Switched-Capacitor Converters: Big & Small

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Outline

- Problem & motivation
- Applications for SC converters
- Switched-capacitor fundamentals
- Power conversion for energy-harvesting sensor nodes
- SC converters for microprocessors
- Conclusions

Problem & Motivation

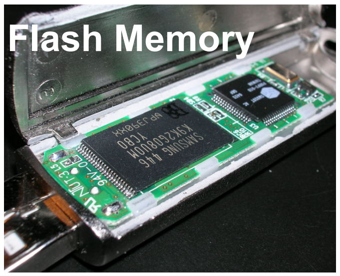
- Inductor-based Converters:
  - – Cannot be integrated
  - – The inductor is often the largest and most expensive component
  - – Causes EMI issues
  - \+ Efficient at arbitrary conversion ratios
- Switched-capacitor (SC) converters:
  - \+ Can easily be integrated
  - \+ No inductors
  - \+ EMI well controlled
  - – Efficient at a single (or a few) conversion ratios

Applications

Existing:

Proposed:

Flash Memory

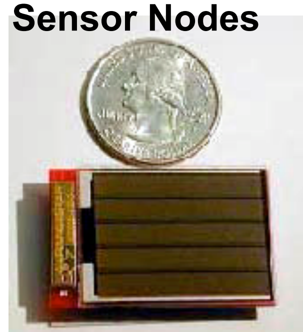


LED Lighting

Microprocessors

RS-232 Interfaces

Sensor Nodes

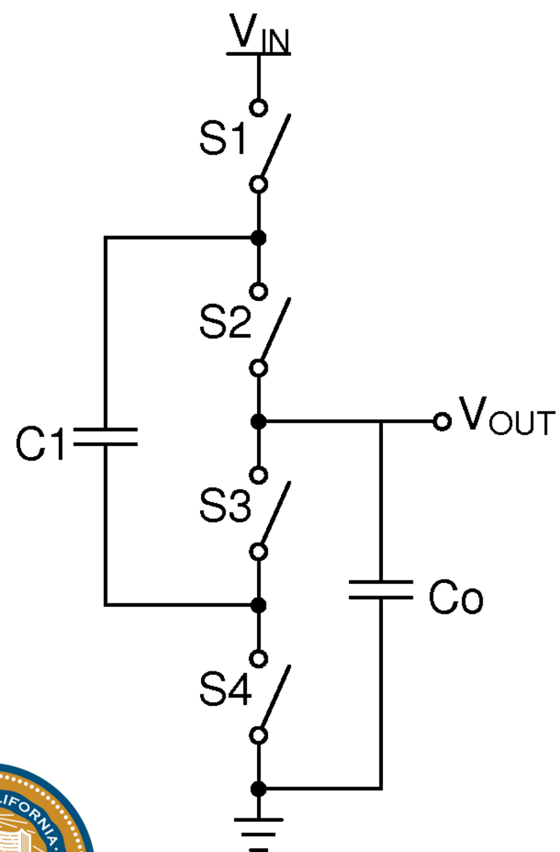


Motor Drive

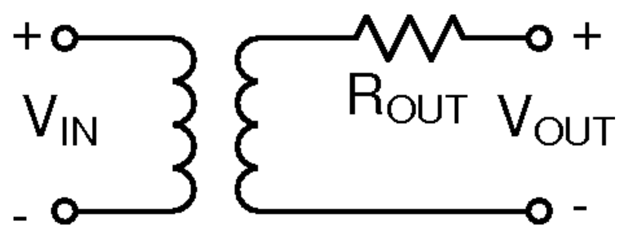
And more…

Switched-Capacitor Fundamentals

Simple 2:1 converter:



- The flying capacitor C1 shuttles charge from V_{IN} to V_{OUT}.
  - Fixed charge ratio of 2:1
- A voltage sag on the output is necessary to facilitate charge transfer
- Fundamental output impedance:



Switched-Capacitor Losses

Capacitor Losses:

Charge transfer loss:

$$P_{SSL} = I_{OUT}^2 \sum_{caps} \frac{a_{c,i}^2}{C_i f_{sw}}$$

Bottom plate loss:

$$P_{CAP} = f_{sw} \sum_{caps} \alpha C_i V_i^2$$

Switch Losses:

Resistive loss:

$$P_{FSL} = 2 I_{OUT}^2 \sum_{switches} a_{r,i}^2 R_i$$

Parasitic loss:

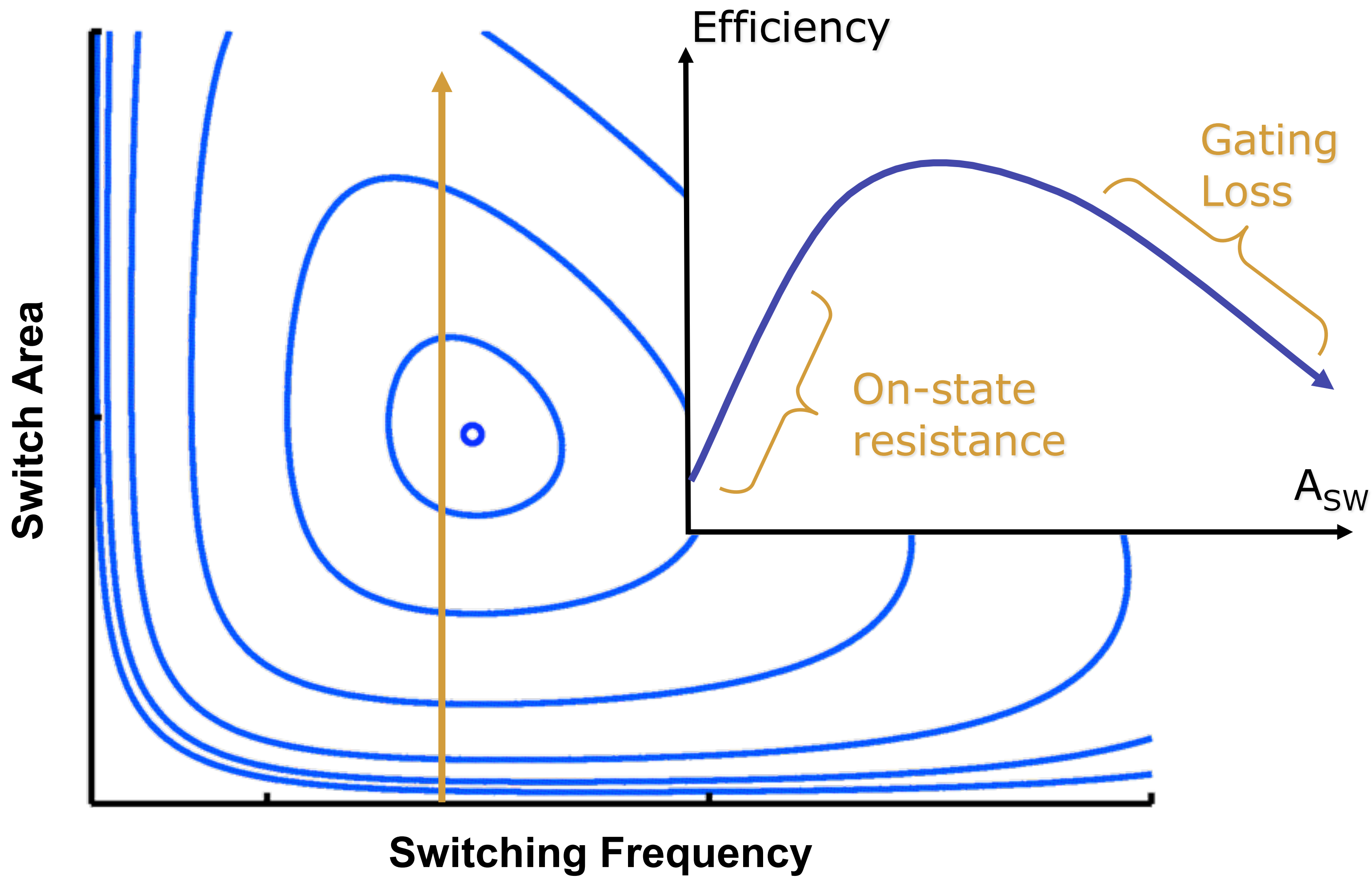
$$P_{SW} = f_{sw} \sum_{switches} C_{GS,i} V_{GS}^2 + C_{DS,i} V_{DS}^2$$

