A Micropower Programmable DSP Powered Using a MEMS-Based Vibration-to-Electric Energy Converter

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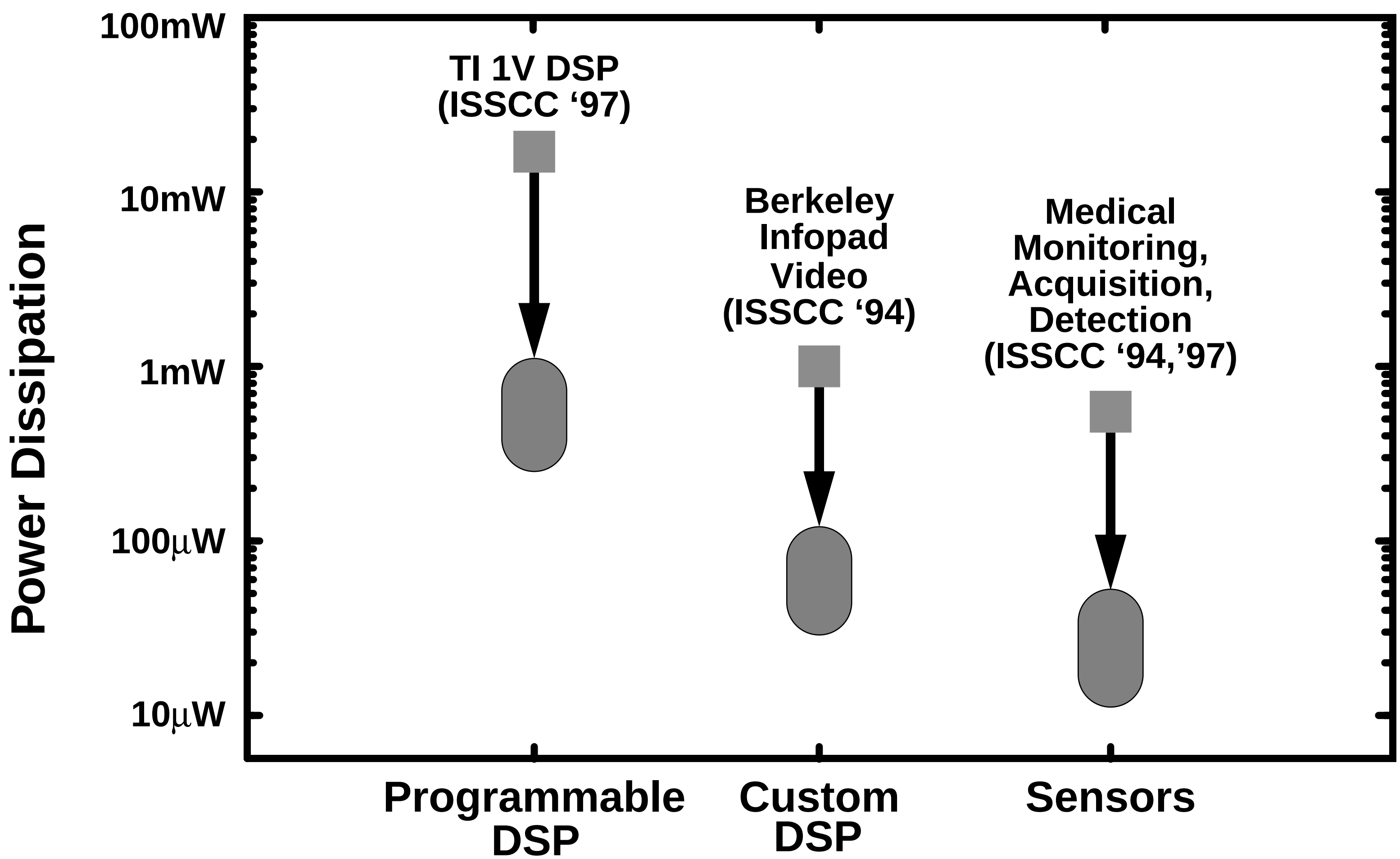
Power Trends for DSP



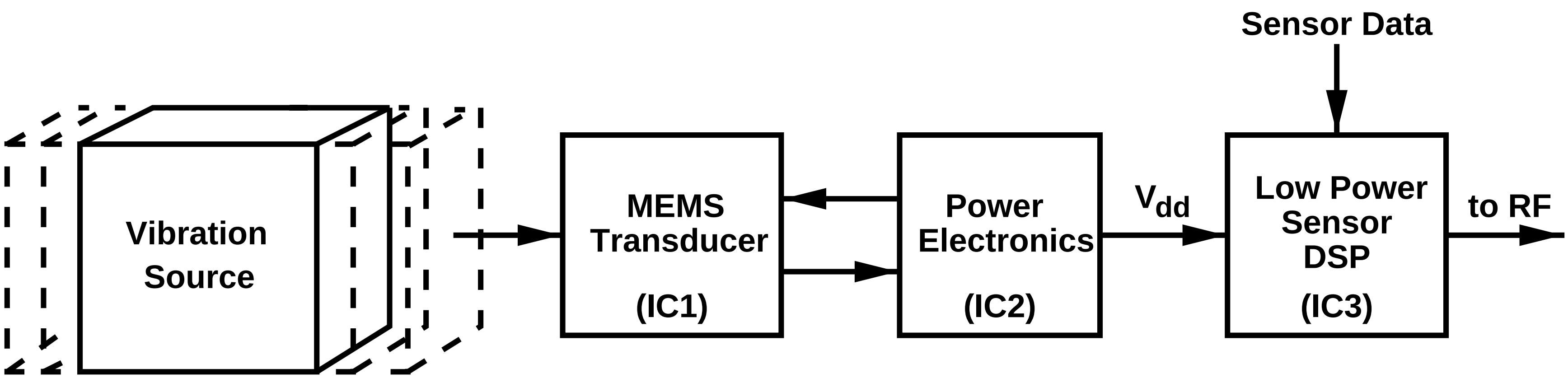
Can we use ambient energy sources to power electronics?

