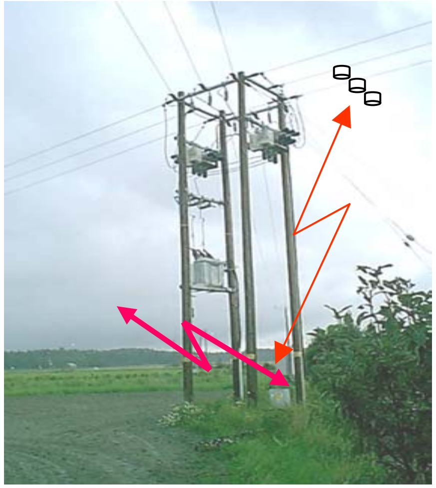
Power Aware Wireless Microsensor Systems

Anantha Chandrakasan, Rex Min,
Manish Bhardwaj, Seong-Hwan Cho, Alice Wang

Massachusetts Institute of Technology

Emerging Microsensor Applications

Industrial Plants and Power Line Monitoring (courtesy ABB)

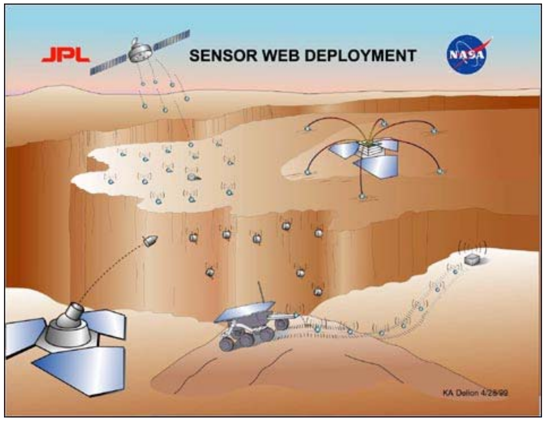


Operating Room of the Future (courtesy John Guttag)

Target Tracking & Detection (Courtesy of ARL)

Location Awareness (Courtesy of Mark Smith, HP)

NASA/JPL *sensorwebs*



Sensor System Requirements

Predictable Constraints

Application Characteristics	Typical Values
Data Rate	bps to kbps
Spatial Density	0.1-10 nodes/m^2
Transmission Distance	10 – 100m
Extended Lifetime	5 years
Small Size	1 “AA” battery

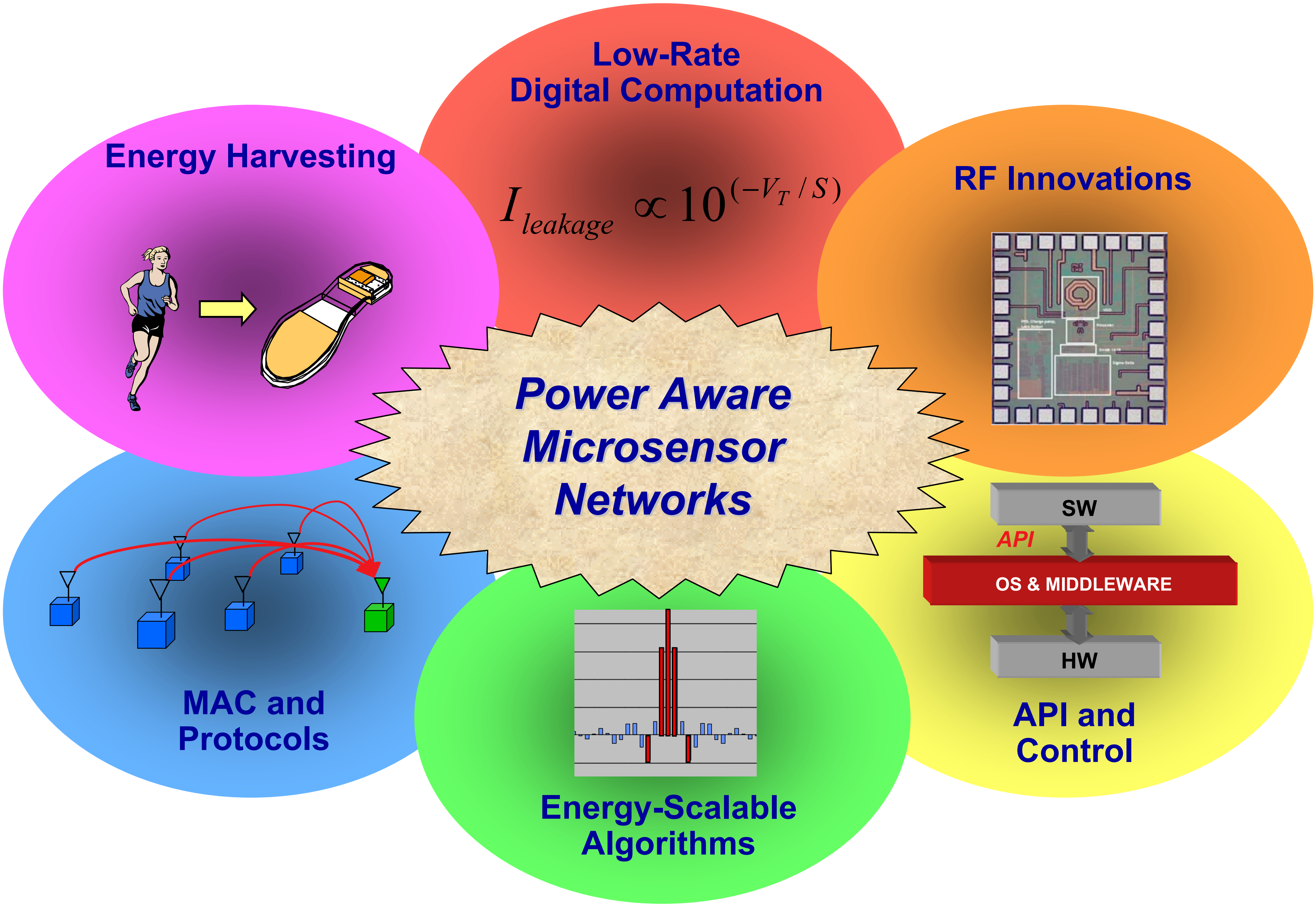
Application-specific designs provide energy efficient point solutions

Unpredictable Diversity

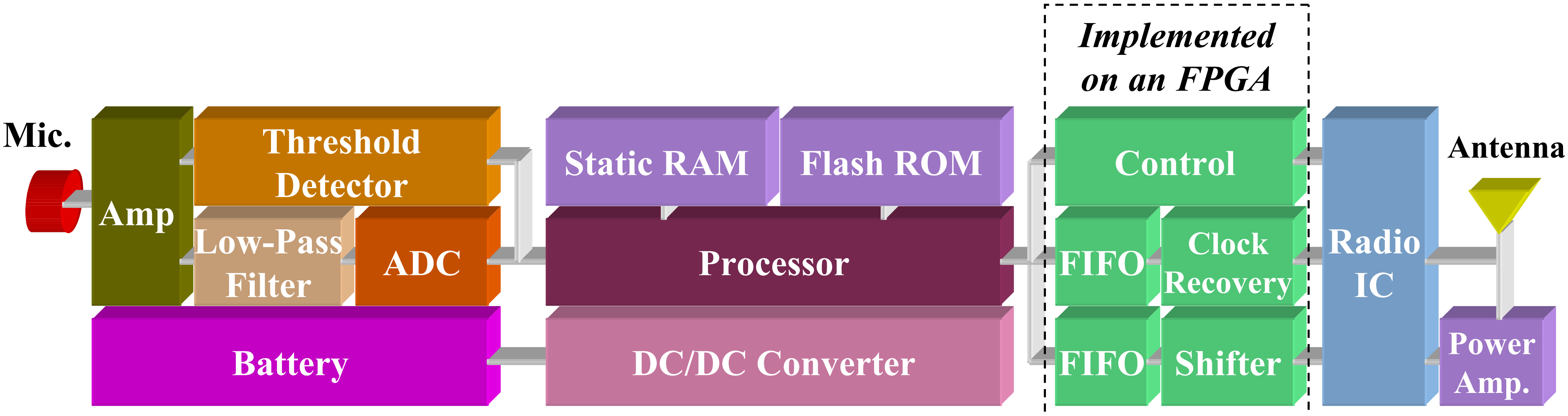
- ***Network roles:***
  relay, sensor, aggregator
- ***Environment:***
  event and signal statistics
- ***User/Application:***
  required latency, quality