Contributes to R_{OUT}, V_{OUT}

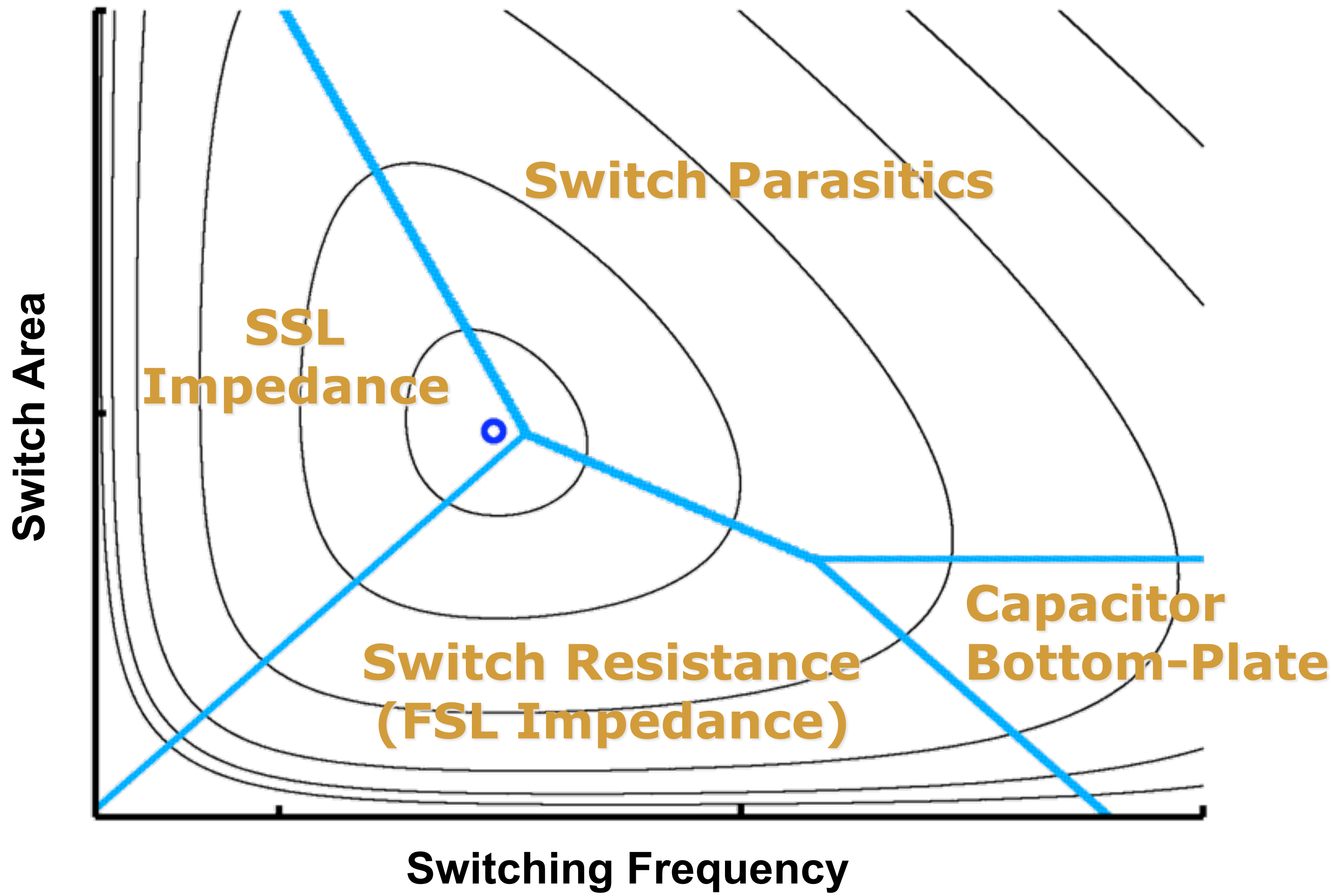
No direct R_{OUT} contribution

[1] Seeman, Sanders, "Analysis and Optimization of Switched-Capacitor Converters," IEEE TPEL, Mar. 2008.