Sources of Ambient Energy

- Solar Power
- Electromagnetic Fields
- Thermal Gradients
- Fluid Flow
- **Mechanical Vibration**
  - Machine mounted sensors
  - Body area sensors

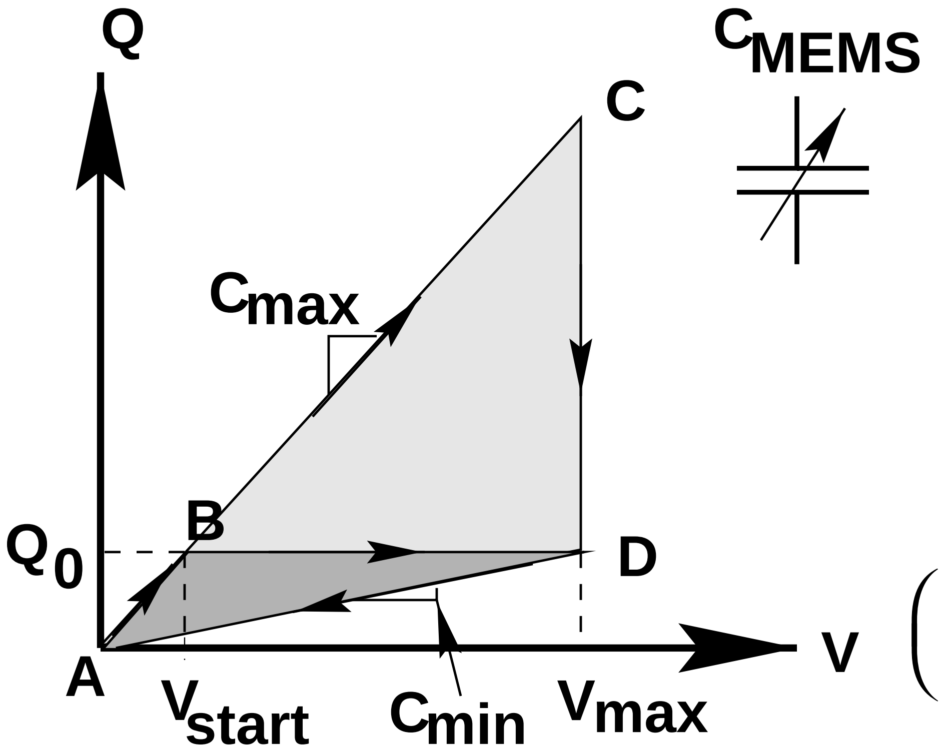
⋮

Self-Powered System Block Diagram



- Ultra low power DSP enables operation using scavenged energy
- MEMS implementation compatible with future systems-on-a-chip
- DSP energy scalability enables tradeoff between quality and available energy

Energy Conversion Cycle



Voltage Constrained ACD:

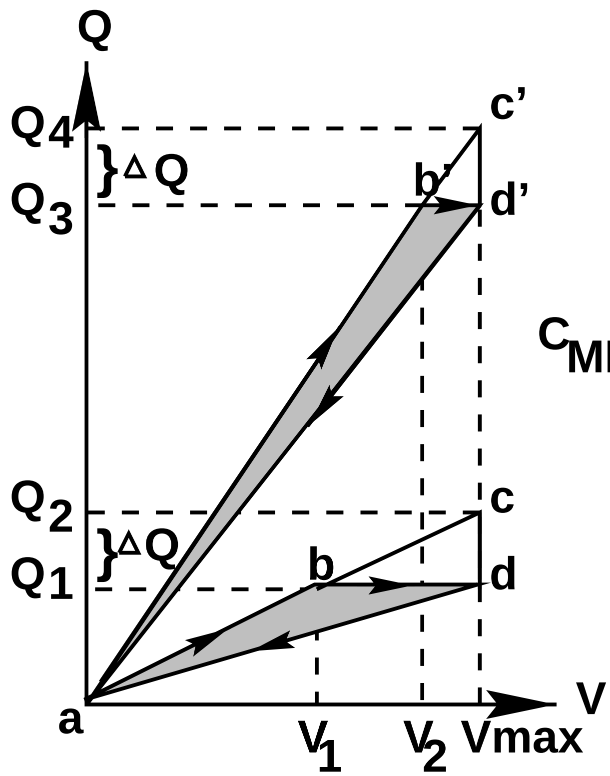
$$\left(\frac{1}{2}C_{max} - \frac{1}{2}C_{min}\right)V_{max}^2$$

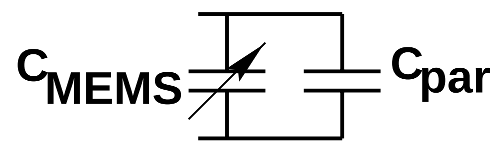
Charge Constrained ABD:

$$\left(\frac{1}{2}C_{max} - \frac{1}{2}C_{min}\right)V_{max}V_{start}$$

Can we get voltage constrained energy with easier implementation?

