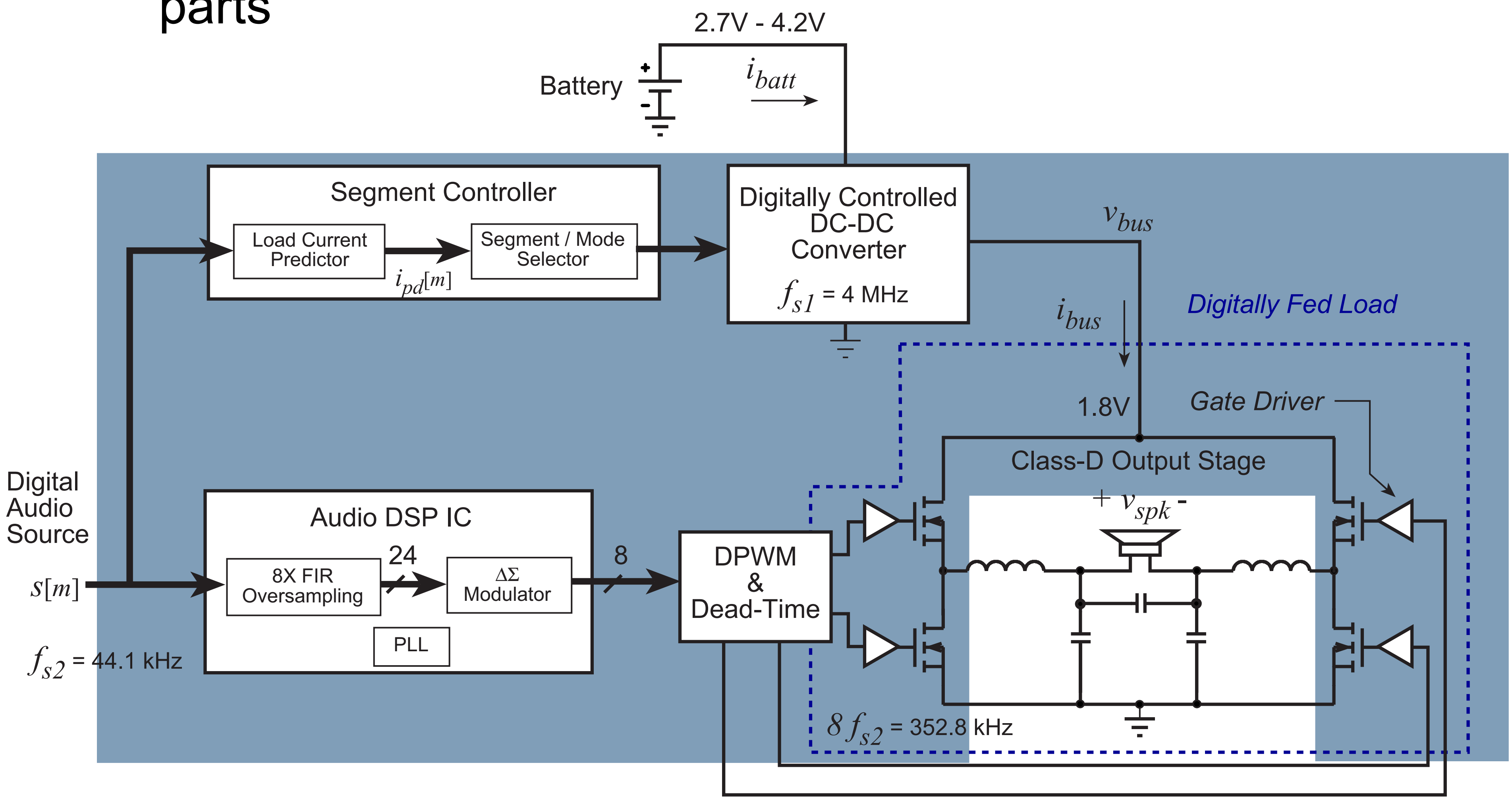
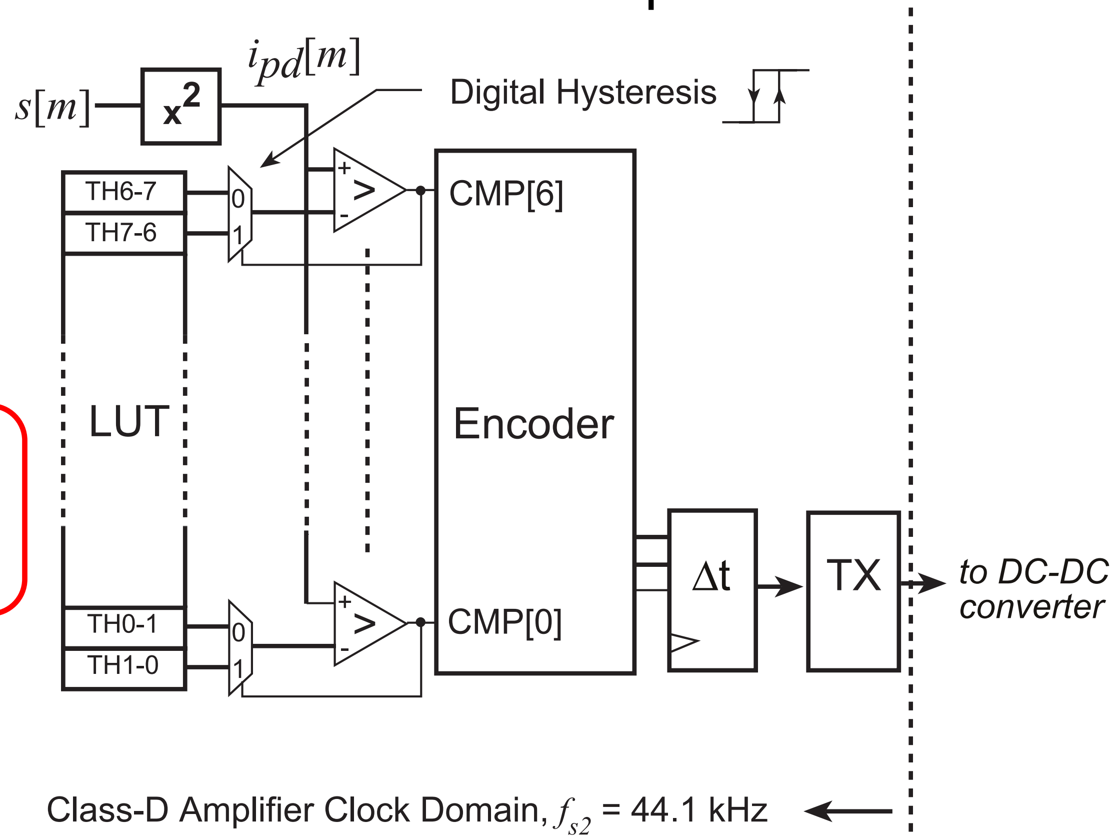