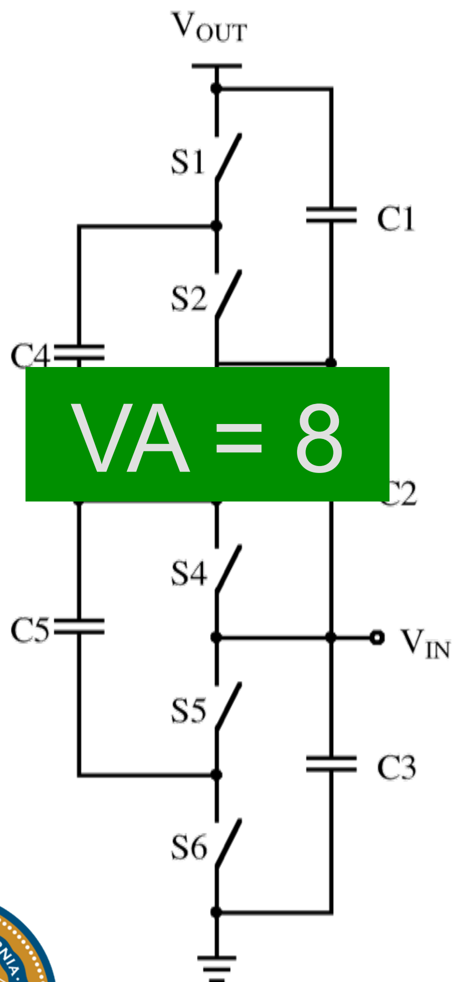
Performance Optimization



Performance Optimization



Comparison vs. Boost



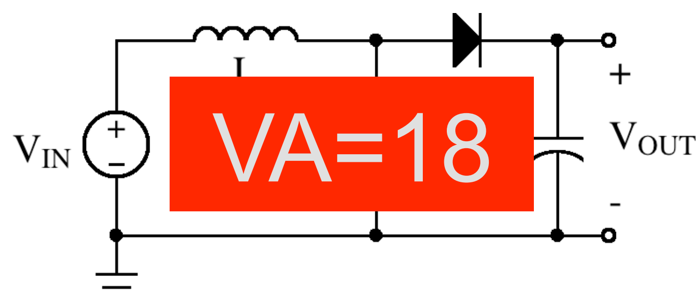
1 V to 3 V Boost: 1A out

1:3 SC Ladder: 6 Switches

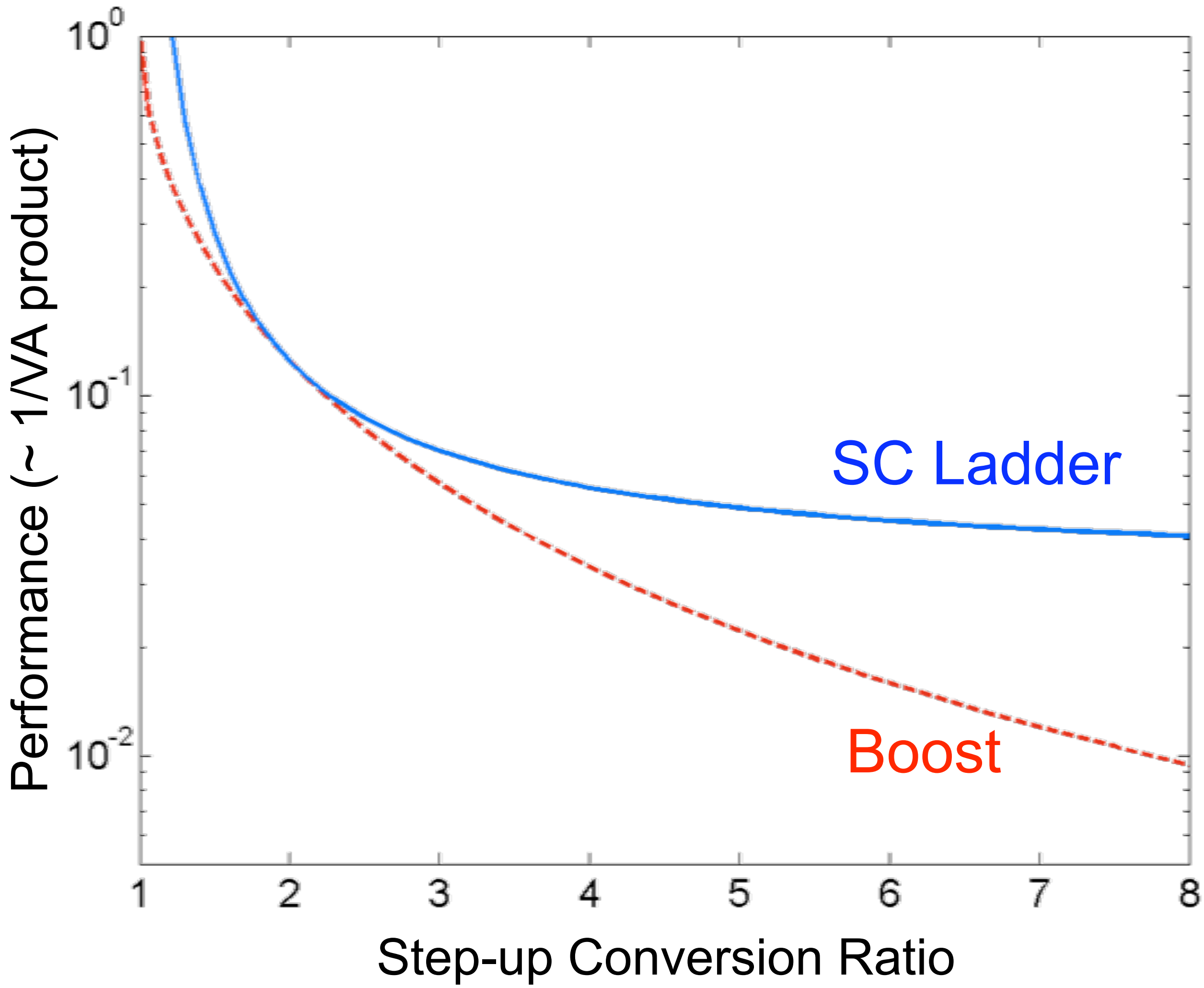
- Top 4: 1 V, 1 A
- Bottom 2: 1 V, 2 A

1:3 Boost: 2 switches

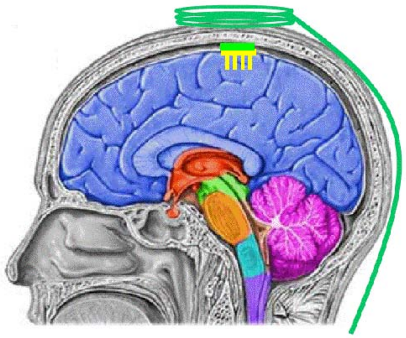
- Each: 3 V, 3 A

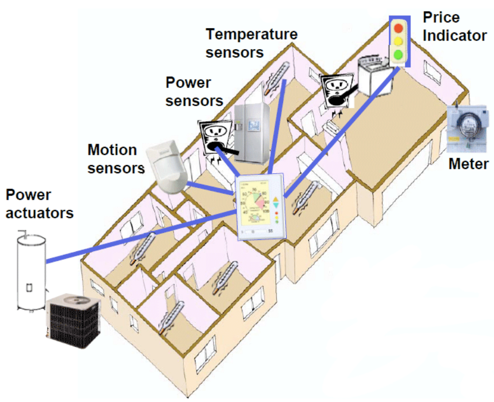


Comparison vs. Boost



Wireless Sensor Node Converters

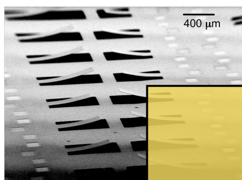


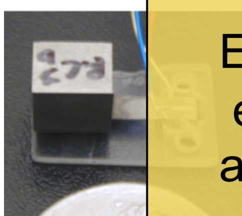
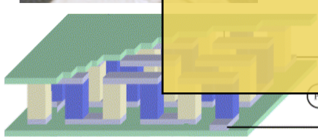
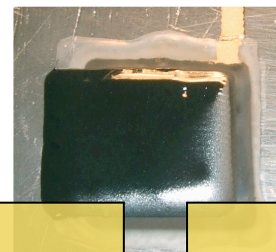
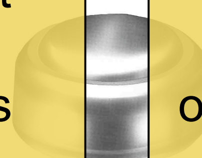
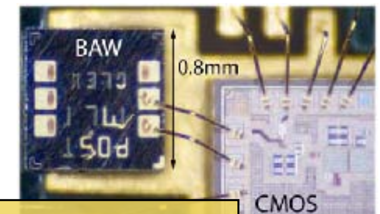


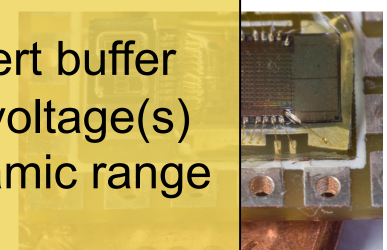
- Distributed, inexpensive sensors for a plethora of applications
- Batteries and wires increase cost and liability
- Low-bandwidth and aggressive duty cycling reduces power usage to microwatts
- Miniaturization expands application space

Node Structure

Energy Harvester → Power Conditioning → Energy Buffer → Power Conversion → IC Loads



Efficiently convert input energy when it occurs and at varying voltages

Efficiently convert buffer voltage to load voltage(s) over a large dynamic range

Environmental Energy

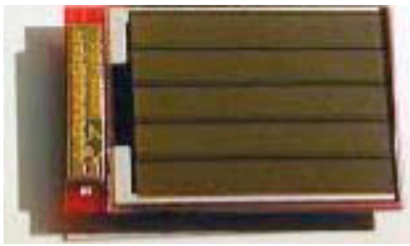
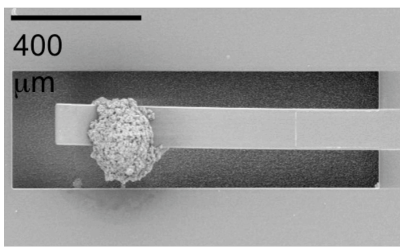
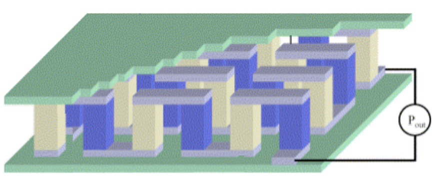
Power Source	Power [μW/cm^3]	Notes
Solar (outside)	15,000	(per square cm)
Solar (inside)	30	(per square cm)
Temperature	40-5,000	(per square cm, 5 K gradient)
Air flow	380	(5 m/s, 5% efficiency)
Pressure variation	17	
Vibrations	375	

AC appliances vibrate at multiples of 60 Hz!