Power-aware designs adapt energy consumption to operating conditions

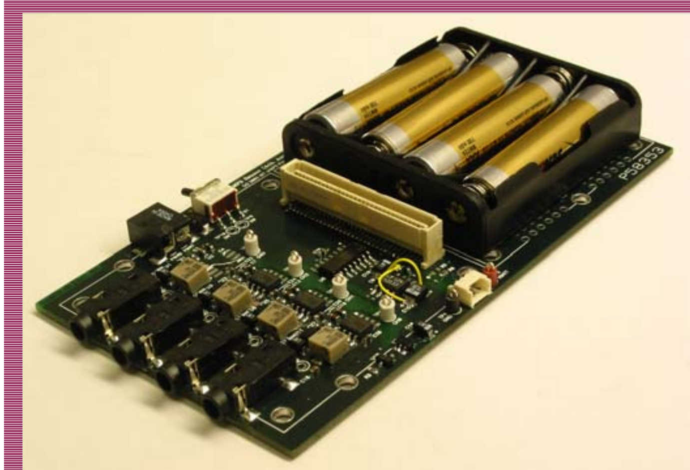
Power Aware Microsensor Considerations



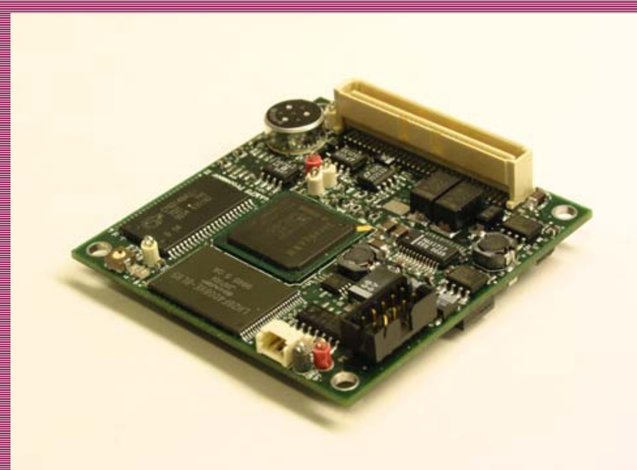
First Generation Wireless Microsensor



Sensor | **Processor** | **Radio**



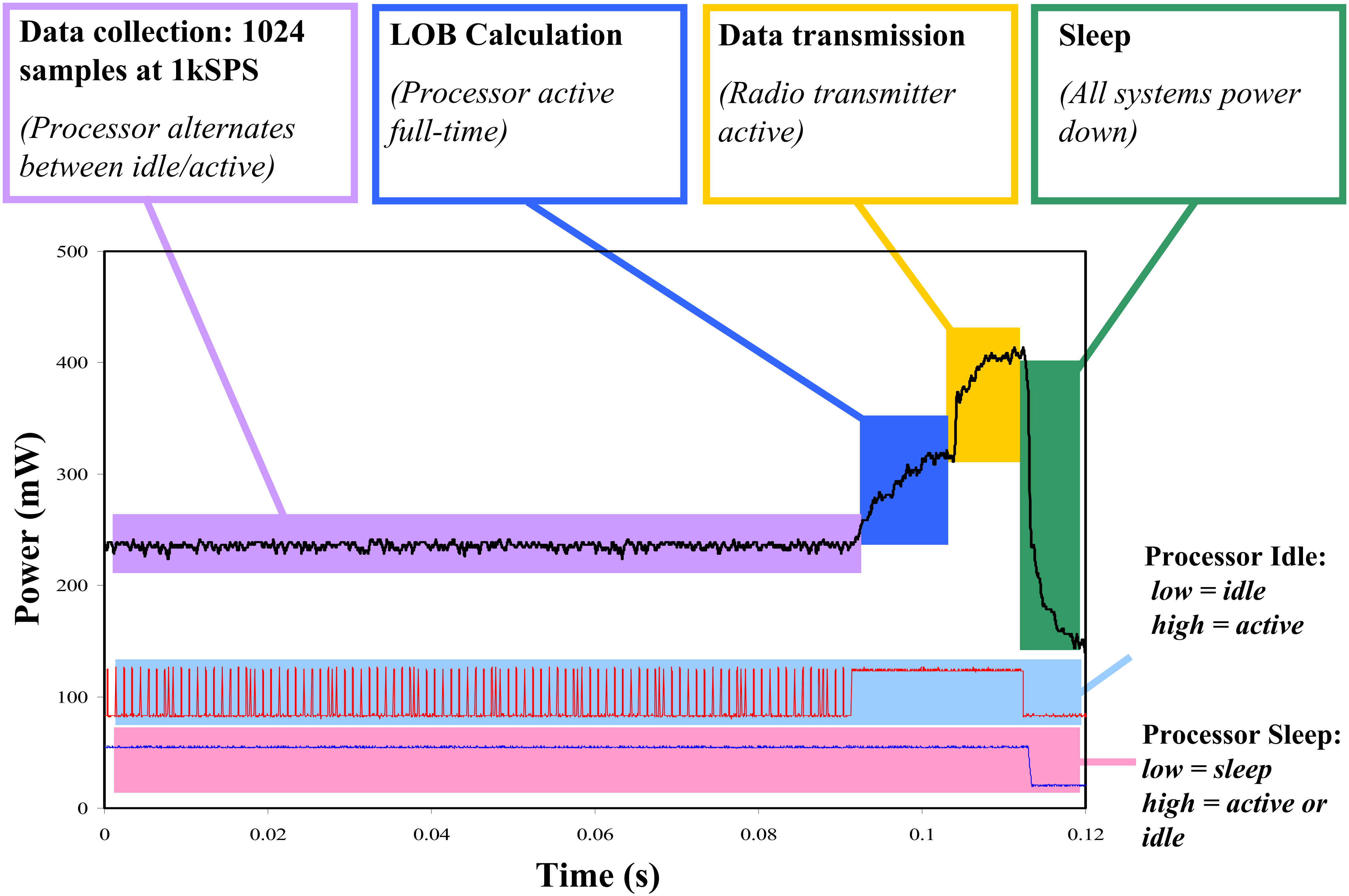
4-channel acoustic



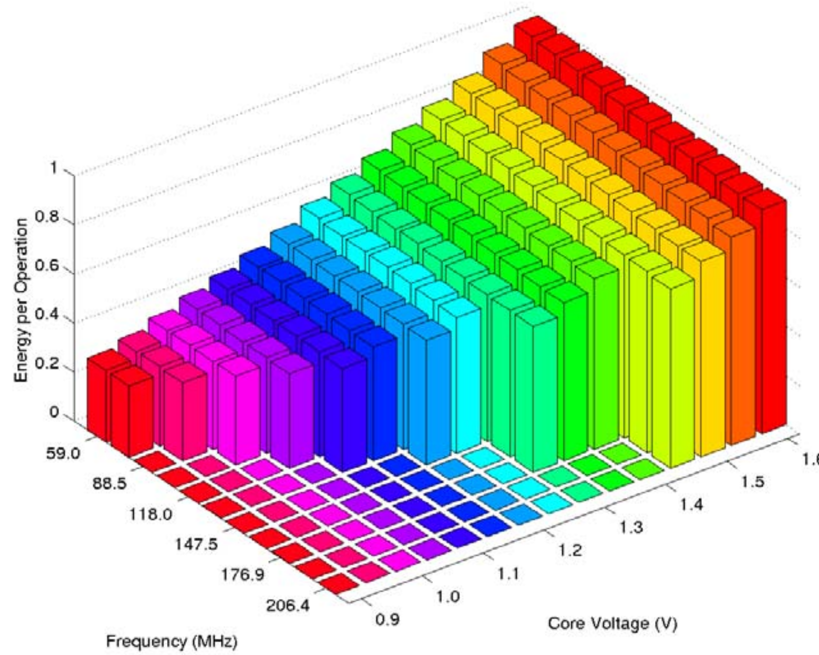
206MHz StrongARM

2.4GHz ISM band

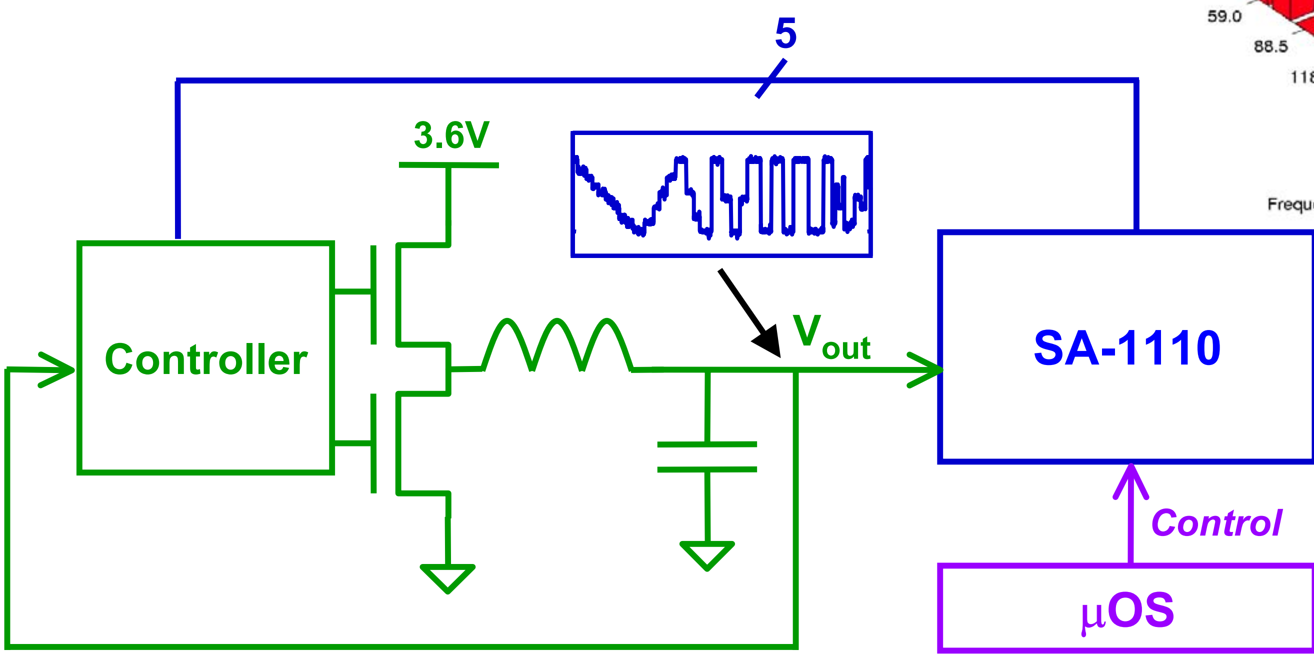
OS-Controlled Power Down Modes



Dynamic Voltage Scaling

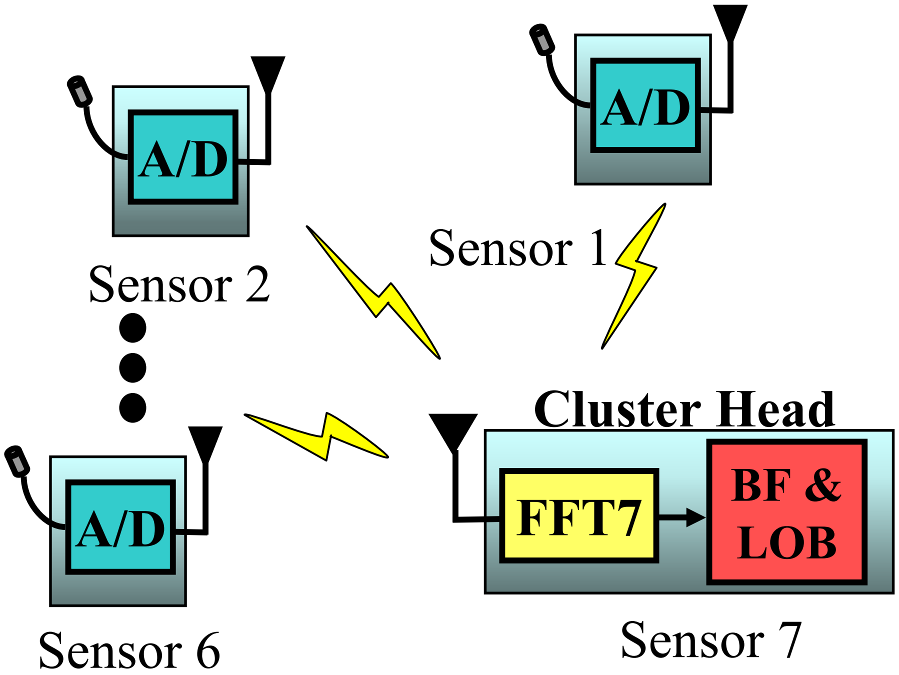


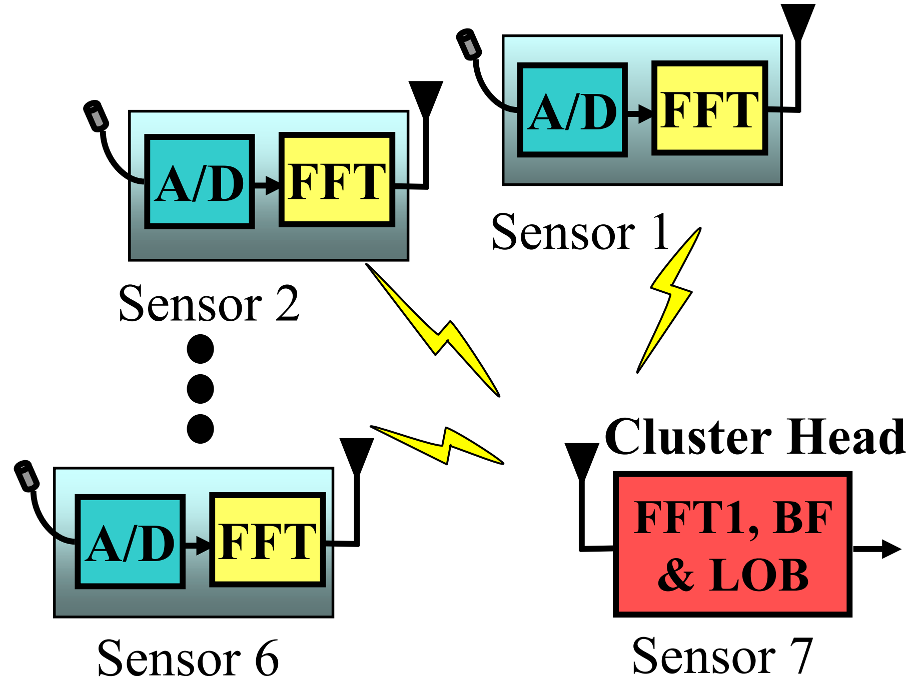
Digitally adjustable DC-DC converter powers SA-1110 core