Modified Charge Constrained Conversion



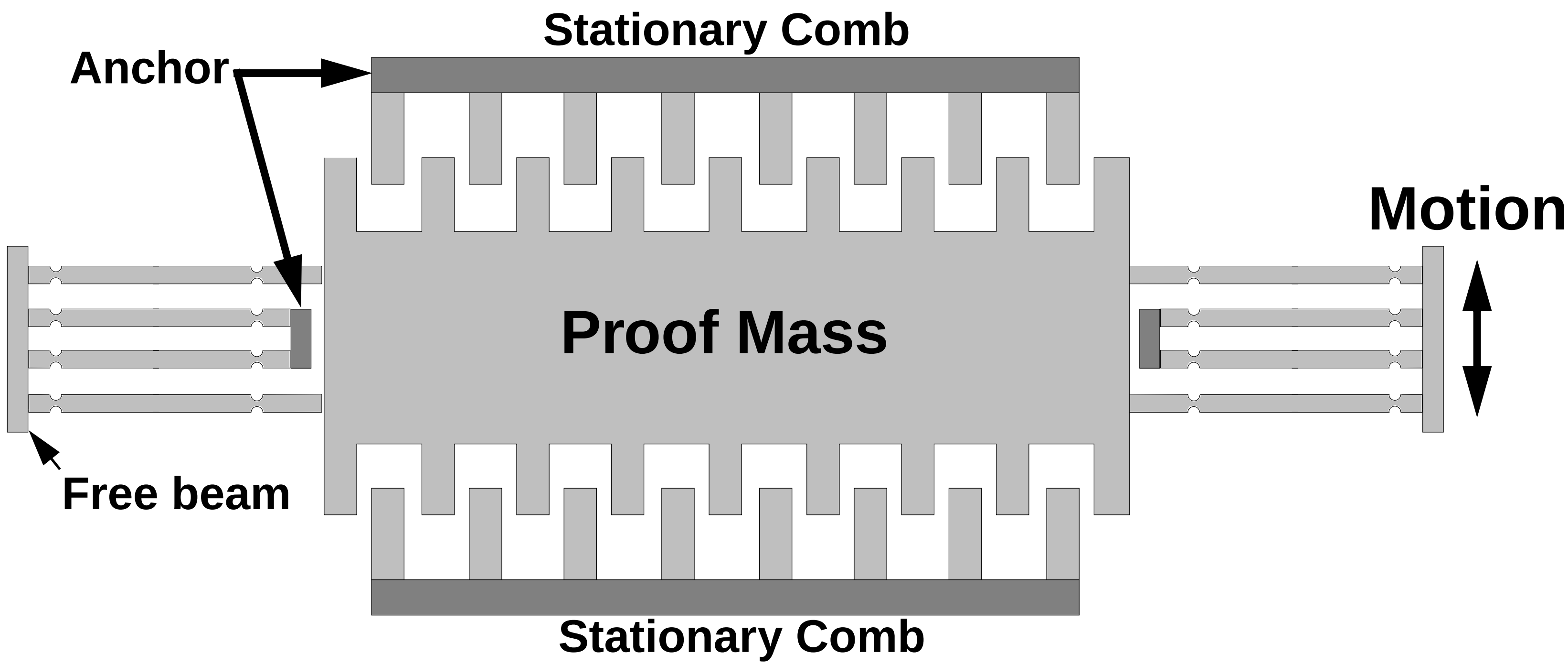


0 if $C_{par} \rightarrow \infty$

$$E_{chrgconstr} = E_{voltconstr} - \frac{(\Delta Q)^2}{2(C_{par} + C_{max})}$$

$$\mathbf{E_{chrgconstr}} \longrightarrow \mathbf{E_{voltconstr}}$$

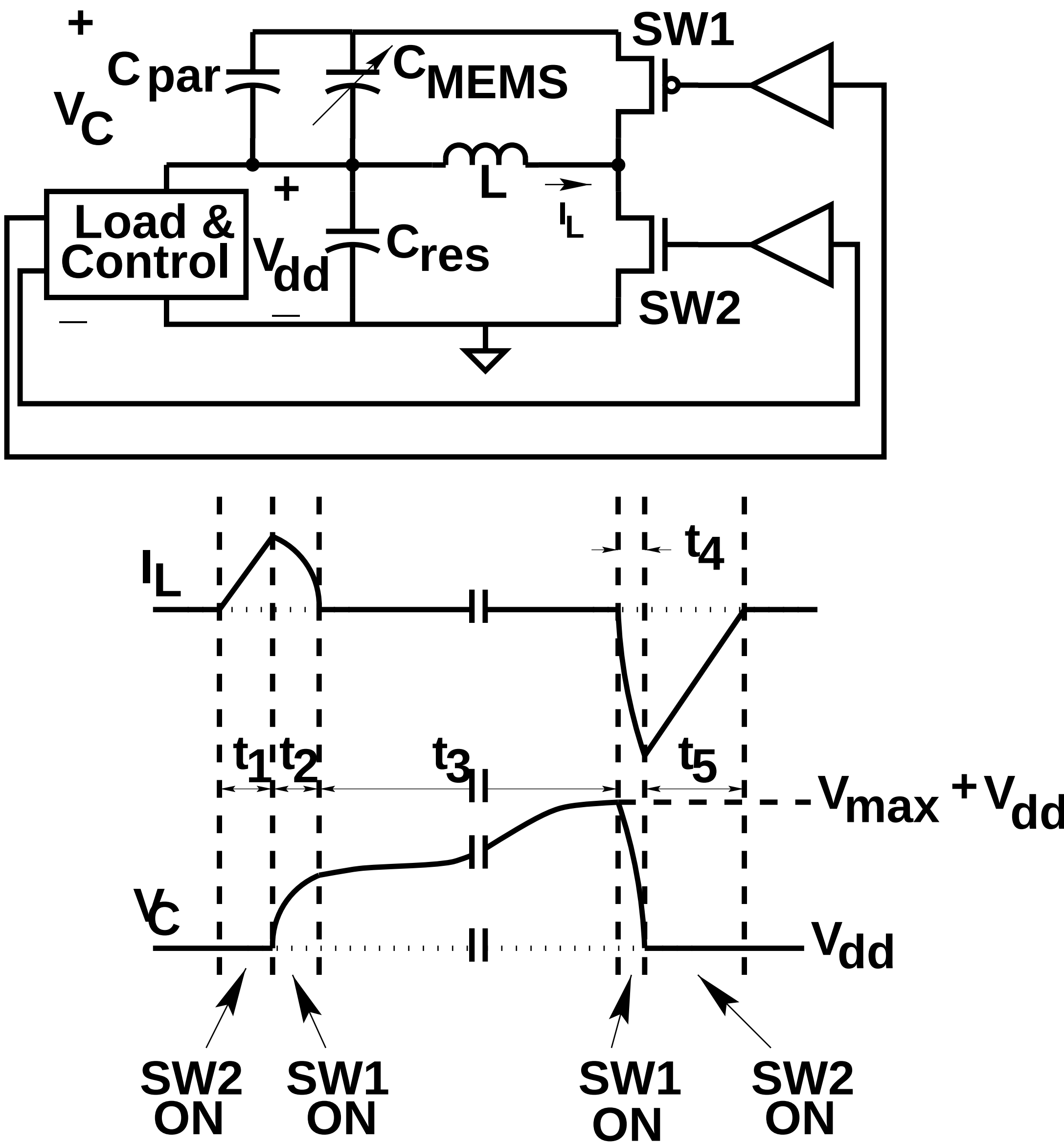
MEMS Capacitor Transducer



- Vibration moves plates
- This is used as a transducer

- C_{min} = 2 pF
- C_{max} = 258 pF
- Device size: 1cm X 0.5cm

Power Electronics (Single Phase)