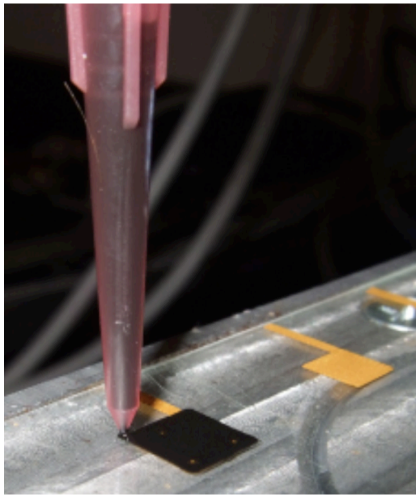
Vibration Source	Frequency [Hz]	Peak Acceleration [m/s^2]
Clothes Dryer	121	3.5
Small Microwave Oven	121	2.25
HVAC vents in office building	60	0.2-1.5
Wooden Deck (with people walking)	385	1.3
External Windows (next to busy street)	100	0.7
Refrigerator	240	0.1

S. Roundy, et. al., “Improving Power Output for Vibrational-Based Energy Scavengers,” IEEE Pervasive Computing, Jan-Mar 2005, pp. 28-36.

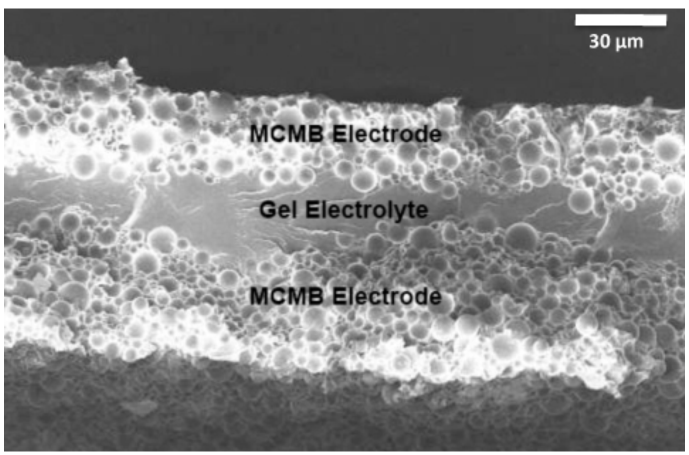
Energy Harvesters

		Voltage	Considerations
Solar		0.6V/cell (outdoors) 0.1V/cell (indoors)	Efficiency drops inside due to carrier recombination and spectrum shift
Vibrational		1-100V (macro) 10mV-1V (MEMS)	Resonance must be tuned to excitation frequency for maximum output, sensitive to variation
Thermal		1-3 µV/K / junction 1mV-1V / generator	Requires large gradient and heat output; low output voltage unless thousands of junctions used

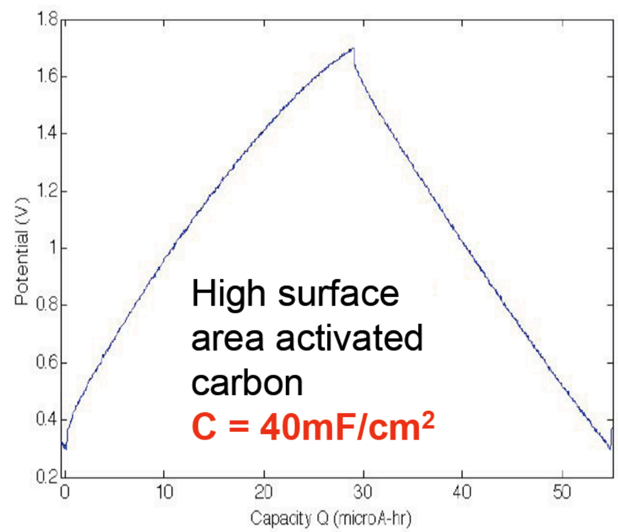
Ultra-compact Energy Storage



- Commercial LiPoly batteries only get down to ~5mAh; 300mg
- Printed batteries and super-capacitors allow flexible placement and size
- Li-Ion and AgZn batteries under development

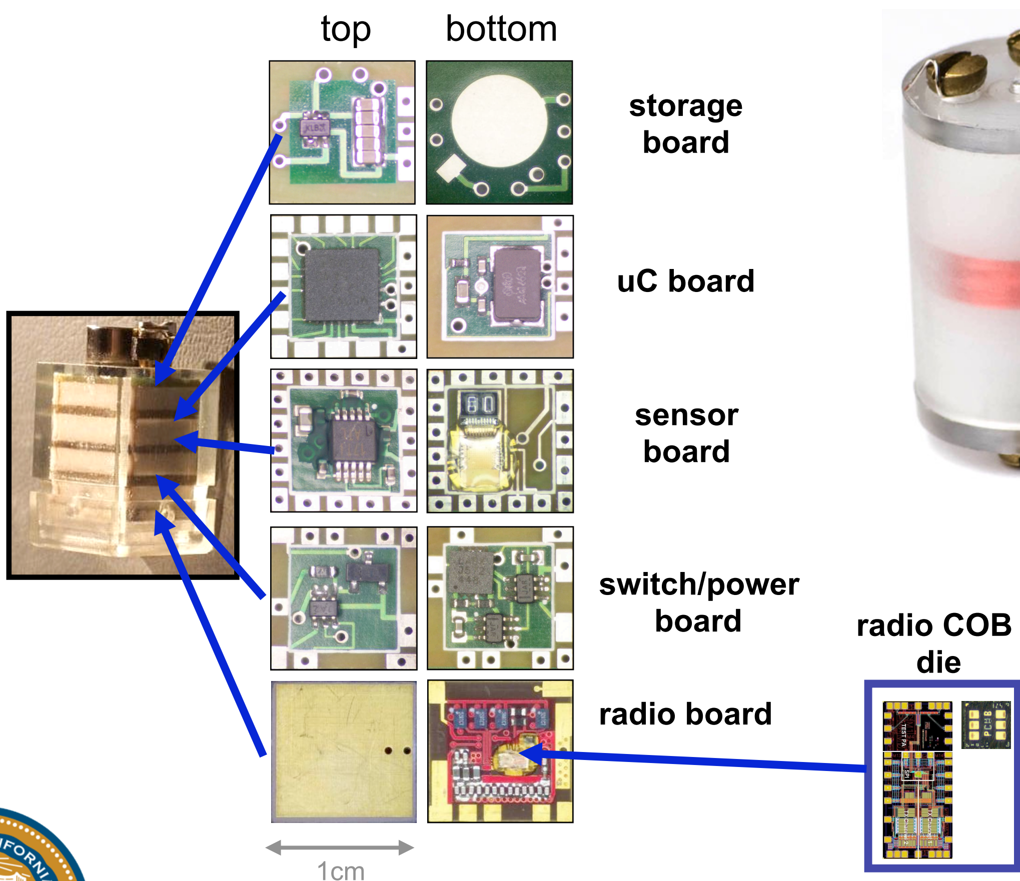


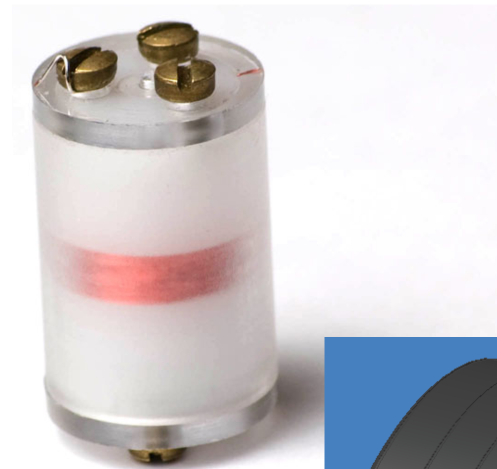
Christine Ho, UC Berkeley



Example: PicoCube TPMS

A wireless sensor node for tire pressure sensing:





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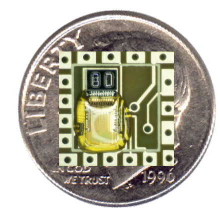
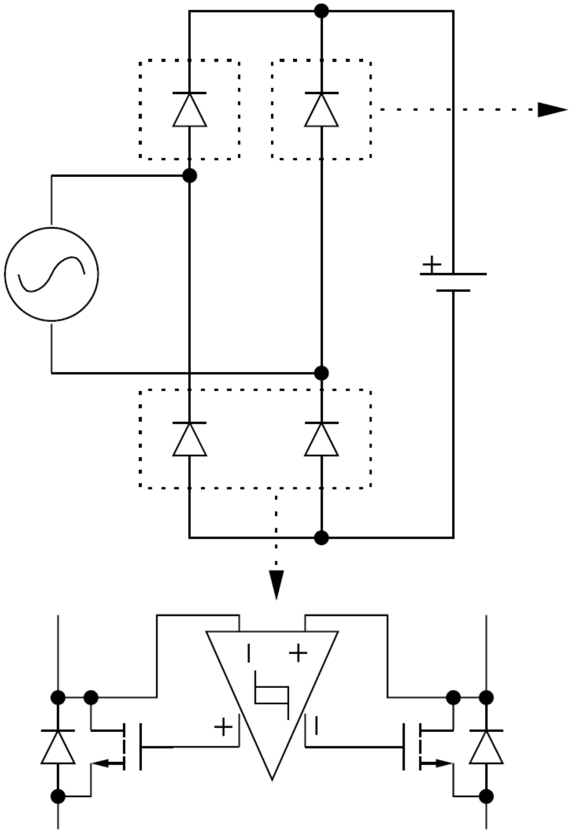
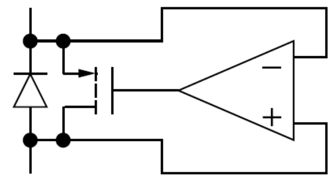


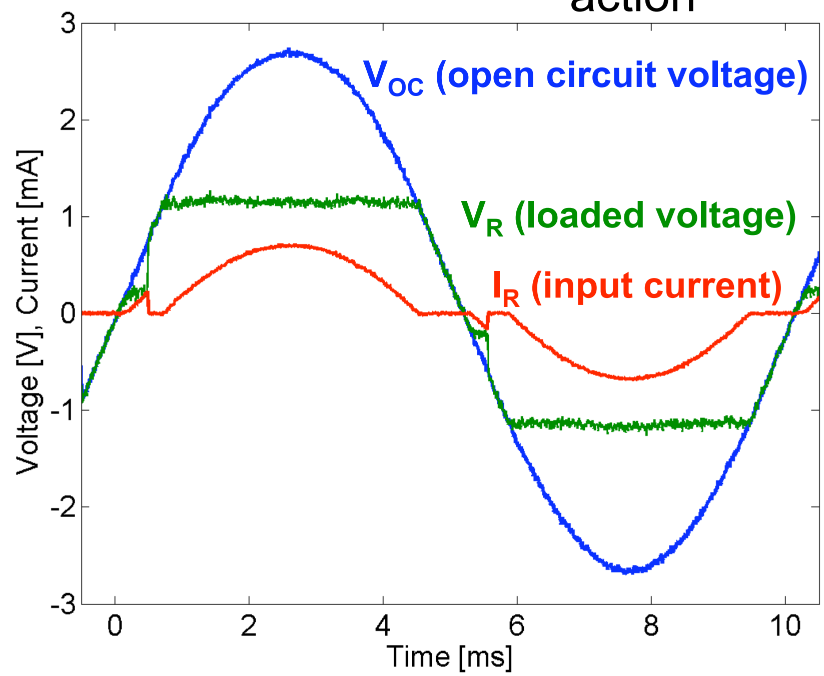
Yuen-Hui Chee, et. al., “PicoCube: A 1cm^3 sensor node powered by harvested energy,” ACM/IEEE DAC 2008, pp. 114-119.

Synchronous Rectifier





High gain amplifier controls high-side switches to provide lossless diode action

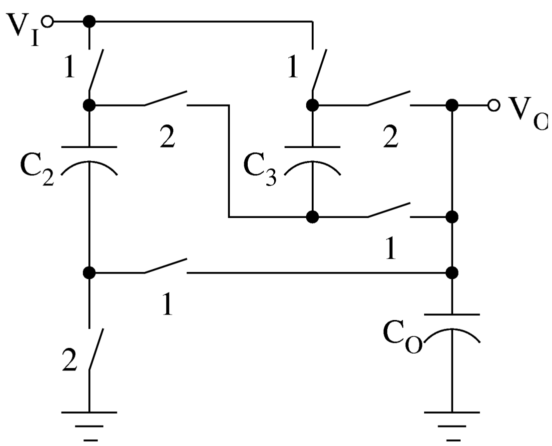


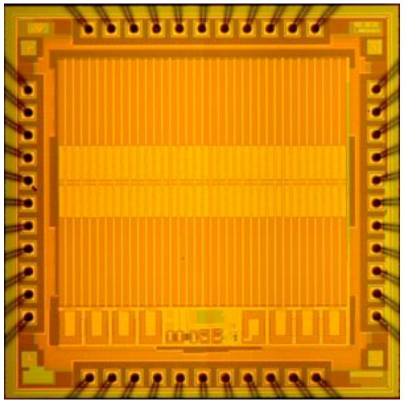
Hysteretic low-side comparator reduces power consumption at zero-input

100 Hz input, 2.1kΩ source impedance

Converter Designs

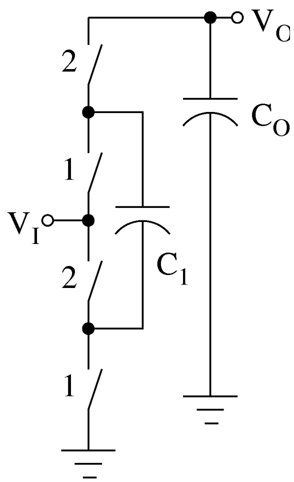
3:2 Converter (0.7V)





STMicro 130nm CMOS
Fall 2007

1:2 Converter (2.1V)



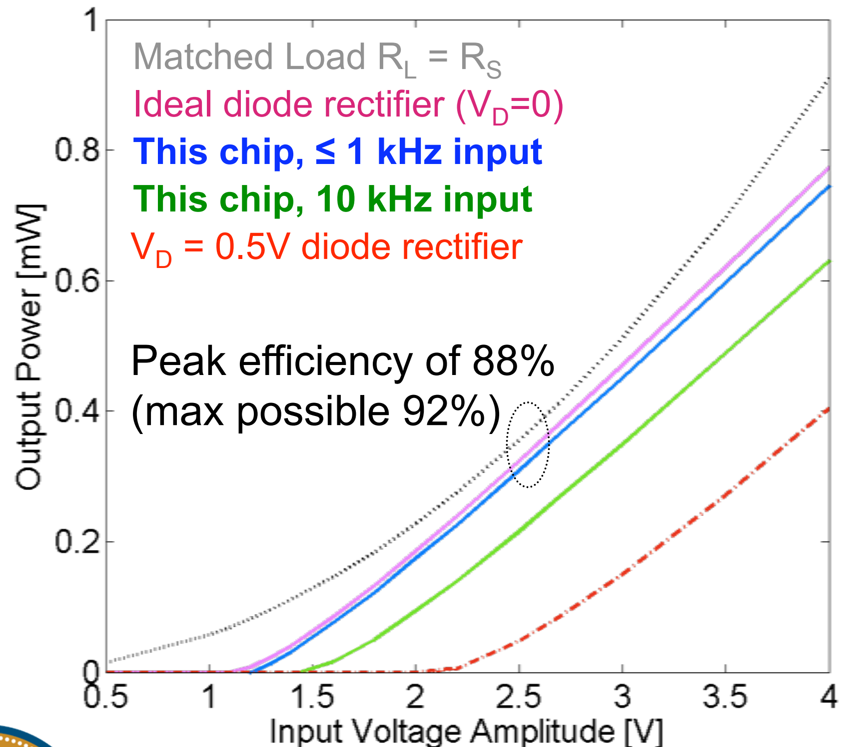
- Native 0.13μm NMOS devices used for high performance
- 30 MHz switching frequency using ~1nF on-chip capacitors
- Hysteretic feedback used to regulate output voltage by varying converter switching frequency
- Novel gate drive structures used to drive triple-well devices

Seeman, et. al. *An ultra-low-power Power Management IC for energy-scavenged Wireless Sensor Nodes*. IEEE PESC 2008.