Segment Controller

- Segment controller estimates class-D load current a resistive approximation
- Enable code is calculated each audio sample (f_{s1} = 44.1 kHz)
- Hysteretic thresholds are encoded into a lookup table
- Enable codes are calculated and transmitted asynchronously to the buck converter

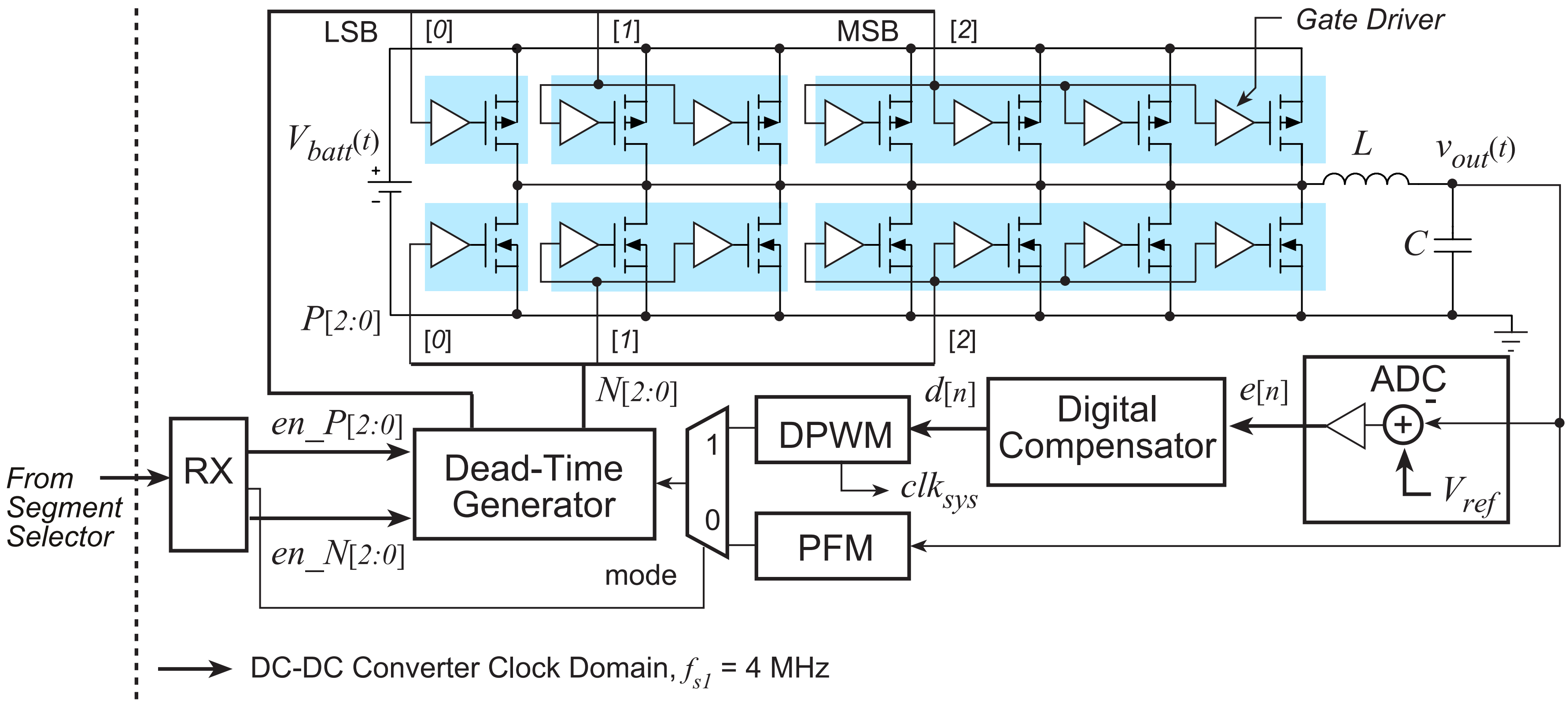
$$i_{bus}(t) = \frac{V_{spk}{}^2(t)}{V_{bus}\eta R} \propto V_{spk}{}^2(t) \propto s[m]^2(t)$$



Digitally Controlled Buck Converter

- Simple digital LUT-PID based compensator is used with f_{s2} = 4 MHz
- Output stage is re-configured according to data from segment selector