μOS selects appropriate clock frequency based on workload and latency constraints

Distributed Processing Exploiting DVS





Approach 1: **All latency-critical computation at aggregating node**

$$E_{comp}(V_{dd}=1.5V) = 7E_{fft}+E_{bf}+E_{LOB}$$

= **27.27 mJ** **on SA-1100**

Approach 2: [redacted] **ameliorates** [redacted]

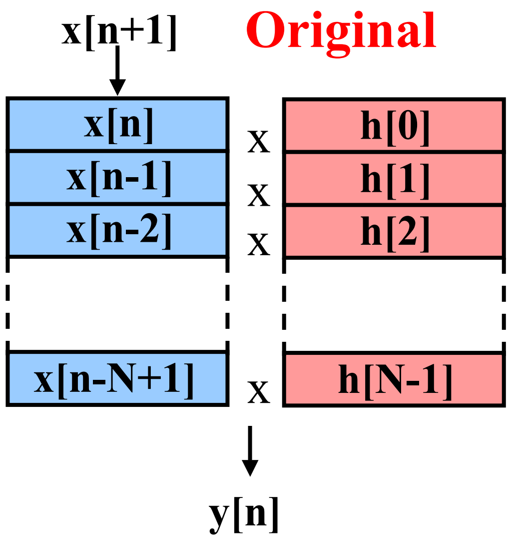
FFT: $V_{dd} = 0.9$ **V**

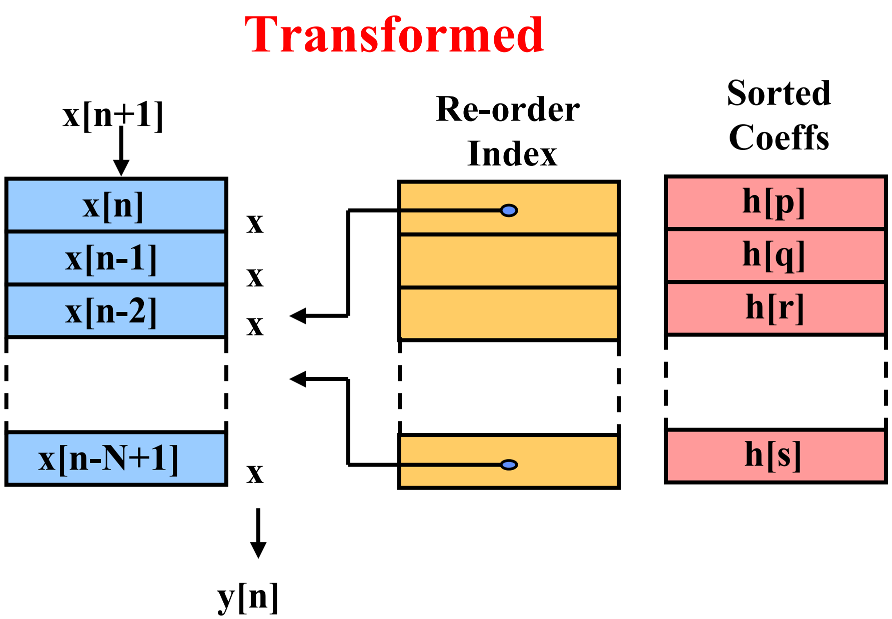
BF & LOB: $V_{dd} = 1.3$ **V**

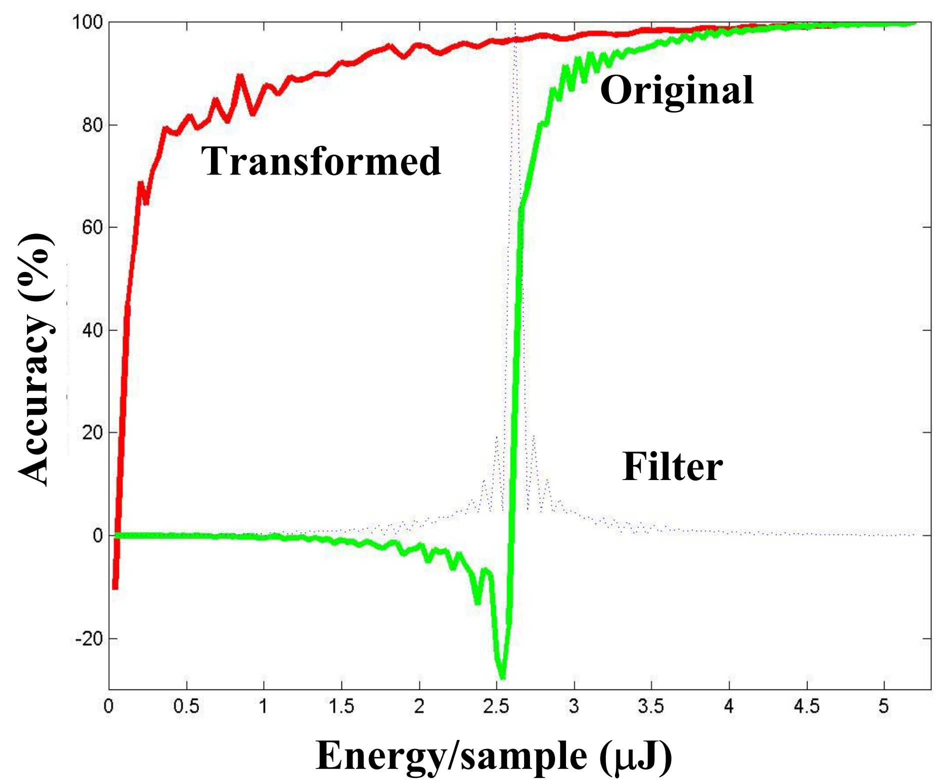
$$E_{comp}(\text{variable } V_{dd}) = 15.16 \text{ mJ}$$

Energy Scalable Algorithms

$$y[n] = \sum_{k=0}^{N-1} h[k]x[n-k]$$



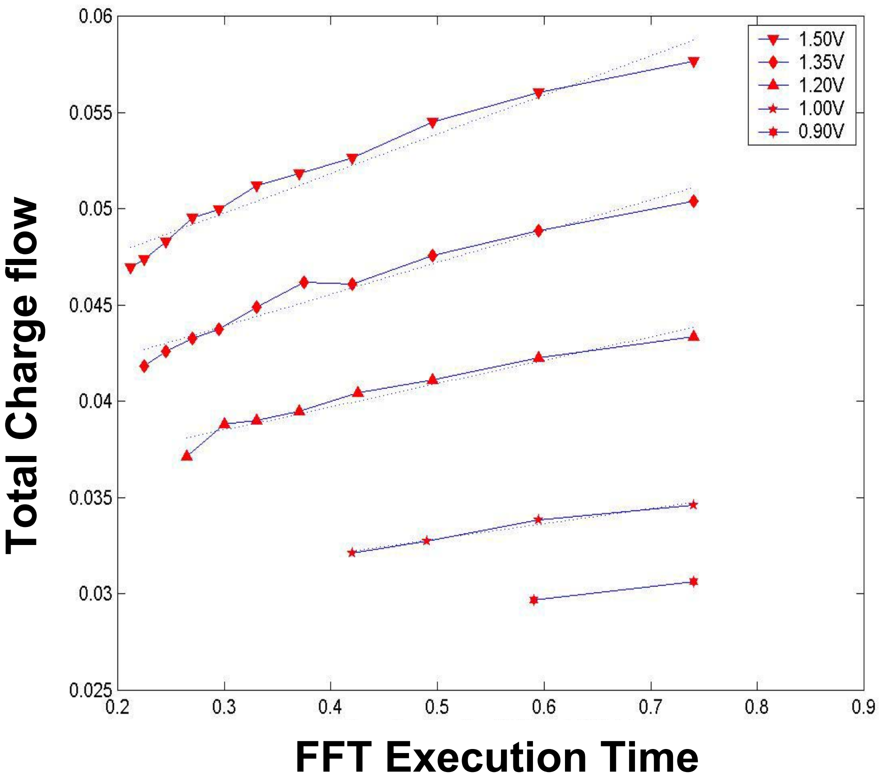


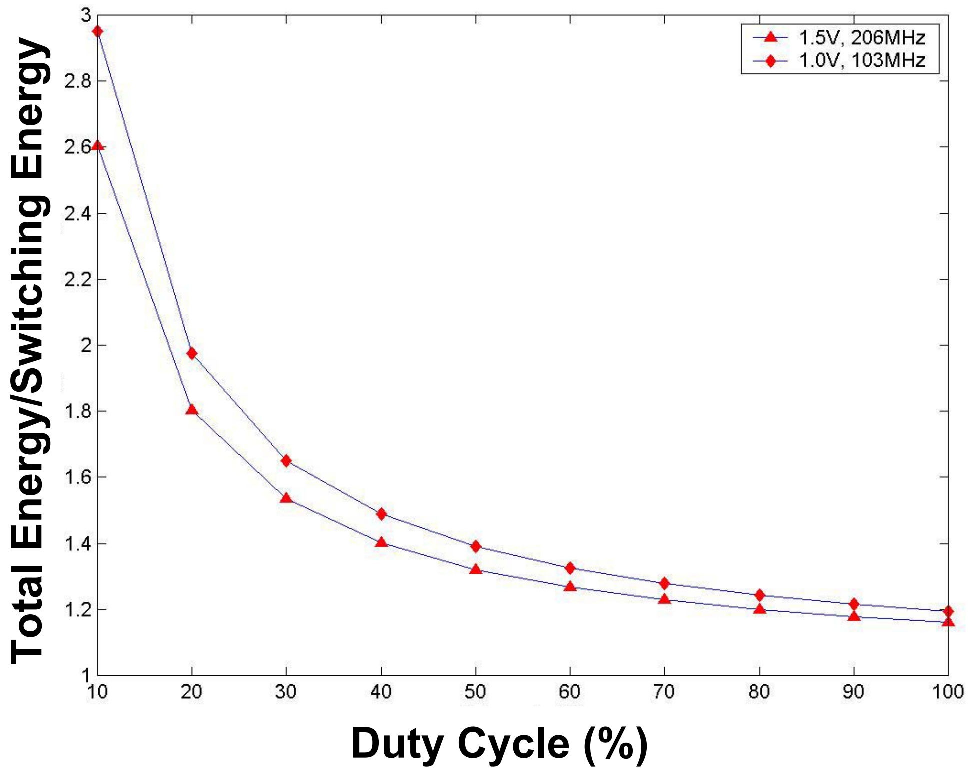


[Sinha, ISLPED '00]