Power Circuitry Performance

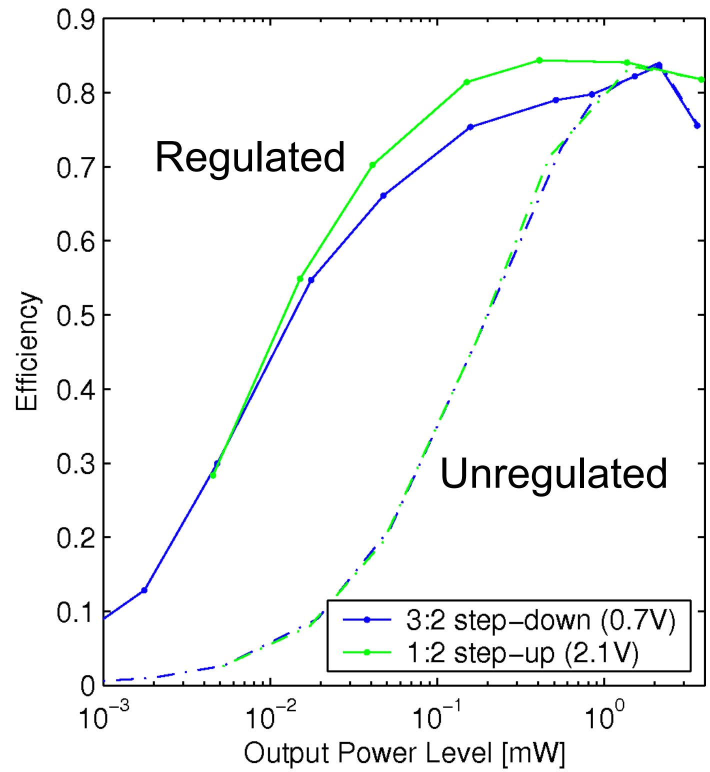
Power Conditioning:

Synchronous Rectifier



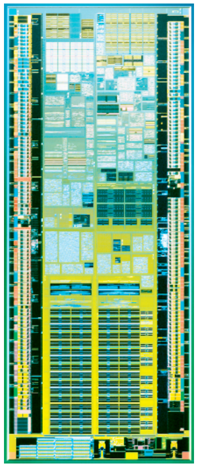
Power Conversion:

Switched-Cap Converters



V_{DD} = 1.1 V NiMH; 2.1 kΩ source

SC Converters for Microprocessors



Intel Atom (2008)
45nm, $25mm^2$
2.5W TDP

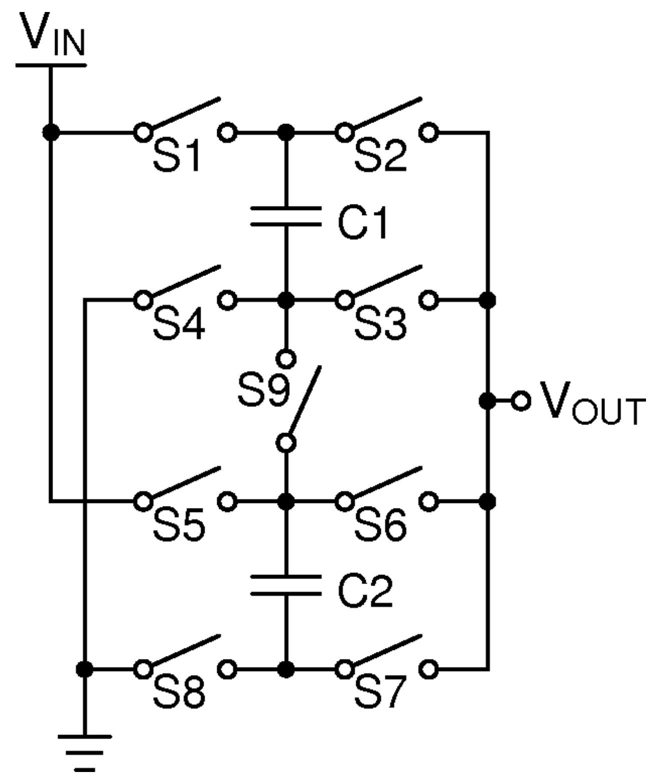
- Power-scalable on-die switched-capacitor voltage regulator (SCVR) to supply numerous on-die voltage rails
- Common voltages:
  1.05V, 0.8V, 0.65V, 0.3V
  - From a 1.8V input
- Small cells are tiled to provide necessary power for each rail

This work was partially supported by Intel Corp.
Also, see "Le, Seeman, Sanders, Sathe, Naffziger, Alon. *A 32nm fully integrated reconfigurable switched-capacitor DC-DC converter delivering 0.55W/mm² at 81% efficiency*, ISSCC 2010