1: Charge L from C_{res}

2: Charge C_{MEMS} from L

3: Vibration moves C_{MEMS} fingers apart

4: Charge L from C_{MEMS}

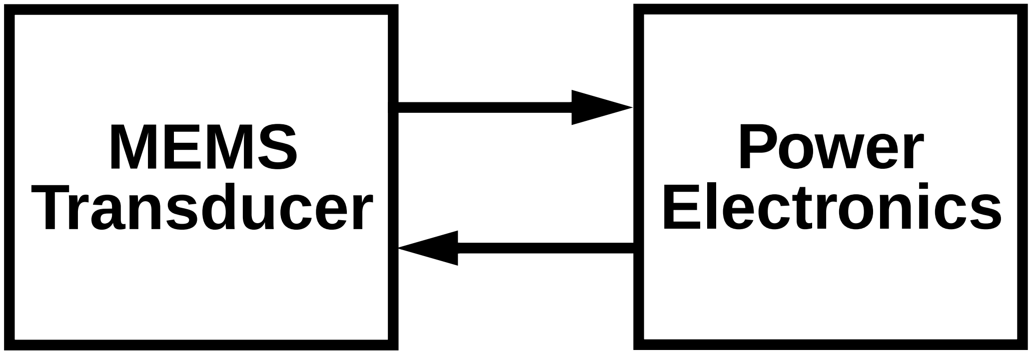
5: Charge C_{res} from L

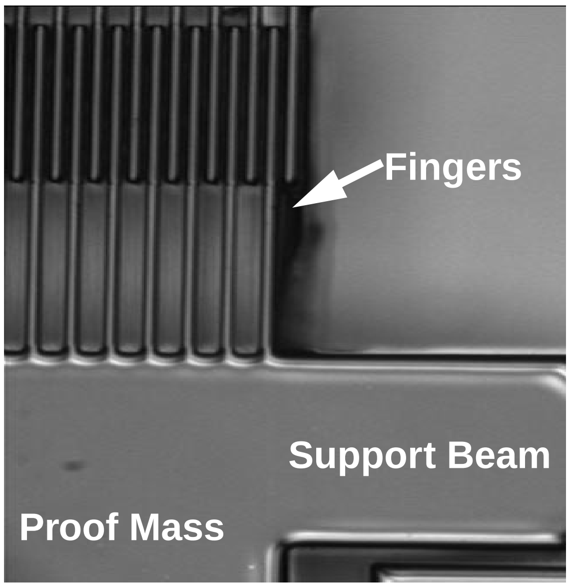
- Mechanical vs Electrical τ

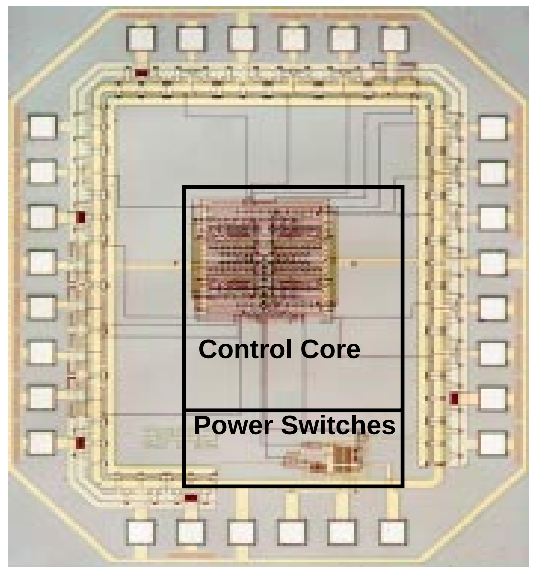
$$T_{LC} \sim 500nS$$

$$T_{vibration} \sim 400\mu S$$

Energy Harvesting Module