- Maximize quality for a given energy availability

Leakage : Low Duty Cycle Concern

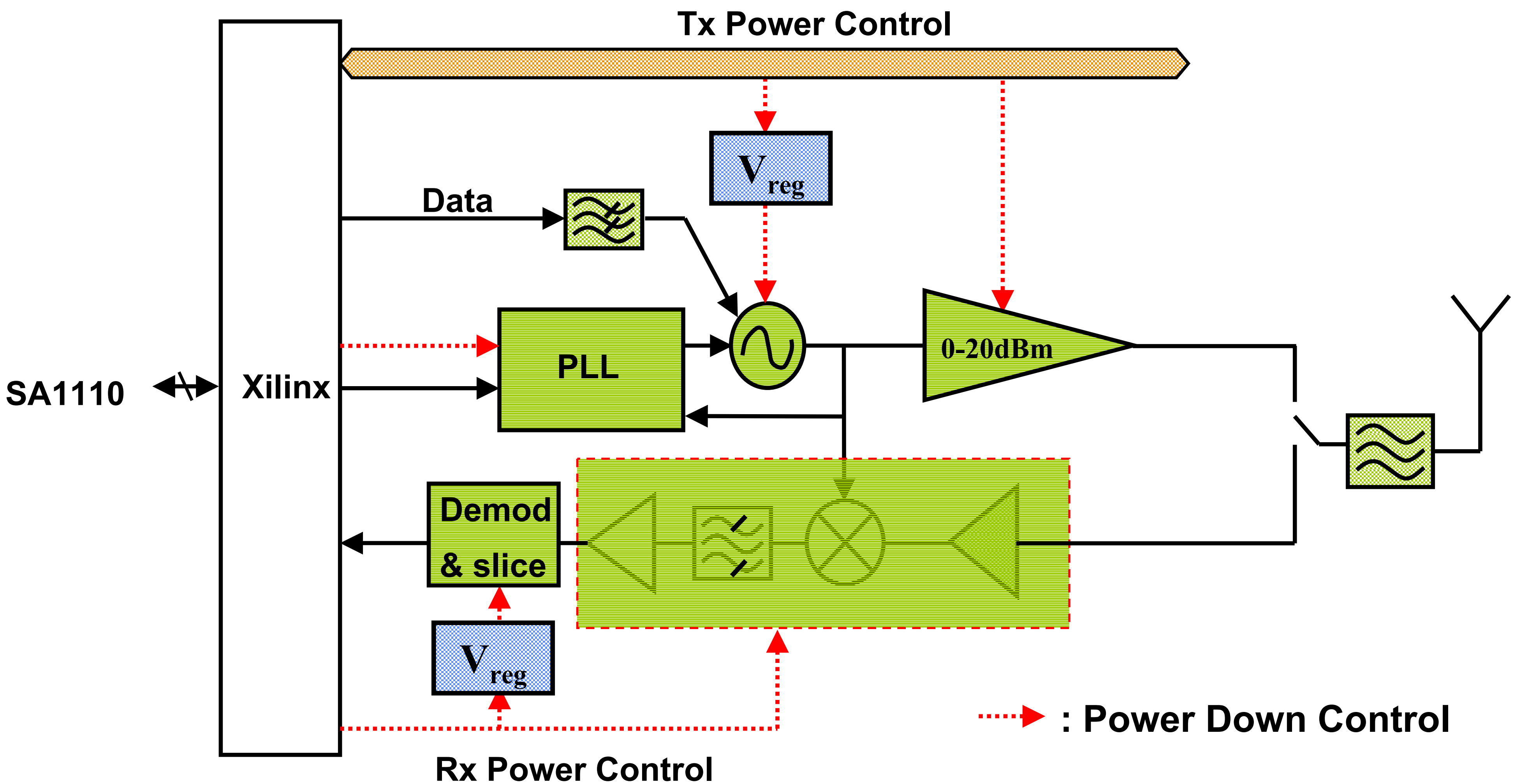




$$I_{leakage} \propto 10^{(-V_T / S)}$$

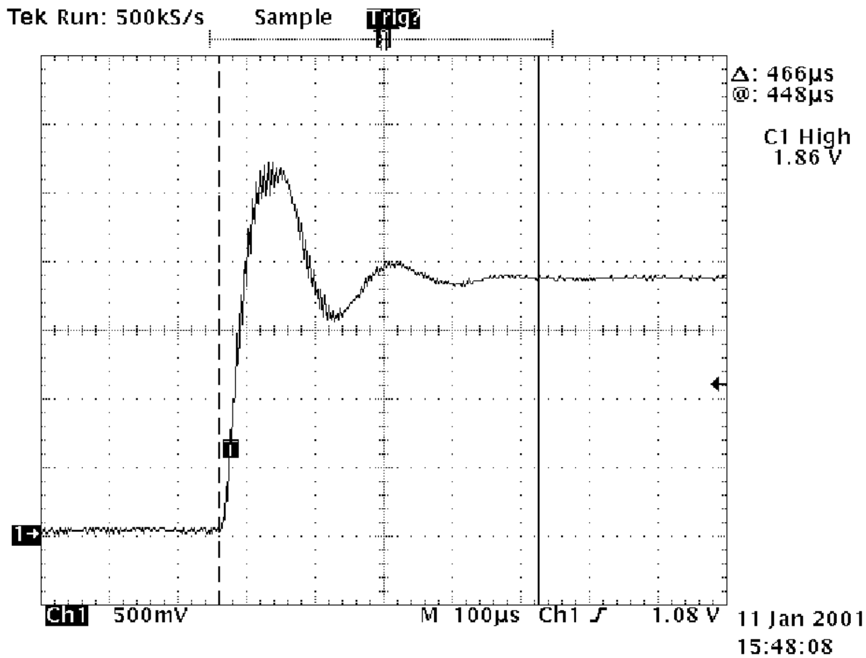
Leakage Dominates Switching Energy for Low Duty Cycles – "Off" State-centric Optimization

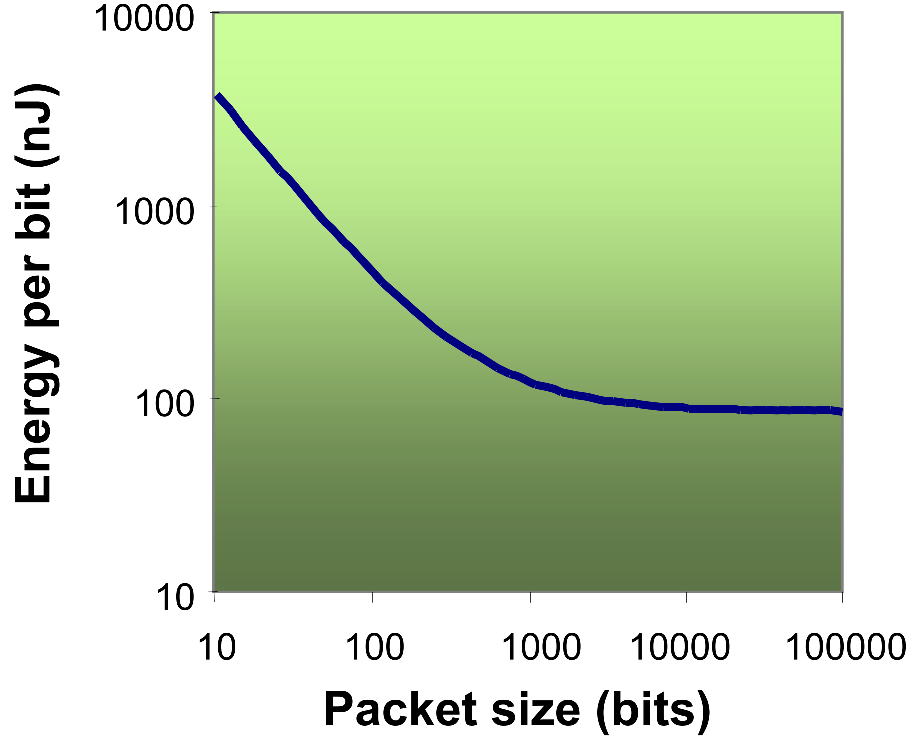
Power Aware Radio



- Fine-grain shutdown through regulators and bias control
- Variable 6-level PA allows efficient transmission for 10m to 100m

RF Start-up Energy Overhead



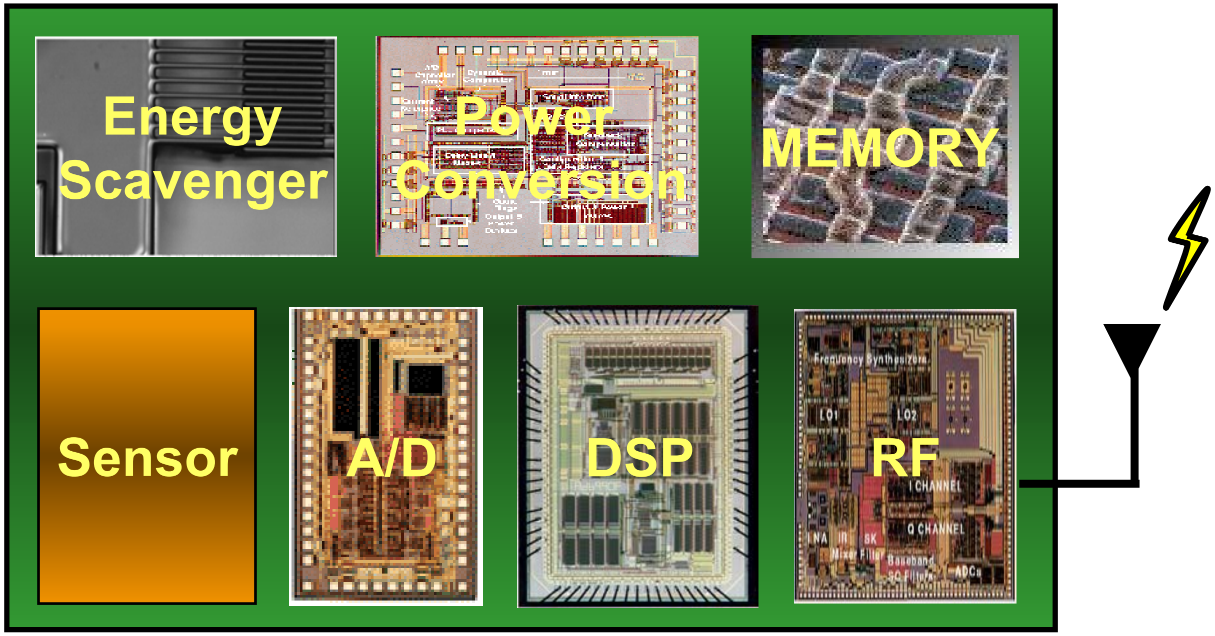


$$Energy = P_{tx\_electronics}(T_{tranmsit} + T_{start}) + P_{out}\, T_{transmit}$$