Digitally Controlled DC-DC Converter

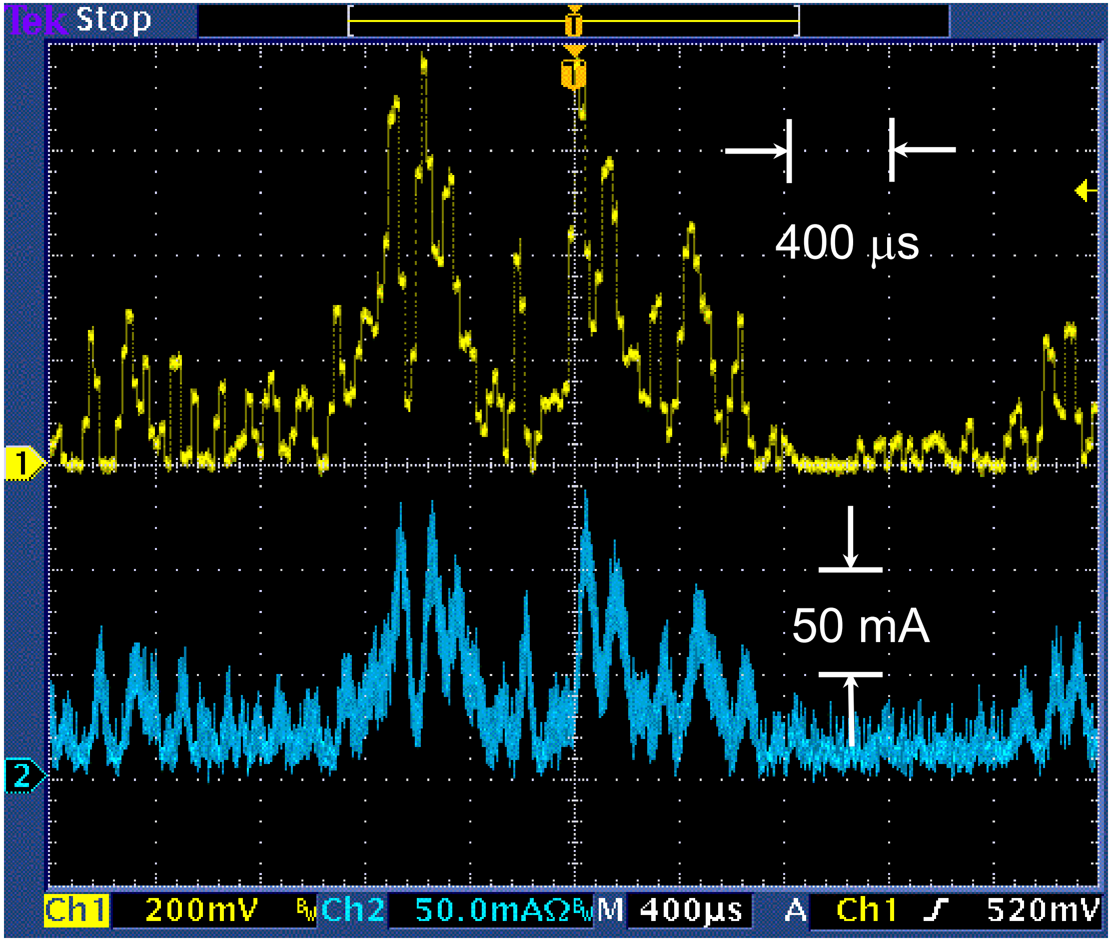


Experimental Results

- High speed flash D/A is used to compared predicted bus current $i_{pd}[n]$ with actual bus current $i_{bus}(t)$ during audio playback