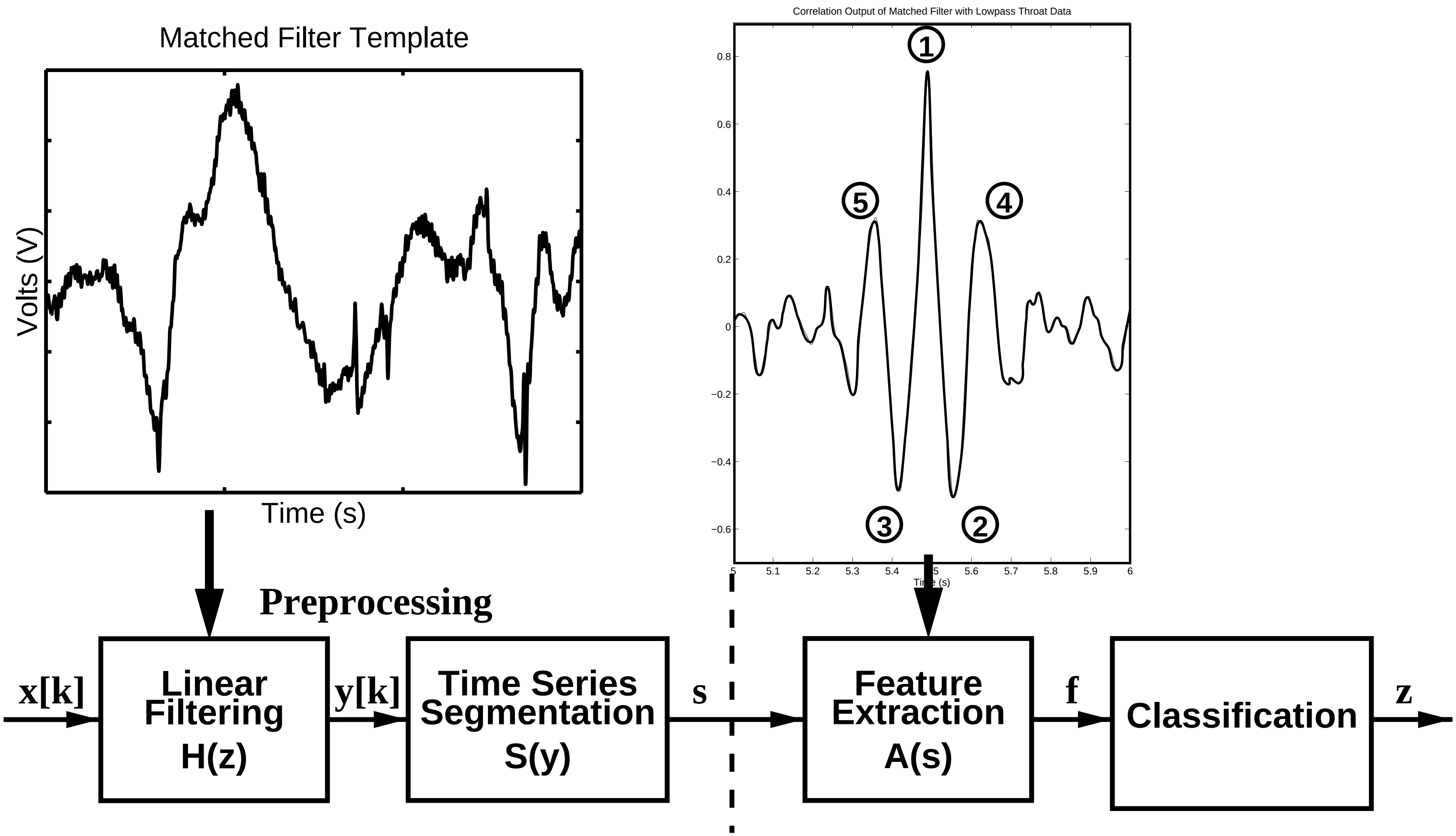
Core Power:
(measured)
456nW

Switch Power:
(measured)
3.87μW

Power Output:
(predicted)
4.29μw

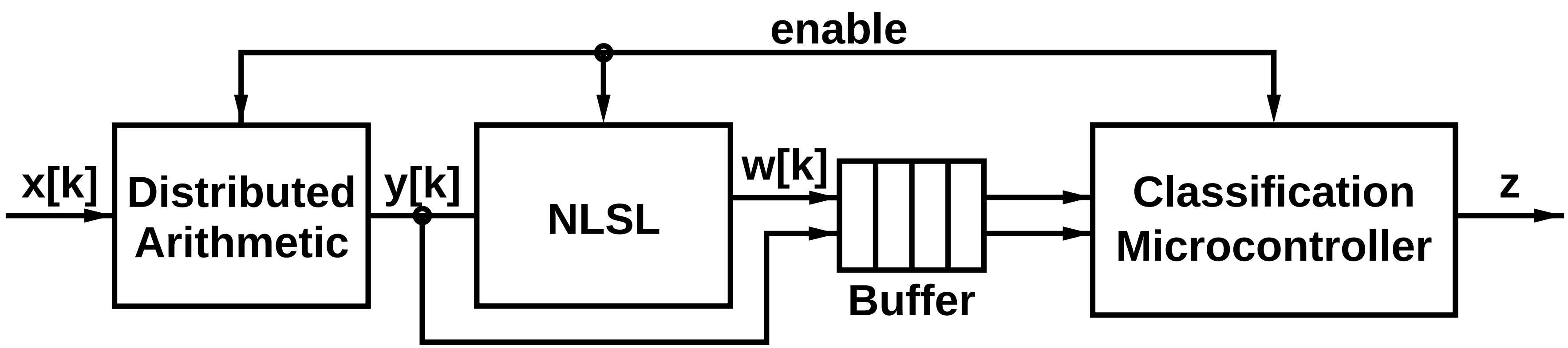
Functional and being characterized

Detection & Classification Algorithm



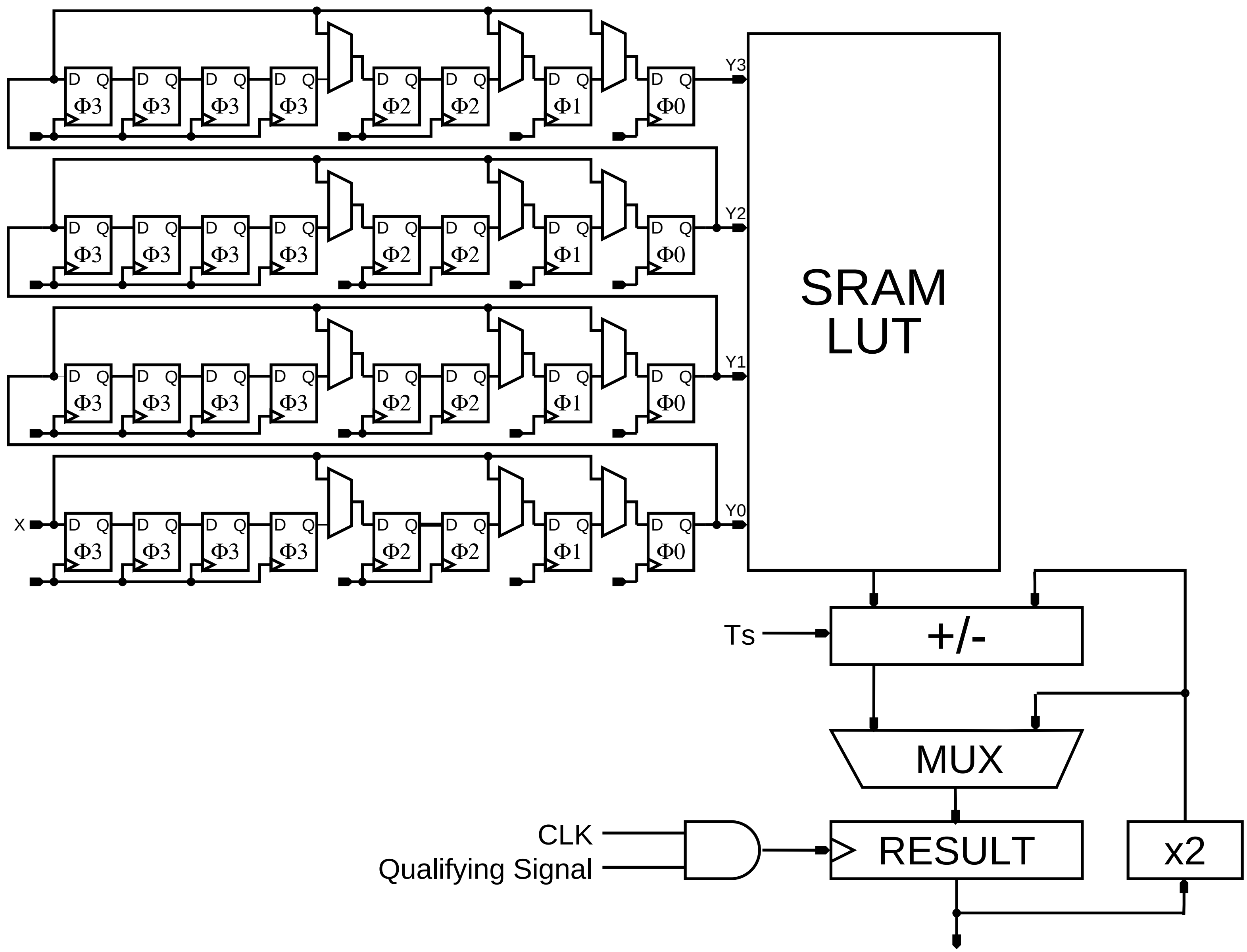
- **All Software Implementation: Preprocessing Dominates Hardware Use**