- Significant loss in energy efficiency for small packet sizes

Startup Costs are Fundamental –
Innovative Circuits and Protocols Required

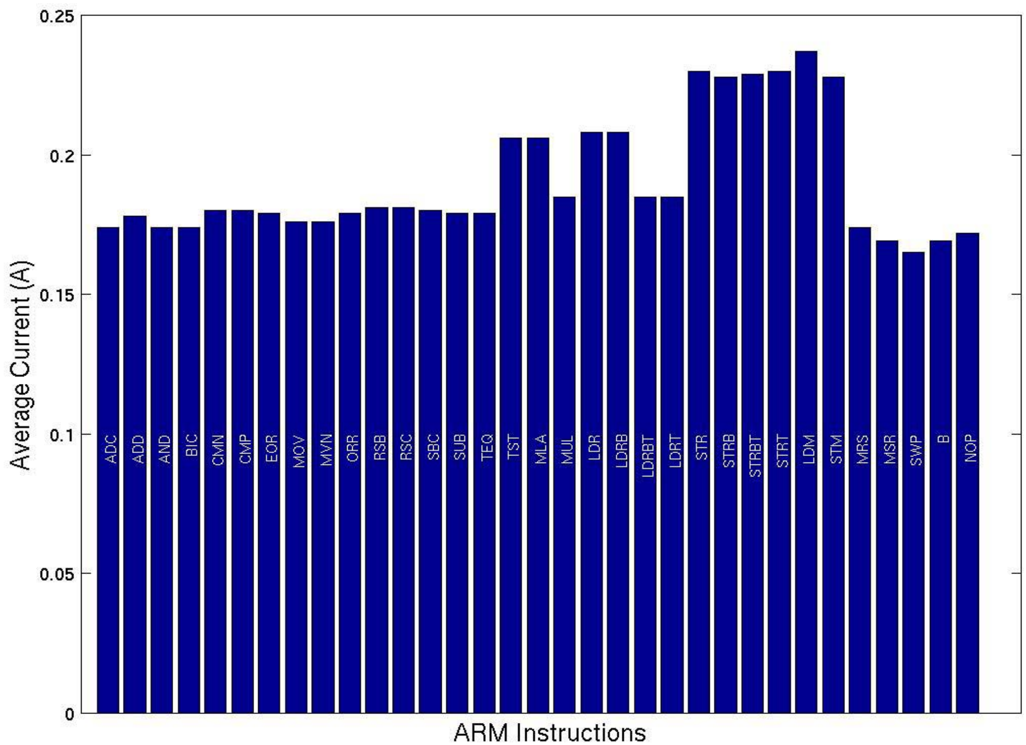
Integrated System-on-a-Chip Vision

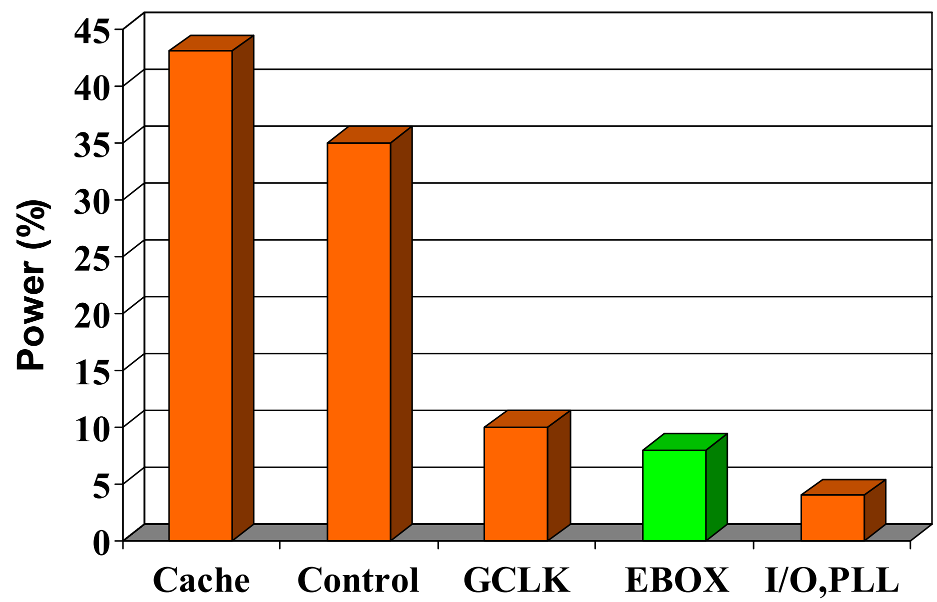


- Compact Form Factor (mm^3 – cm^3)
- Requires interconnection of diverse process technologies
- Low computational requirement, but requires flexibility to adapt to time-varying scenarios
- Cost, size and energy are the key design constraints

What is the best computation/communication fabric?

Why Not Software?

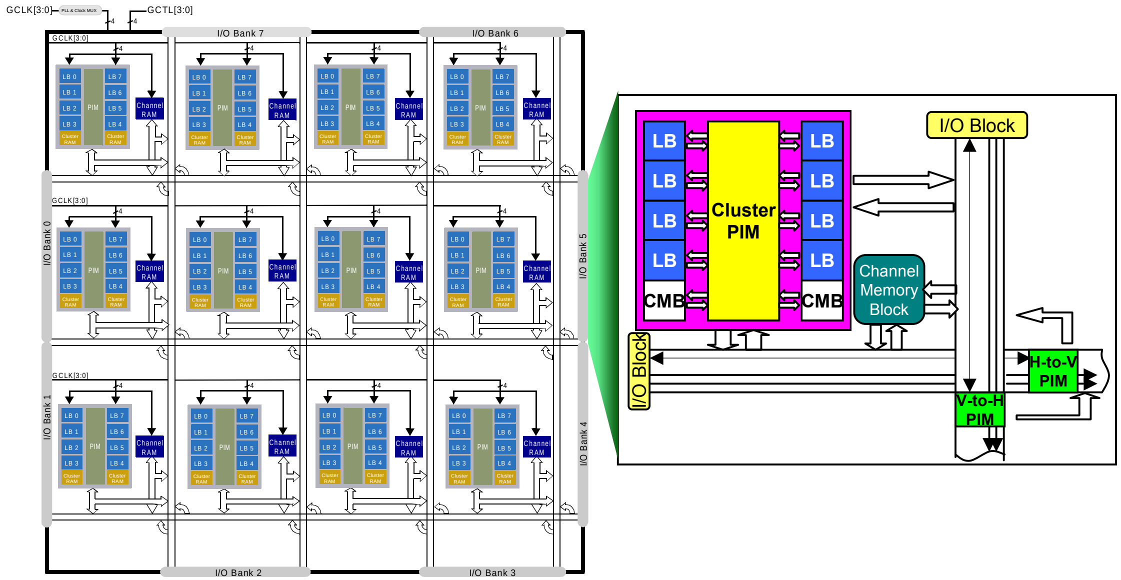


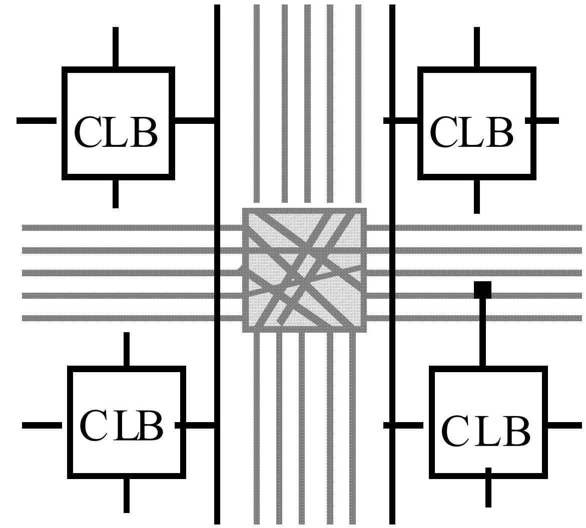


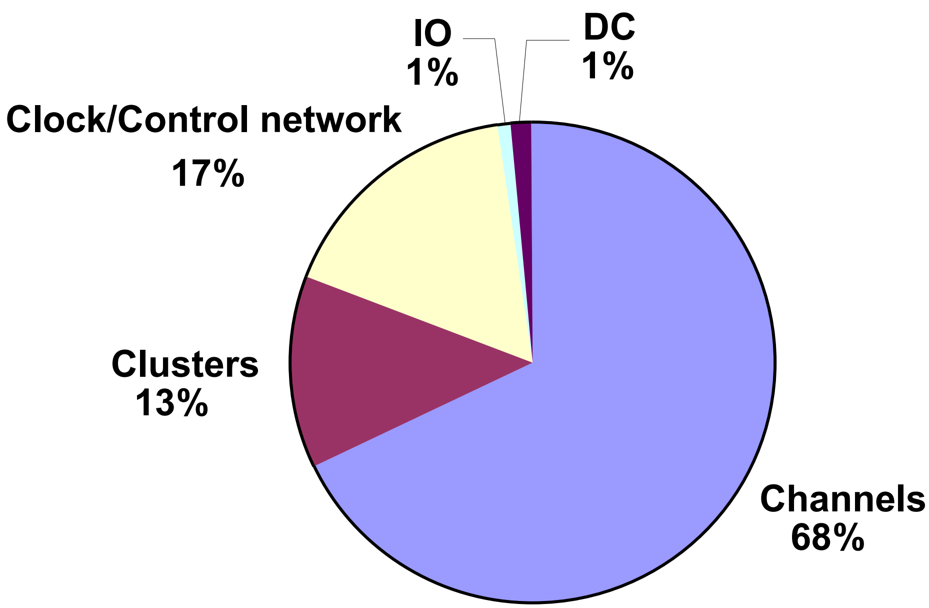
[Montanaro, JSSC '96]

Software Energy Dissipation is Dominated by Overhead and NOT by Useful Work

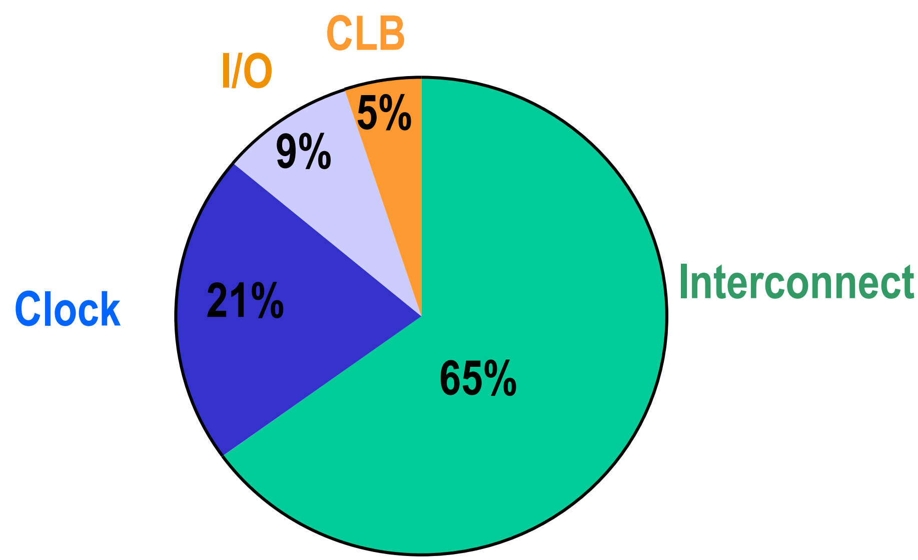
What about FPGAs?