Predicted Bus Current $i_{pd}[n]$

Actual Bus Current $i_{bus}(t)$

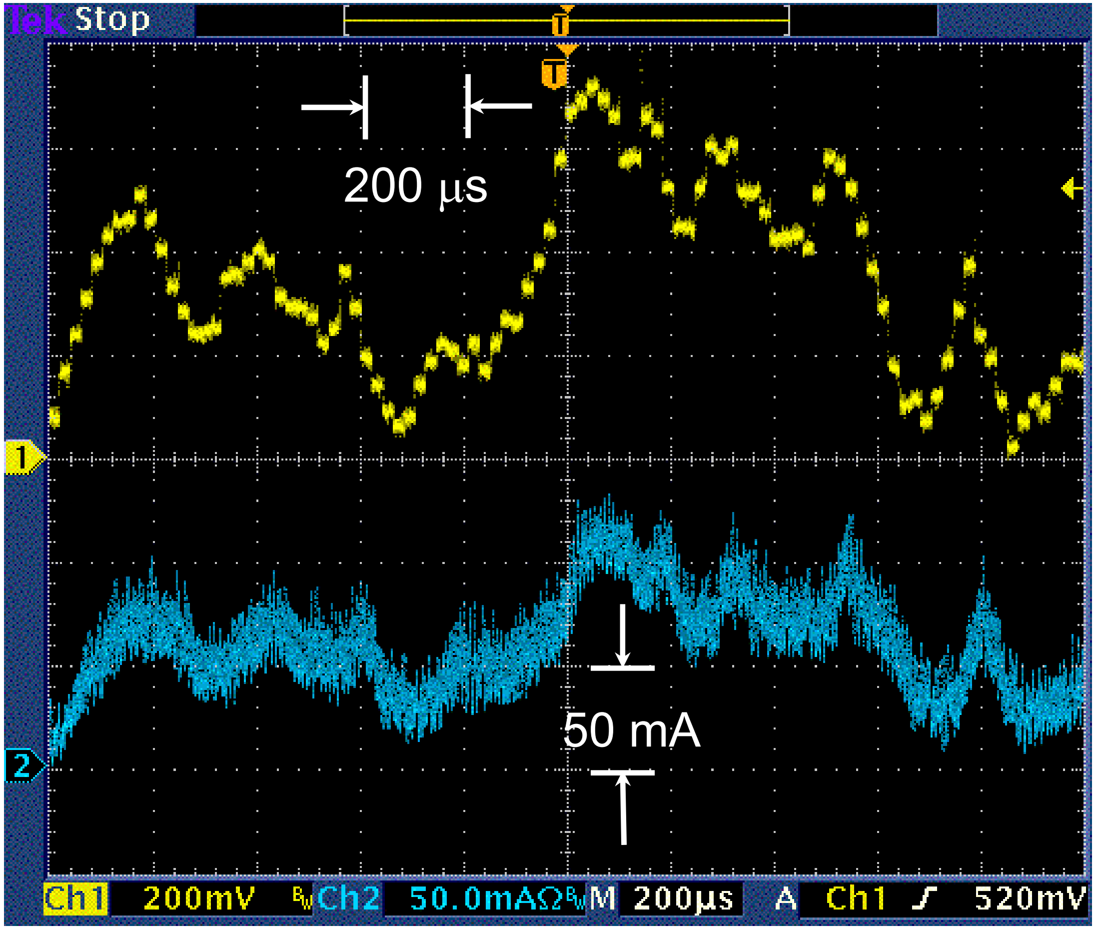


Experimental Results

- Good agreement between the predicted and actual bus current is achieved despite the complex speaker impedance