Sensor DSP Chip Architecture

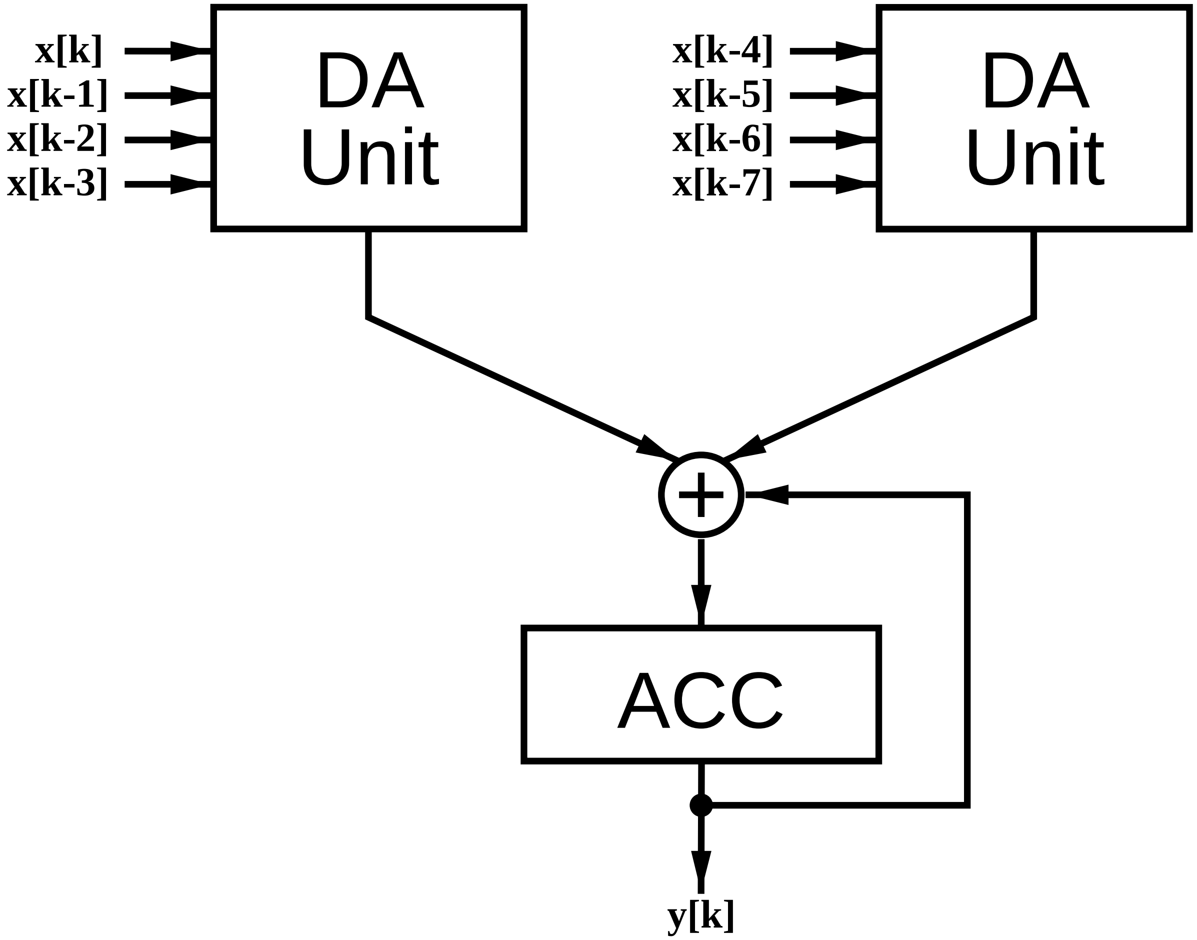


- **Preprocessing:**
  - DA Unit implements matched filter efficiently
  - NLSL Filter Unit optimizes energy computation
  - Buffer stores preprocessed data
- **Classification:**
  - Microcontroller implements classifier