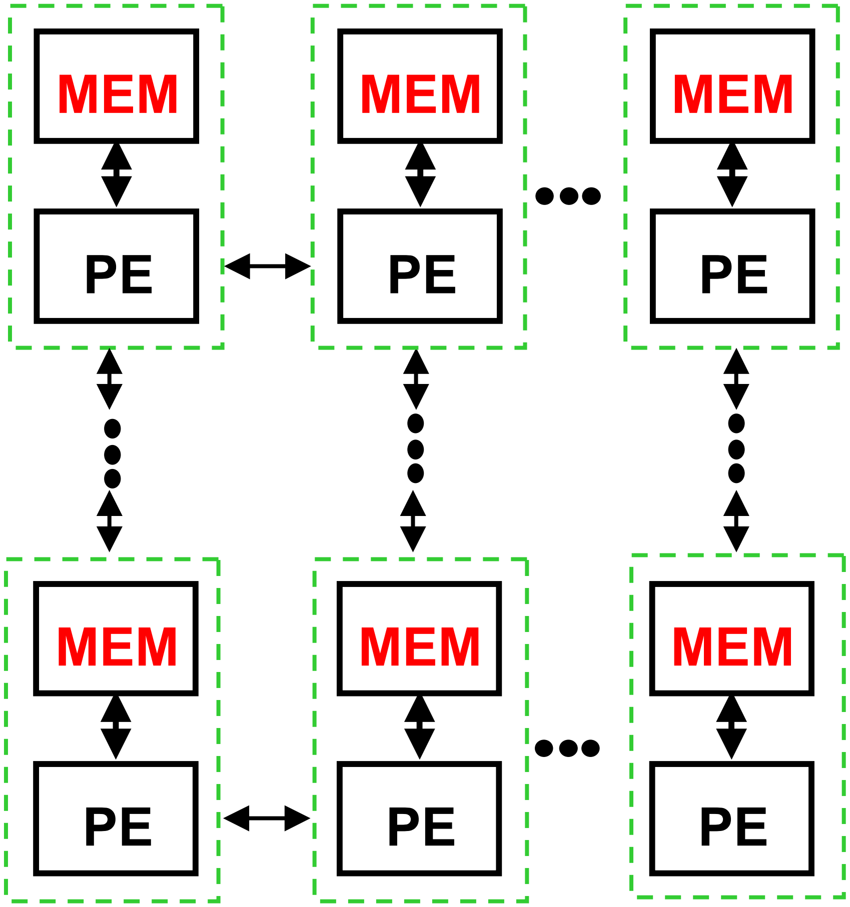


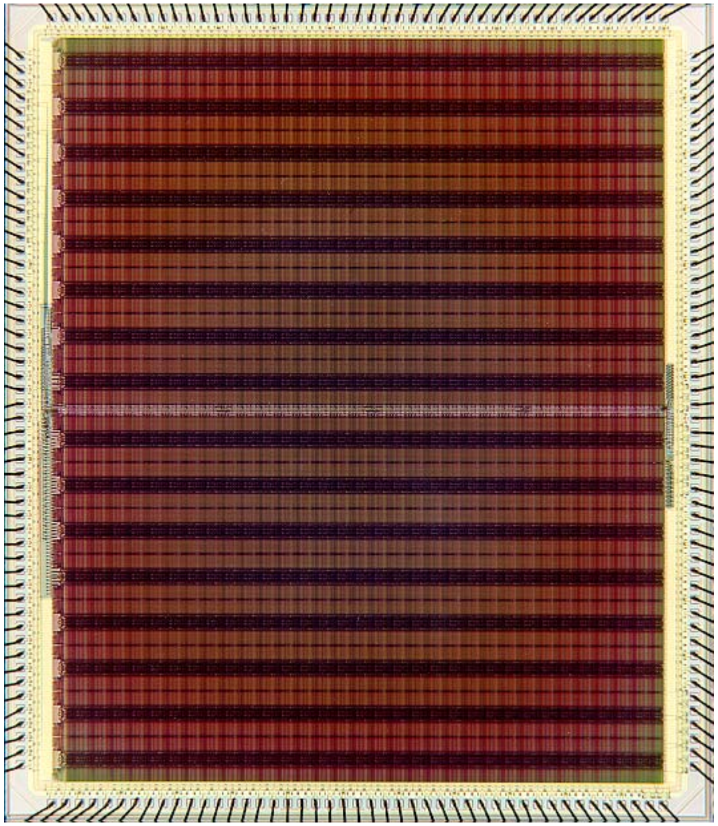
Cypress



Xilinx
(Courtesy of J. Rabaey)

Interconnect-Centric Architectures (Flexibility with Power Efficiency)



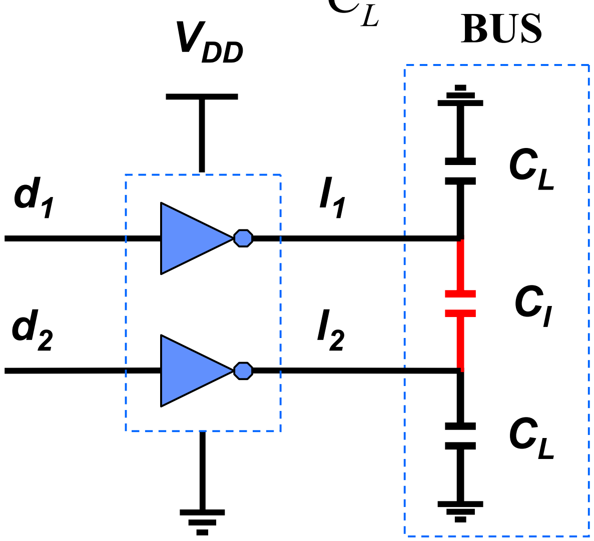


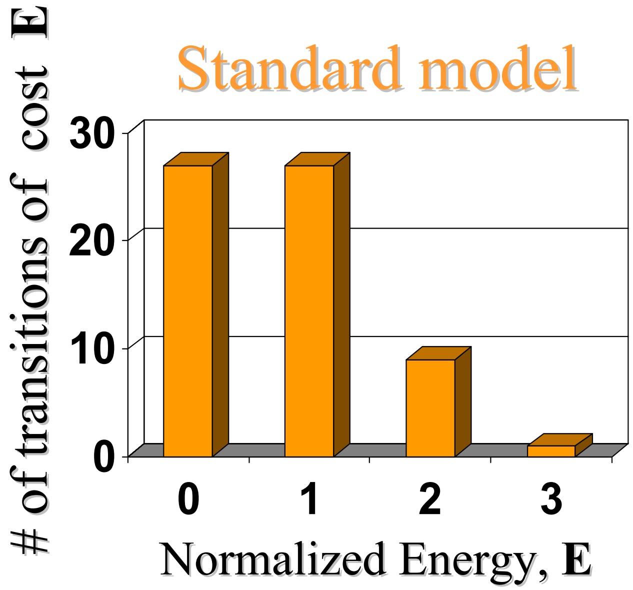
[Simon, JSSC '00]

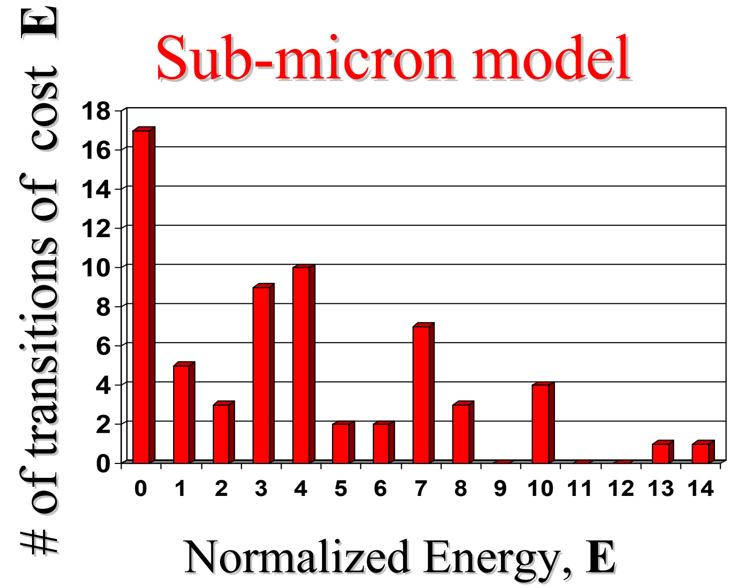
- Massively parallel, "slow" switching processors
- Exploits locality of reference, low interconnect costs
- Image Sensor Application: Wavelet based compression (3 Million Transistors, 0.6μm CMOS, 500μW)

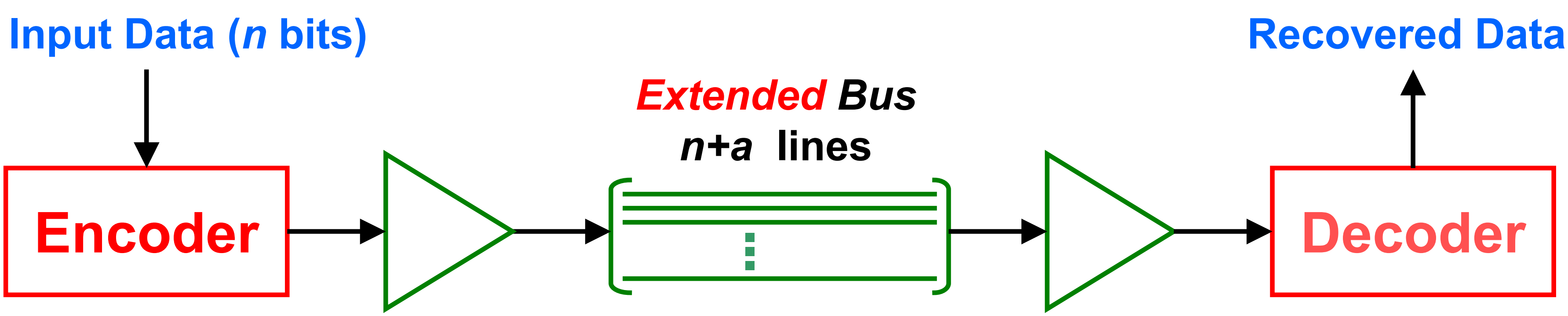
New Energy Metrics in DSM Interconnect

$$\lambda = \frac{C_I}{C_L} = 3$$









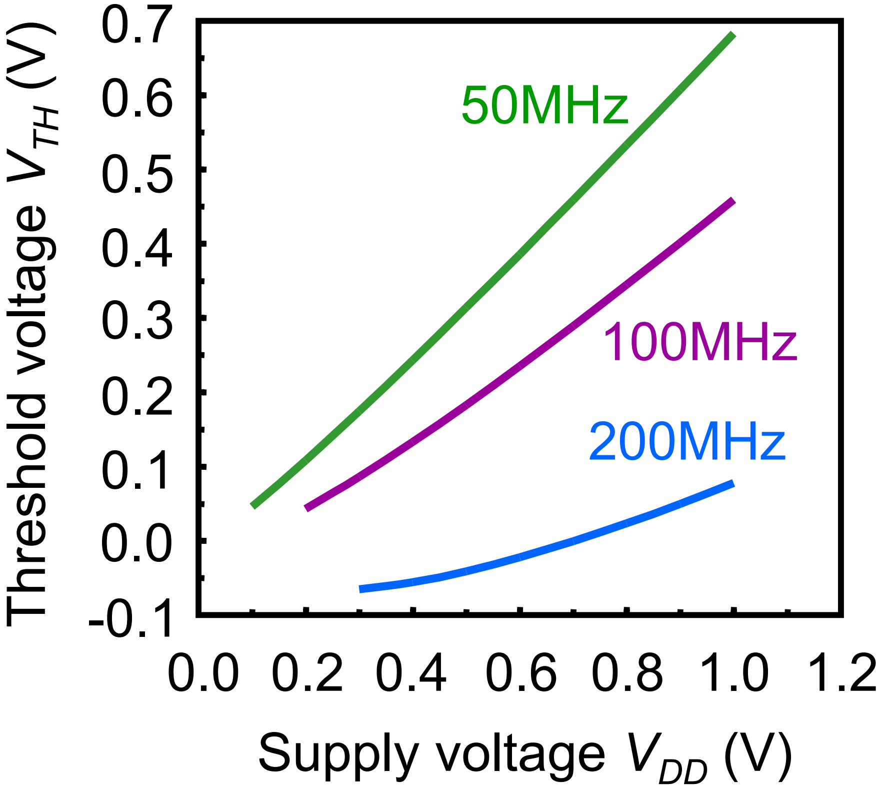
Minimizing Transition Activity is not the Right approach to Minimize Power