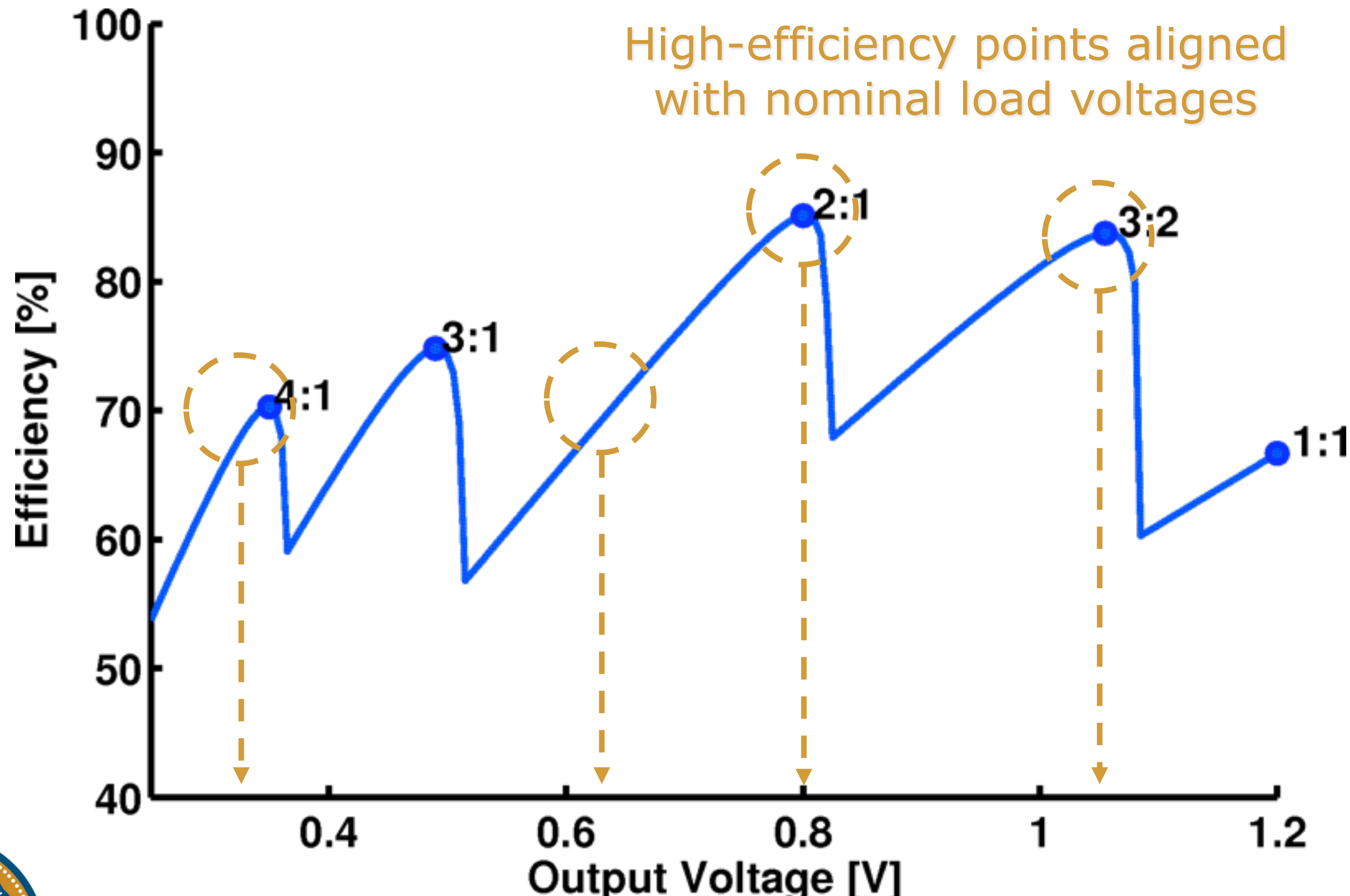
SCVR: Topology

- For low-voltage rails, add an additional 2:1 at the output

Switch	3:2	2:1	3:1
S1	Φ1	Φ1	Φ1
S2	Φ2	Φ2	Φ2
S3	Φ1	Φ1	—
S4	—	Φ2	Φ2
S5	Φ1	Φ1	—
S6	—	Φ2	Φ2
S7	Φ1	Φ1	Φ1
S8	Φ2	Φ2	Φ2
S9	Φ2	—	Φ1

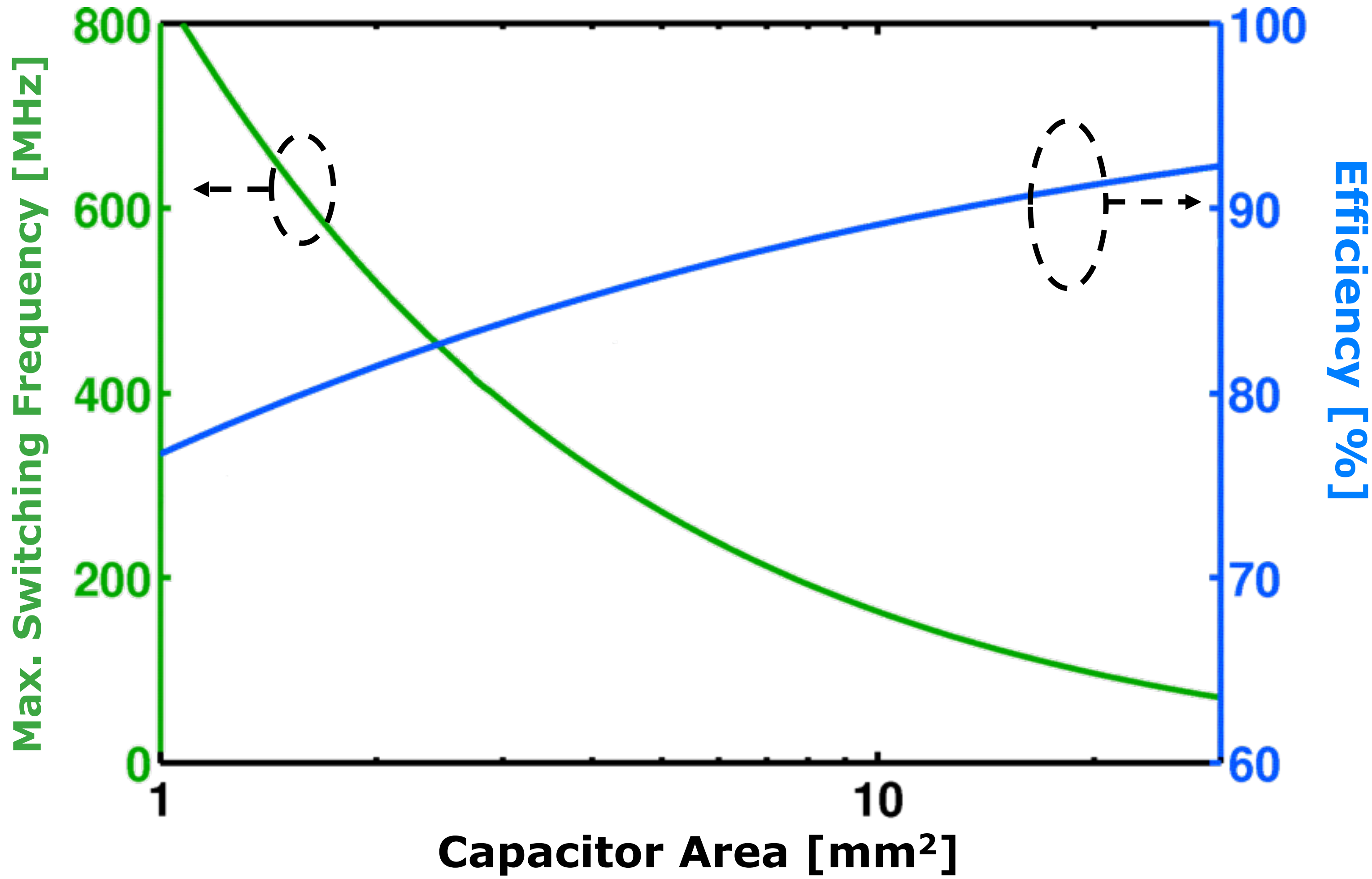


SCVR: Performance



20 fF/mm^2 MIM Cap; 2.5 W in 2.5 mm^2 die area

SCVR: Performance Tradeoffs



20 fF/mm² MIM Cap; 2.5 W in 2.5 mm² die area

Improving SCVR Efficiency

- Improving switch conductance/capacitance
- Improving capacitor technology
  - Higher capacitance density
  - Lower bottom plate capacitance ratio
- Parasitic reduction schemes
  - Charge transfer switches
  - Resonant gate/drain
- Control tricks can help for power backoff