Distributed Arithmetic Implementation



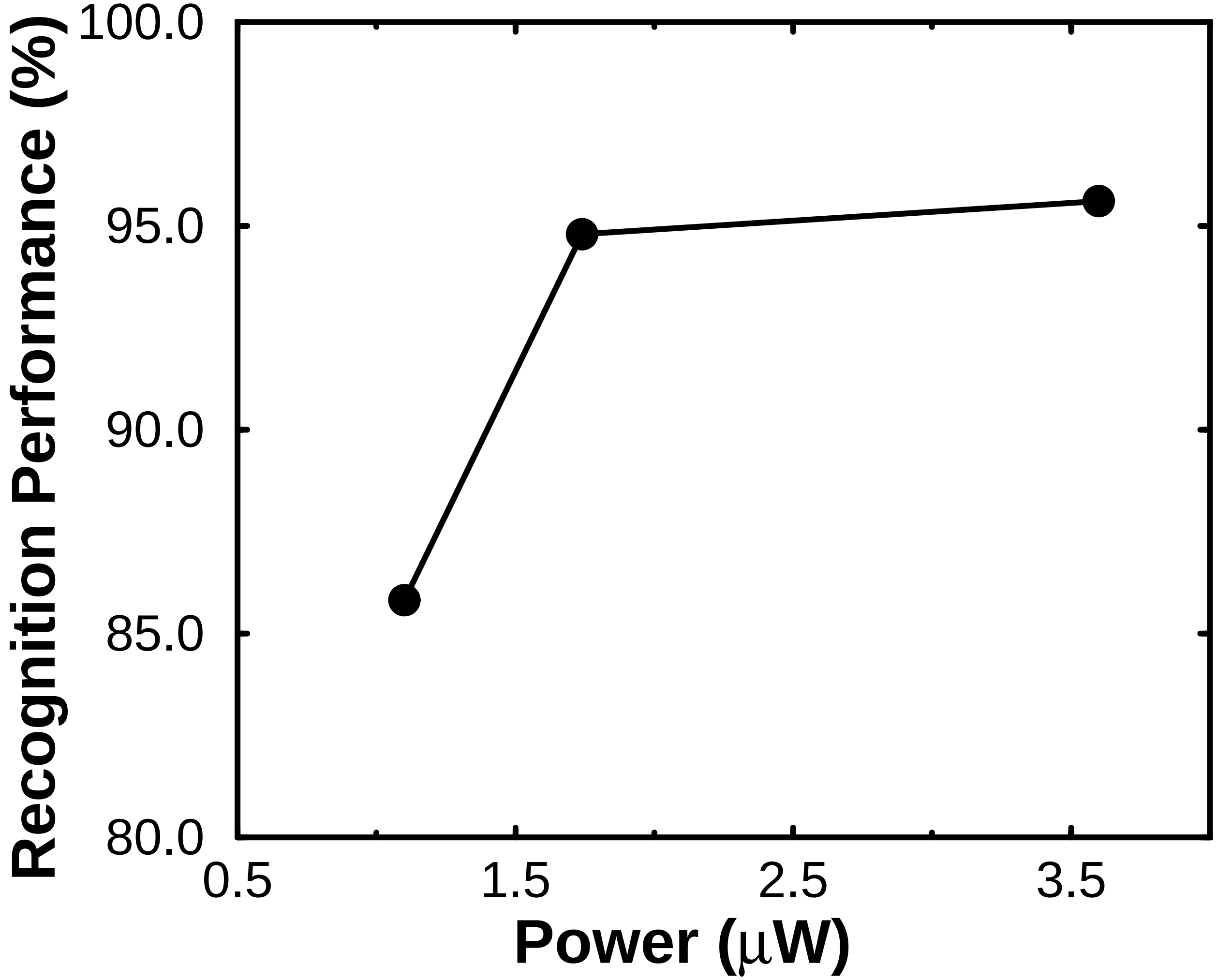
Distributed Arithmetic Filter



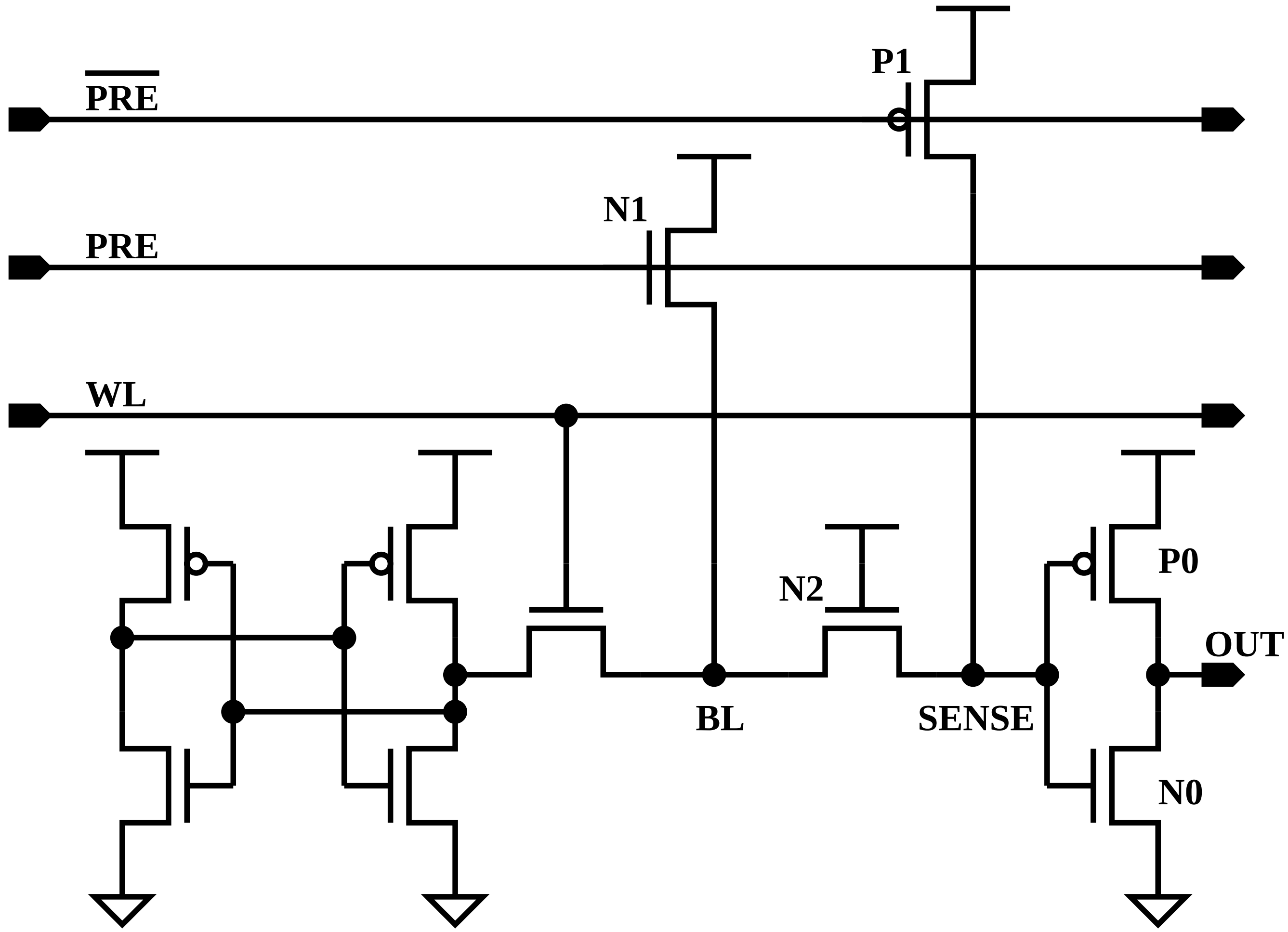
- Distributed bit serial filtering technique
  - Allows computation and power to scale with input data bitwidth

Power Scalable Classification

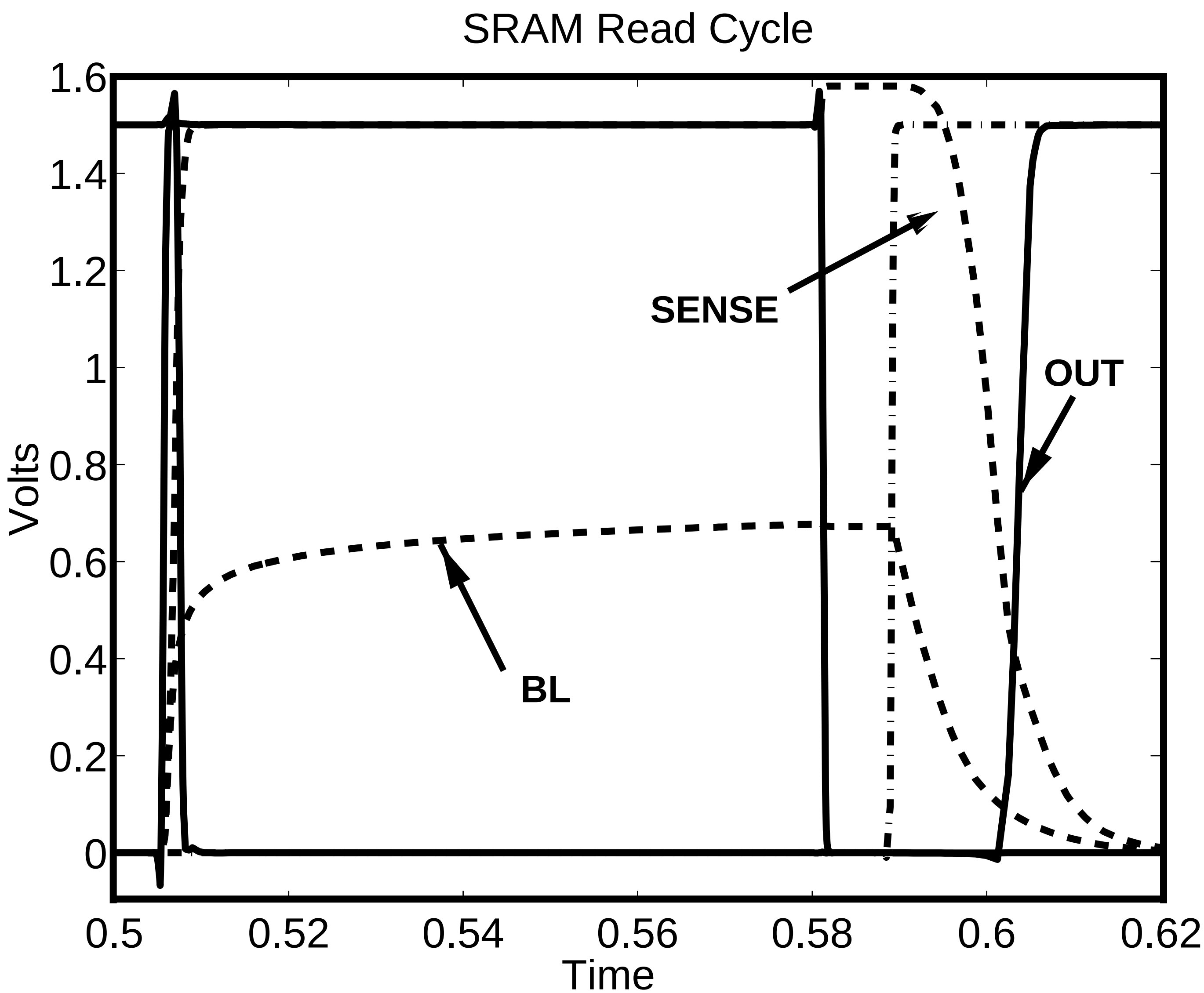
Recognition Performance vs. DA Unit Power