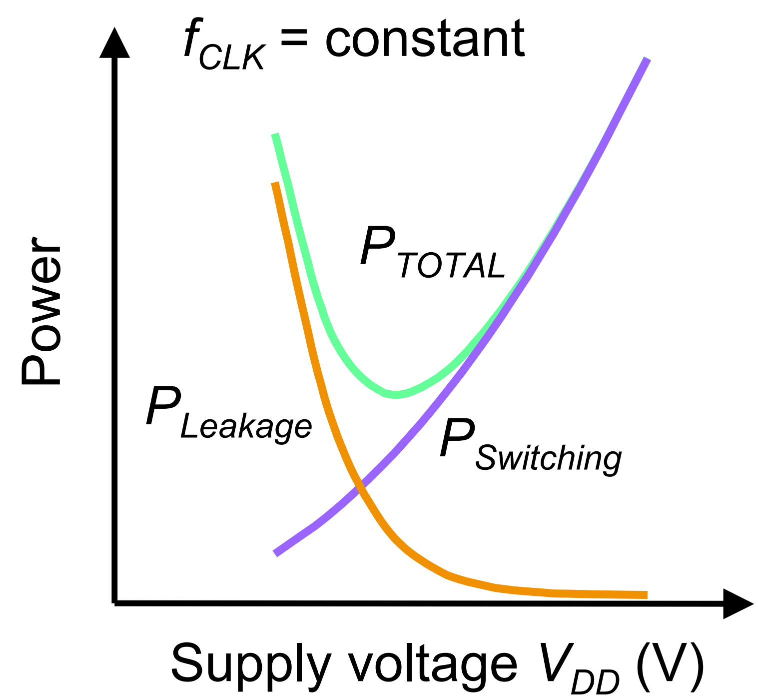
Optimal V_{DD} and V_T Control

$$f_{CLK} = \frac{\beta}{C_L} \cdot \frac{(V_{DD} - V_{TH})^{\alpha}}{V_{DD}}$$

$$P_{Switching} = a \cdot f_{CLK} \cdot C_L \cdot V_{DD}^{2}$$

$$P_{Leakage} = I_{10} \cdot V_{DD} \cdot 10^{-\frac{V_{TH}}{S}}$$

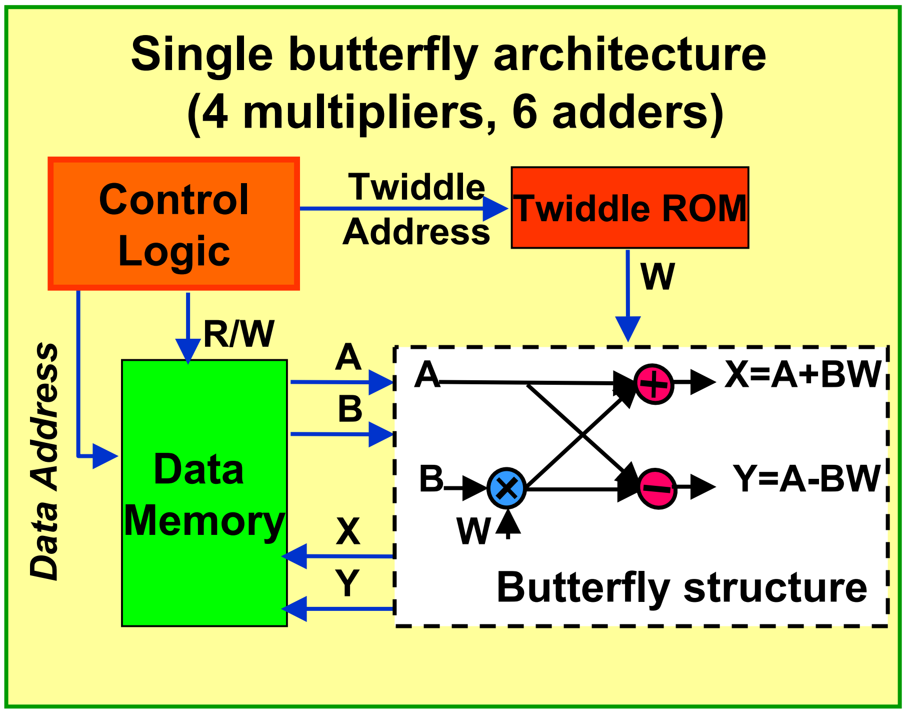


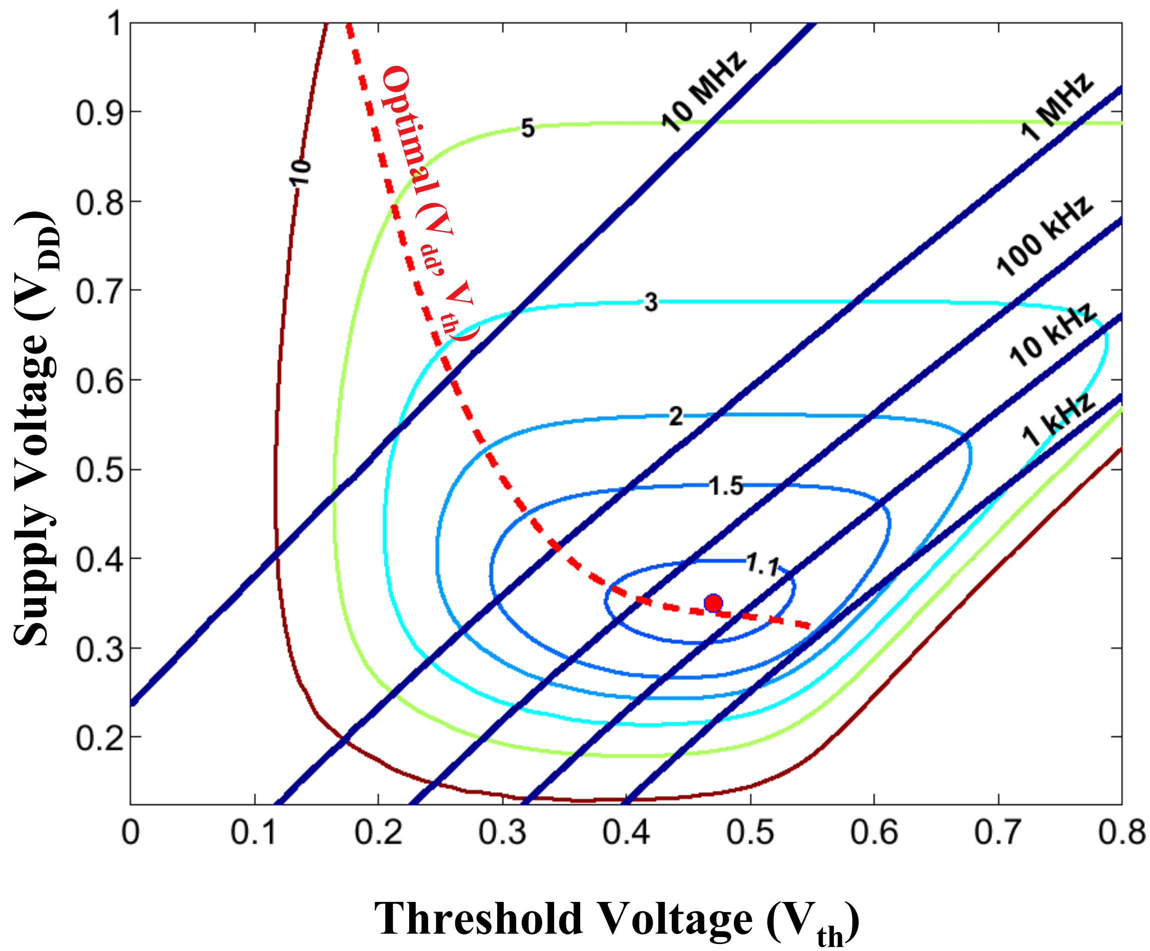


- **V_{DD} and V_{TH} can be varied to keep a fixed performance**

Energy Efficiency of Digital Computation

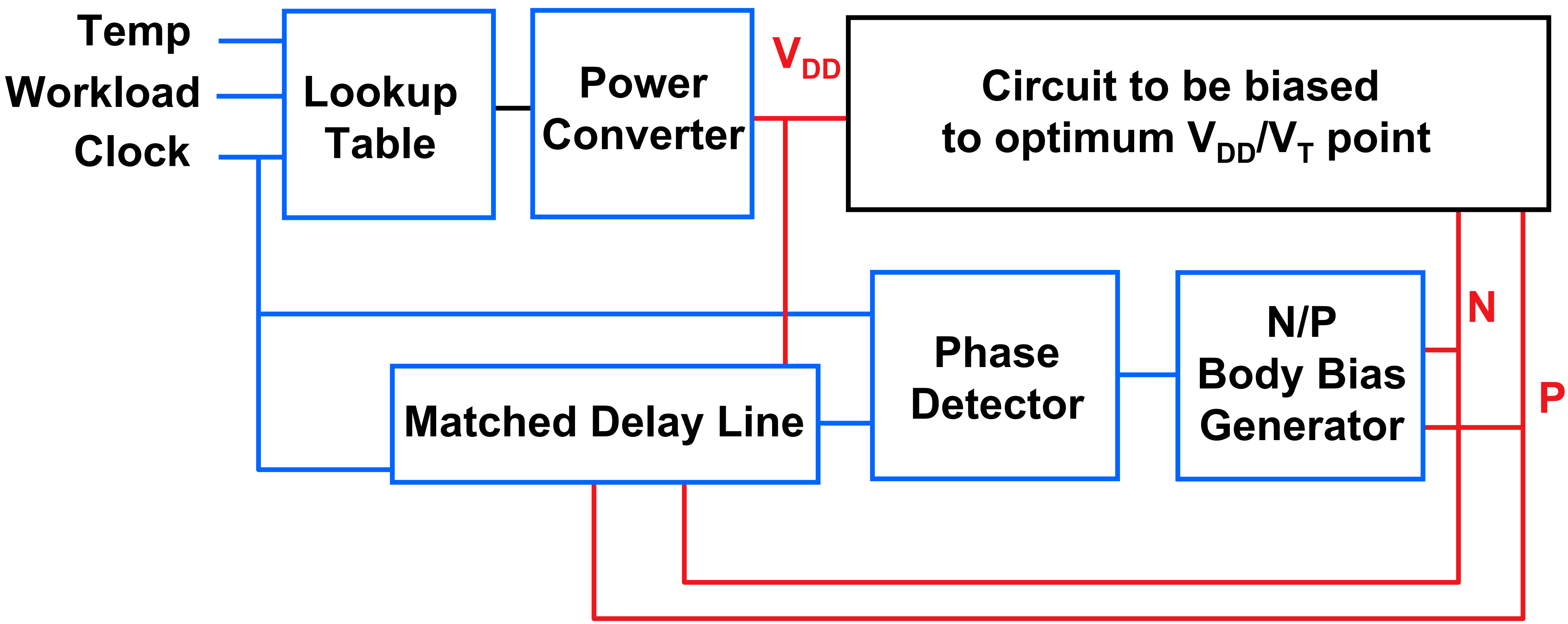