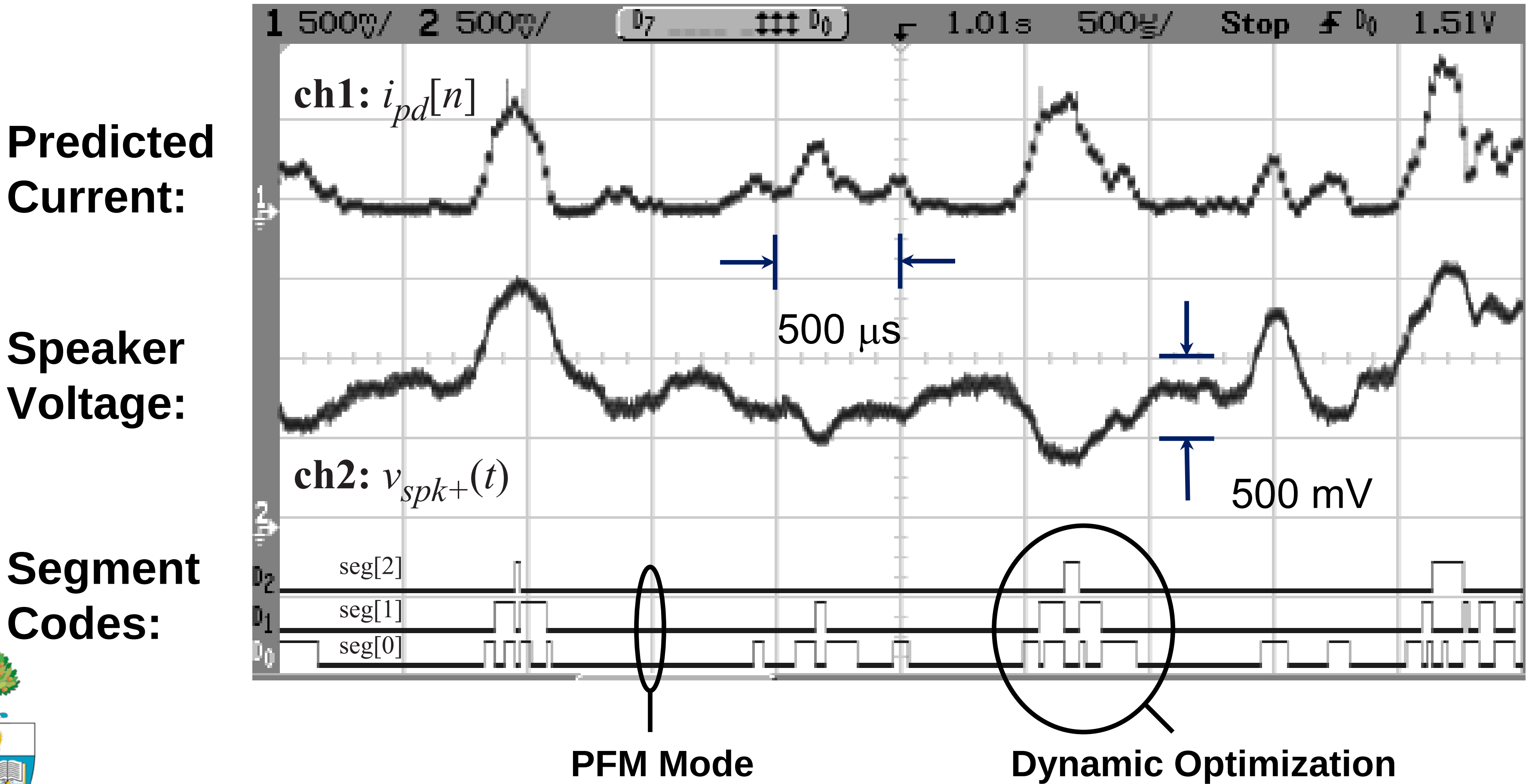
Predicted Bus Current $i_{pd}[n]$

Actual Bus Current $i_{bus}(t)$



Experimental Results

- Output stage is dynamically