Low Voltage SRAM Sense Amplifier

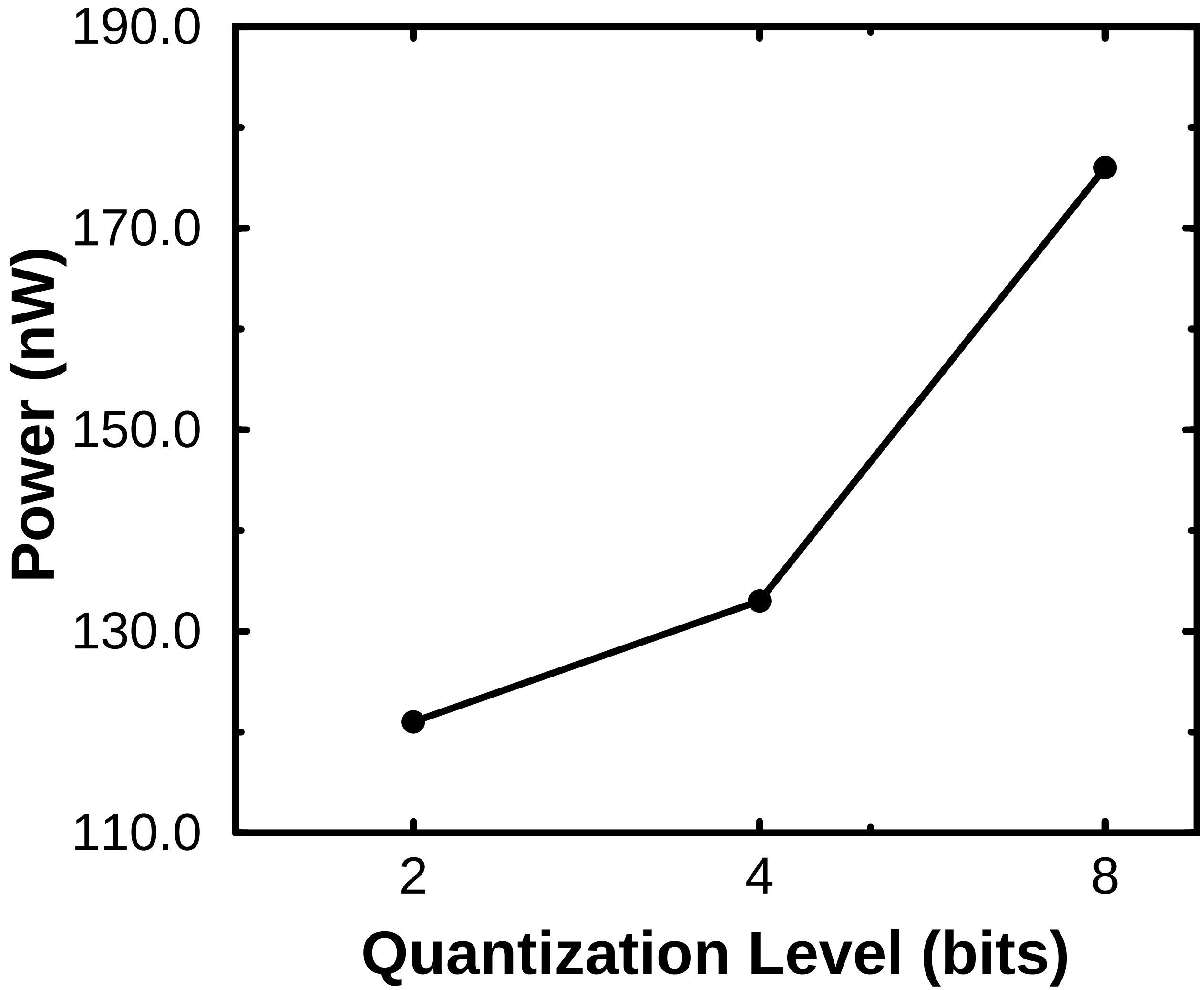


SRAM Read Cycle

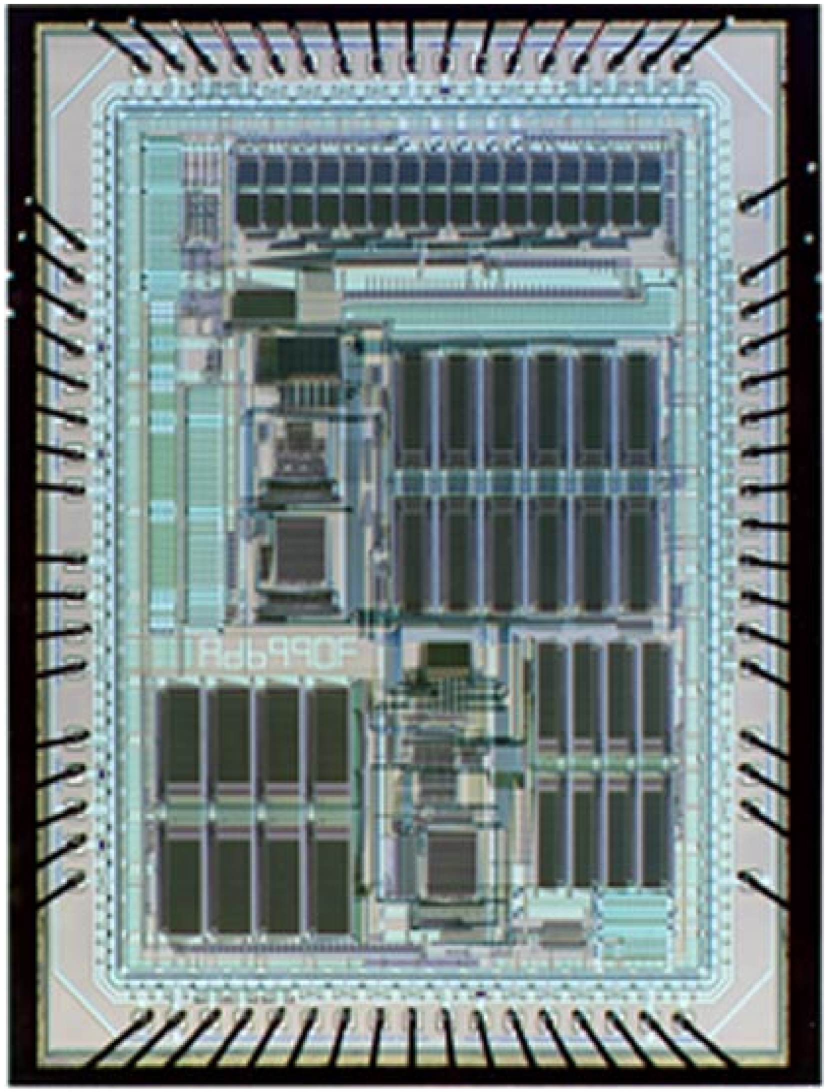


Power Scalable Preprocessing

Chip Power vs. Input Quantization Level



Sensor DSP Die Photo



- 0.6 μm CMOS process
- 4.4 mm x 5.8 mm
- 190K transistors
- V_{dd} = 1.5V
- 1.2 kHz/ 250 kHz clock
- Core Power: 560 nW
- Chip Energy:
  26.6 pJ/sample
- StrongARM SA-110
  Energy: 11 μJ/sample

Conclusions

- Net power of 4 μW delivered from ambient mechanical vibration
- Ultra low power control framework enables positive delivered power
- Integrating energy scavengers into ultra low power DSP enables batteryless operation
- Energy scalable algorithms and architectures enable power/performance tradeoffs for sensor signal processing