Regulation with SCVRs

- Regulation is critical to maintain output voltage under variation in input and load.
- No inductor allows ultra-fast transient response
  - Given ultra-fast control logic
- Regulation by ratio-changing and R_{OUT} modulation:

$$R_{OUT} \propto \frac{1}{Cf_{sw}} + 2\frac{R_{ON}}{D}$$

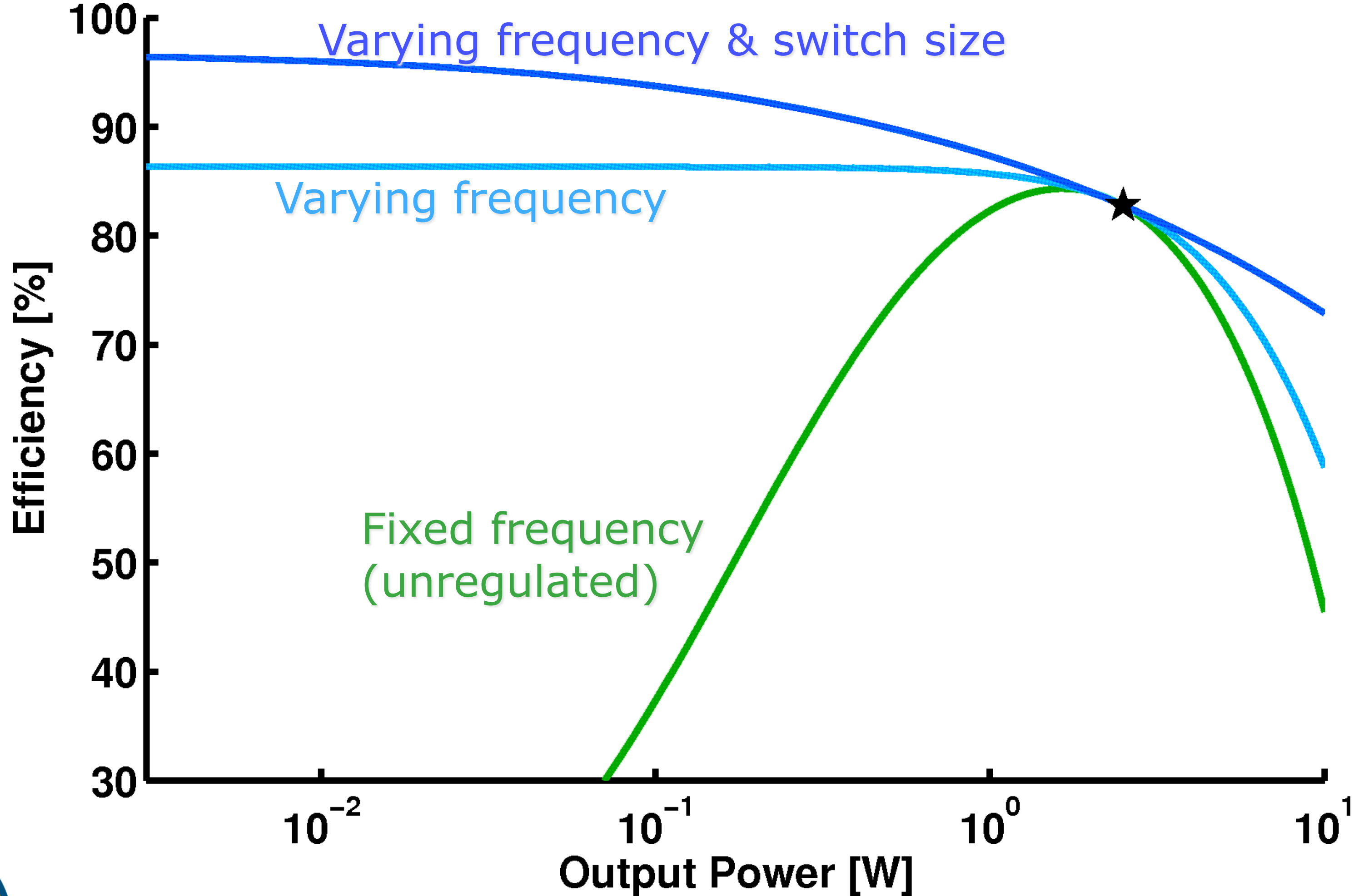
Frequency modulation

Switch conductance modulation

Pulse-width modulation

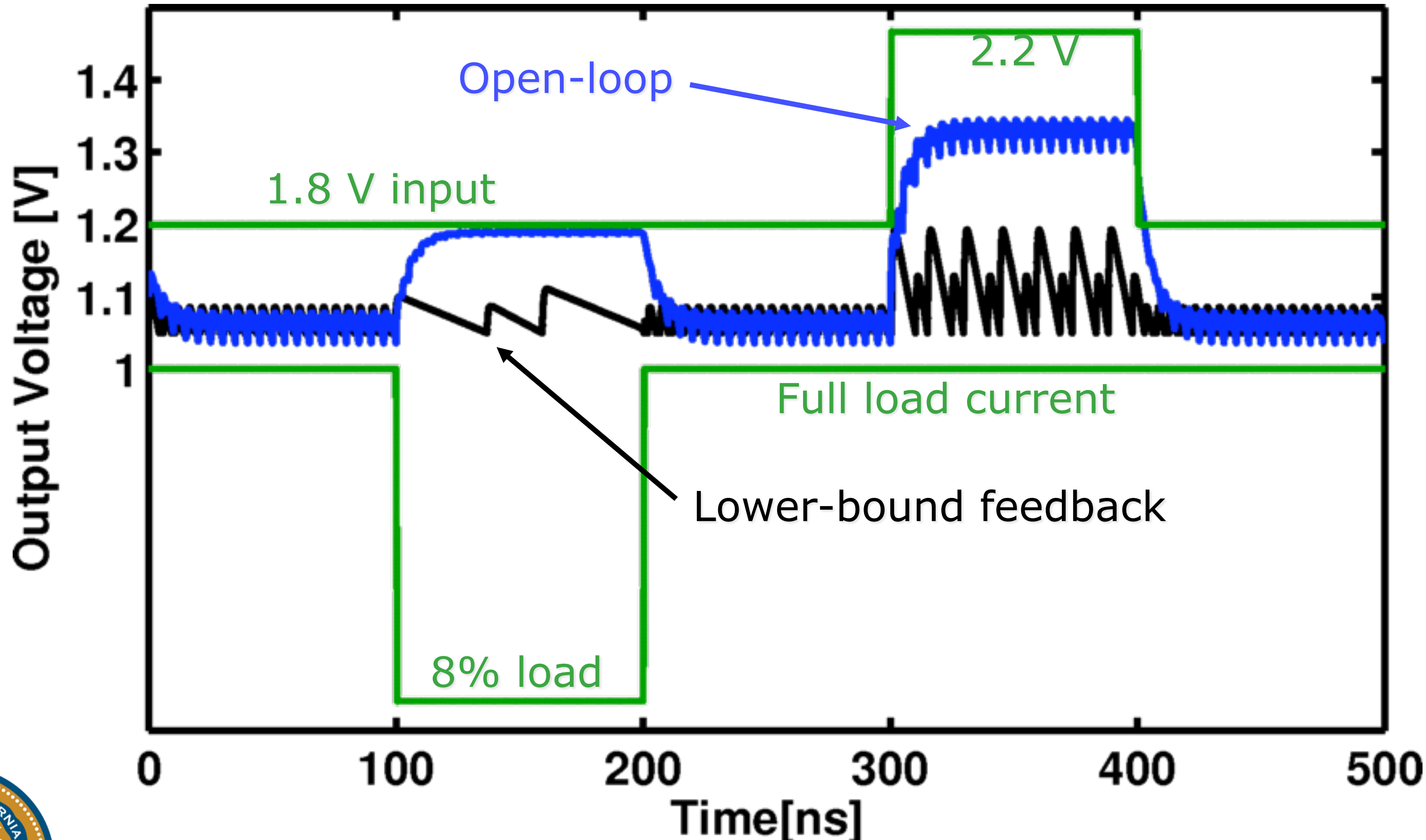
All methods equivalent to linear regulation (zero-th order)

Regulation and Efficiency



3:2 @ 1.05V out; 2.5W using 2.5mm^2 area

Example Transient Response



Conclusions

- Switched-capacitor converters exhibit significant advantages over inductor-based converters in many applications
- SC converters can be easily modeled using relatively simple analysis methods
- SC converters and CMOS rectifiers make ideal sensor node power converters
- Modern CMOS technology allows for high-power-density on-chip power conversion