re-sized according to predicted speaker current



PFM → PWM Operation

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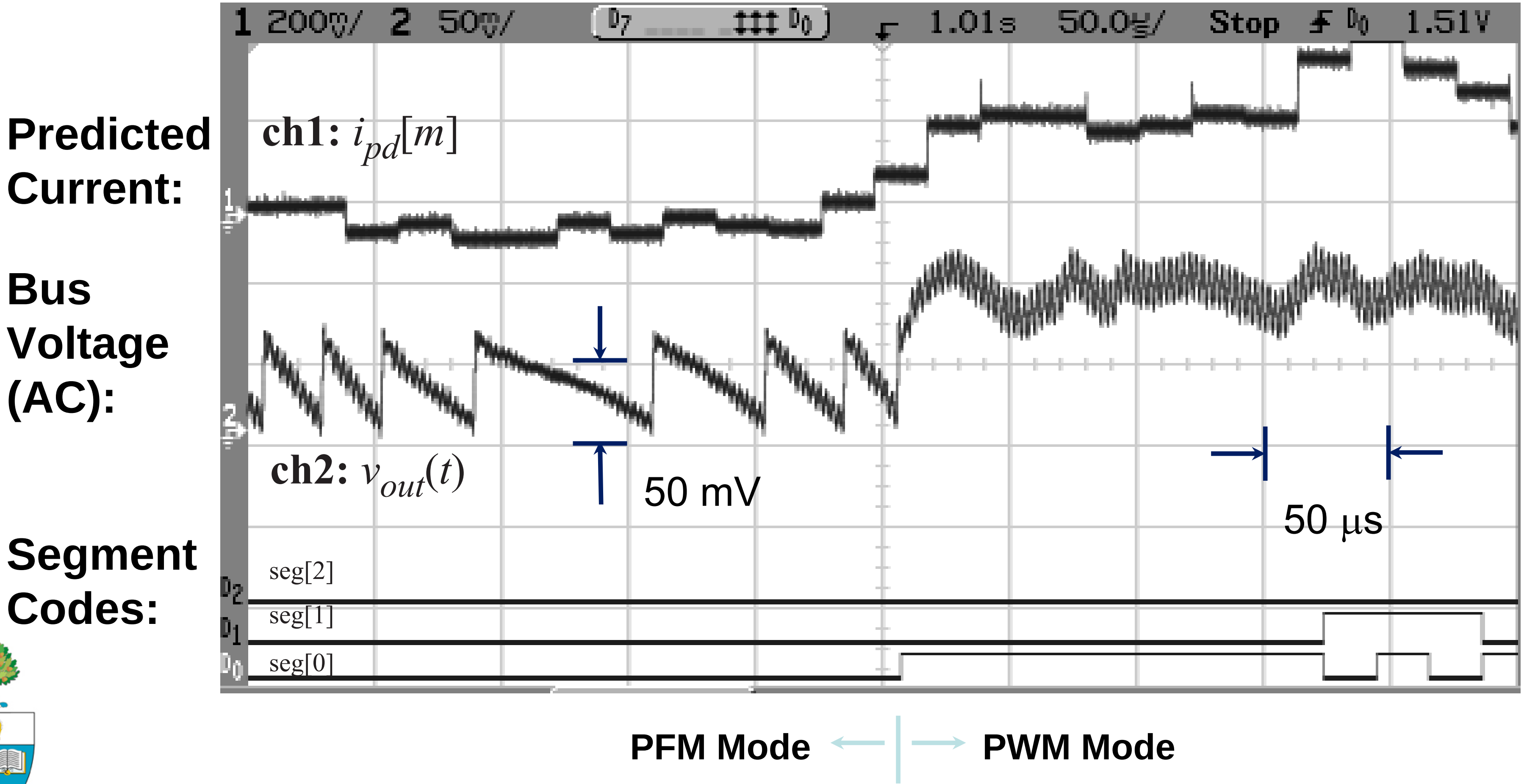


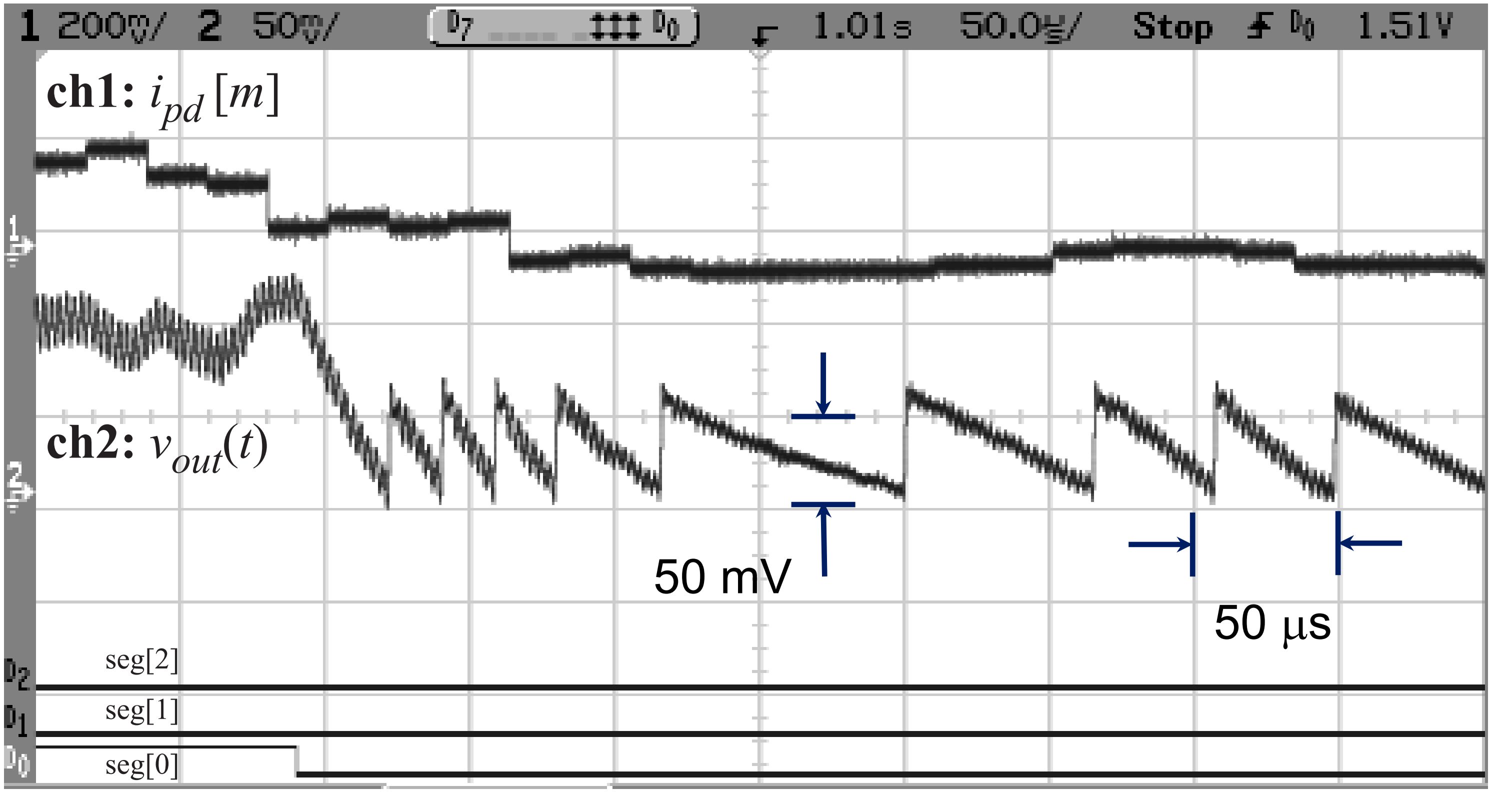
PWM → PFM Operation

- Output stage is dynamically re-sized according to predicted speaker current

Predicted Current:

Bus Voltage (AC):

Segment Codes:



PWM Mode ← | → **PFM Mode**

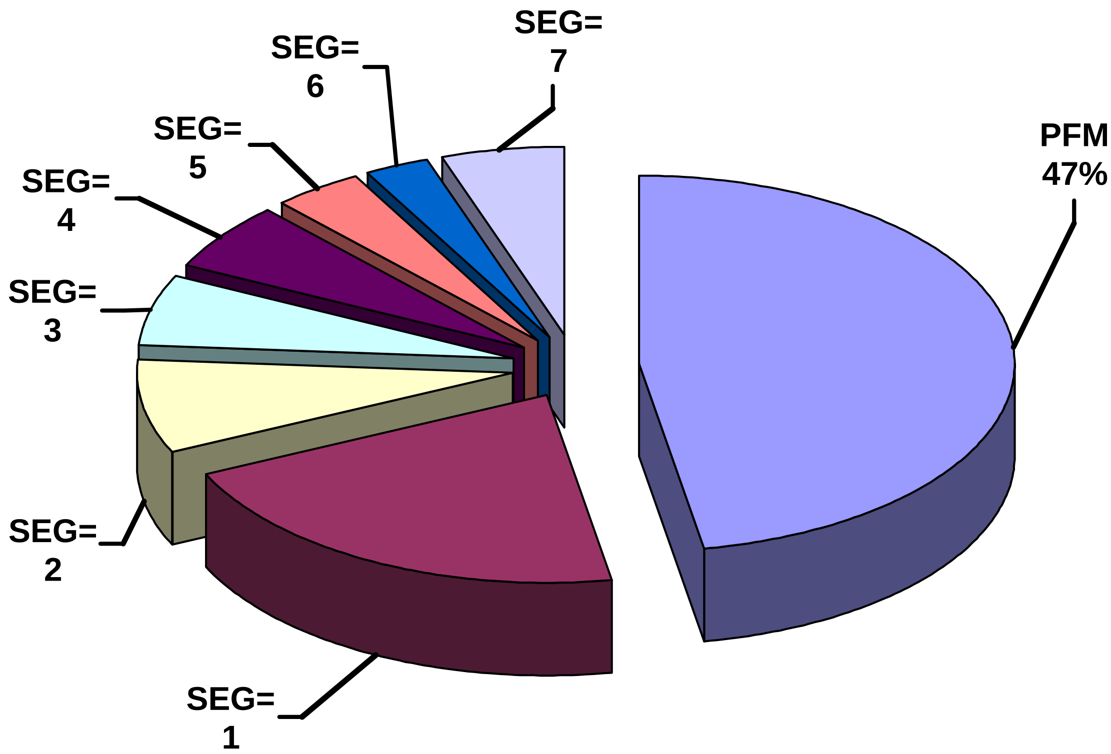
Total Energy Consumption Comparison

- The energy savings is highly dependent on the power distribution of the music sample
- For a given dynamic range, the power savings depends on the amount of time spent in each power bin
  - Rock music has the lowest energy savings (most time spent with seg = ‘111’)
  - Jazz music has the highest energy savings

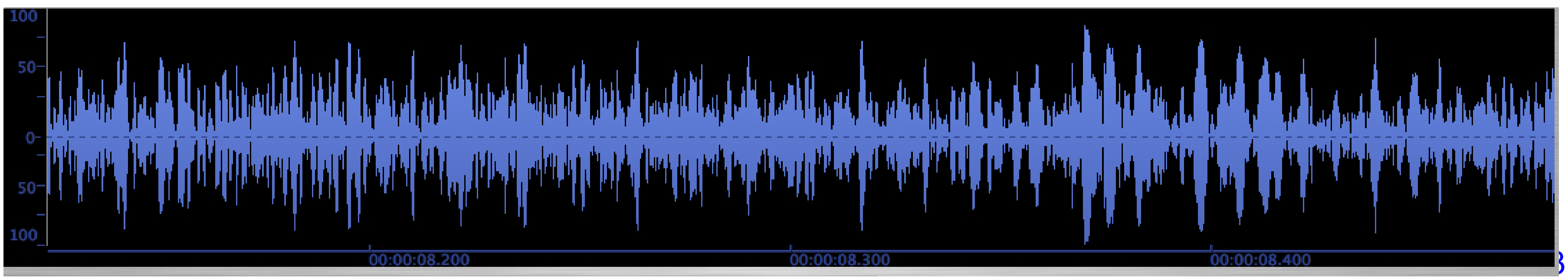
Song Type	Length (s)	Total Energy Consumption (J) @ V_{batt} = 3.6 V		Energy Savings (%)
		PWM Mode, All segments *ON*	Automatic Segment / Mode Control	
1. Rock	149	11.16	8.80	**21.15**
2. Classical	380	23.77	17.18	**27.70**
3. Jazz	140	7.08	4.36	**38.32**

Segment Distribution

- # of samples for each segment code can be determined through audio post-processing



- Audio sample:



Conclusion and On-going Work

- Demonstrated a feed-forward concept to improve energy efficiency in portable applications
- Experimental results reported for a miniature Class-D amplifier
- Maximum of 38 % in total energy savings was achieved
- Energy savings depends on dynamic content of music
- Effect on distortion ?