FFT Computation

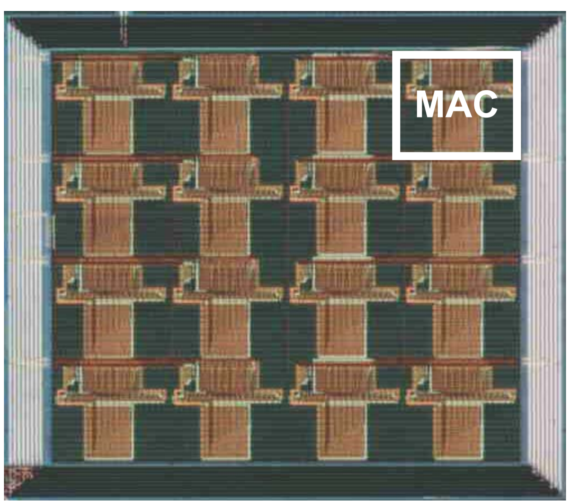


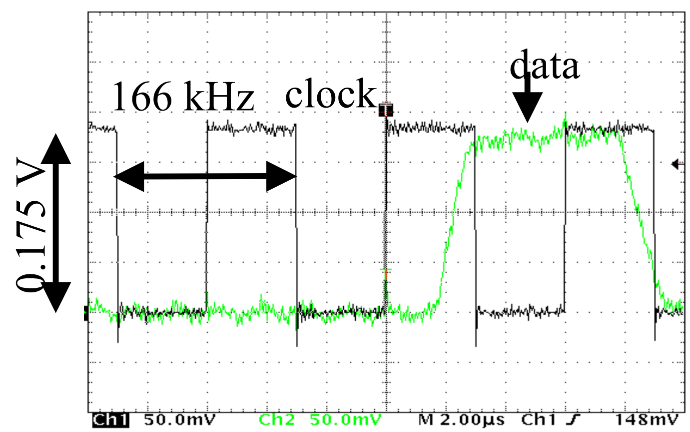


Exploit Sub-threshold Operation for Sensor Circuits

Adaptive V_{DD}/V_T Architecture

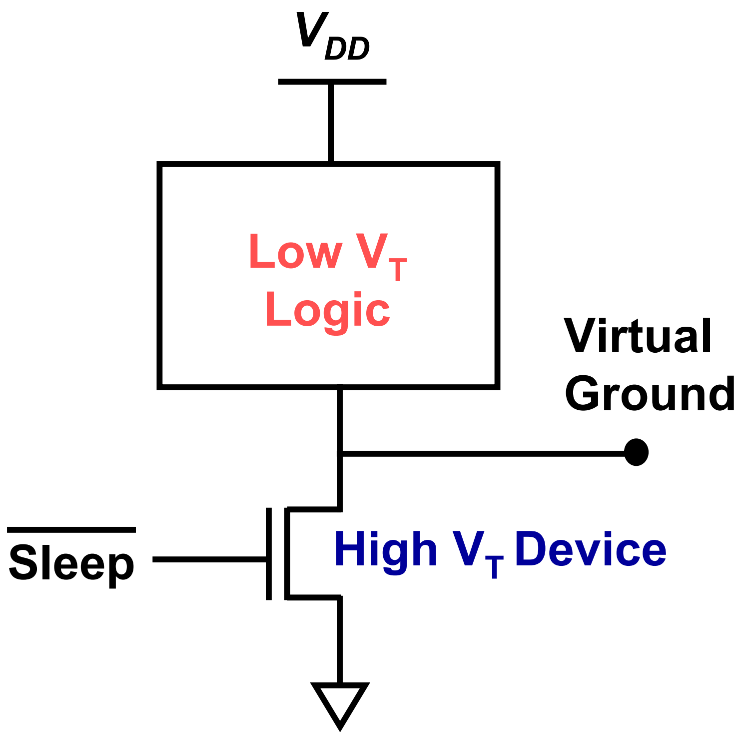


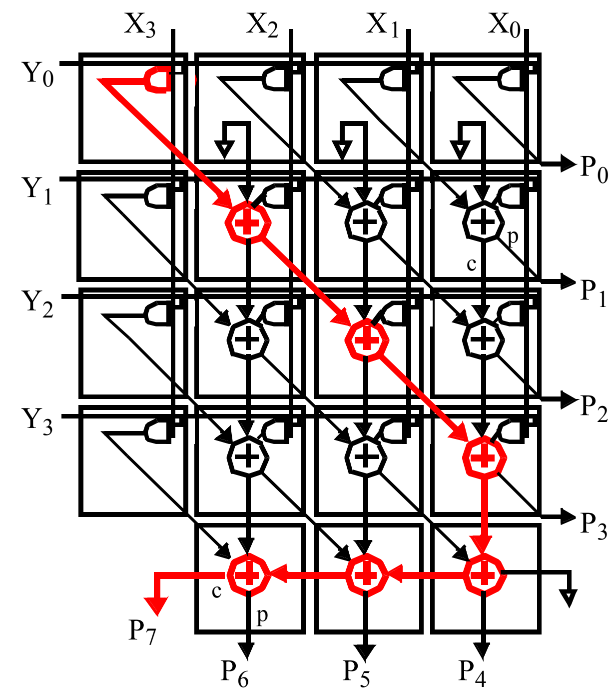


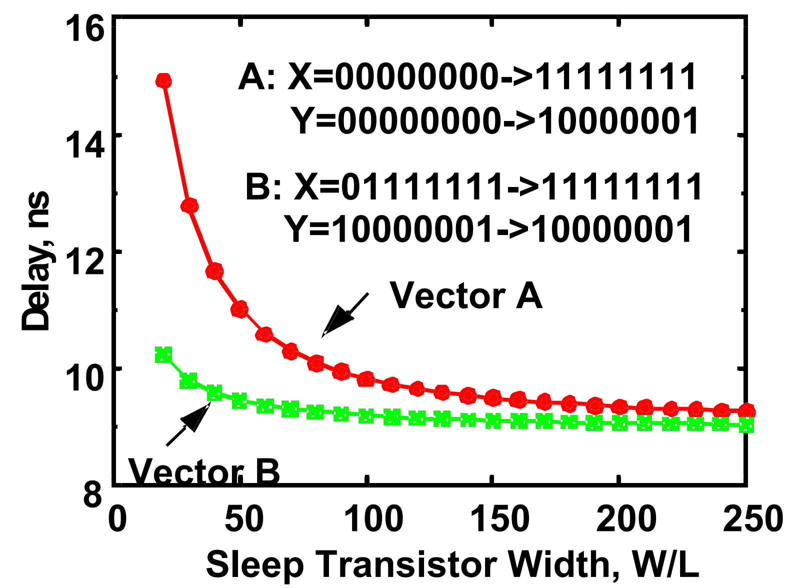


[Miyazaki, ISSCC ’02]

Leakage Mitigation Using MTCMOS



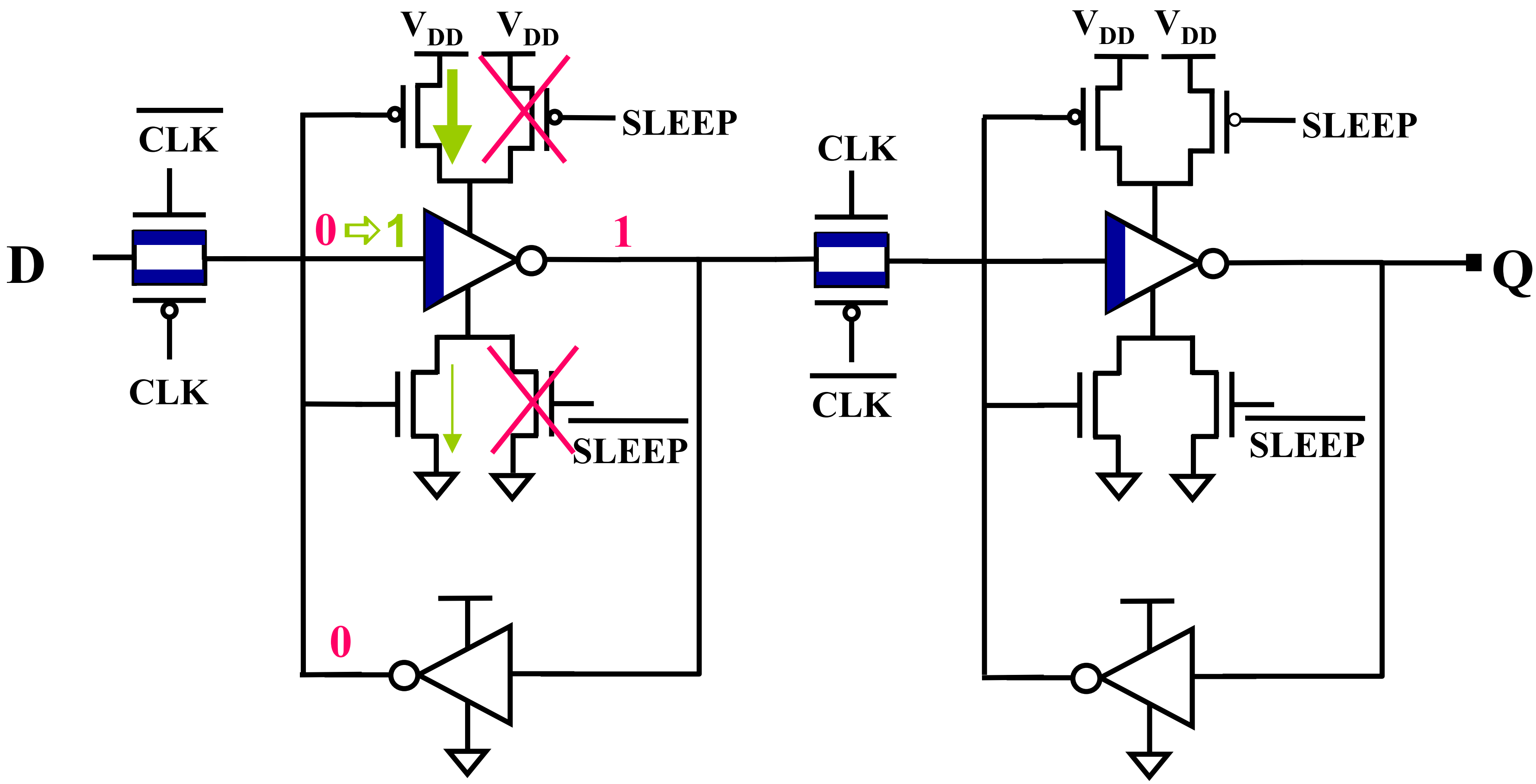




Device Sizing is a Major Concern in Multiple Threshold CMOS

"Leakage Feedback" Flip-Flop

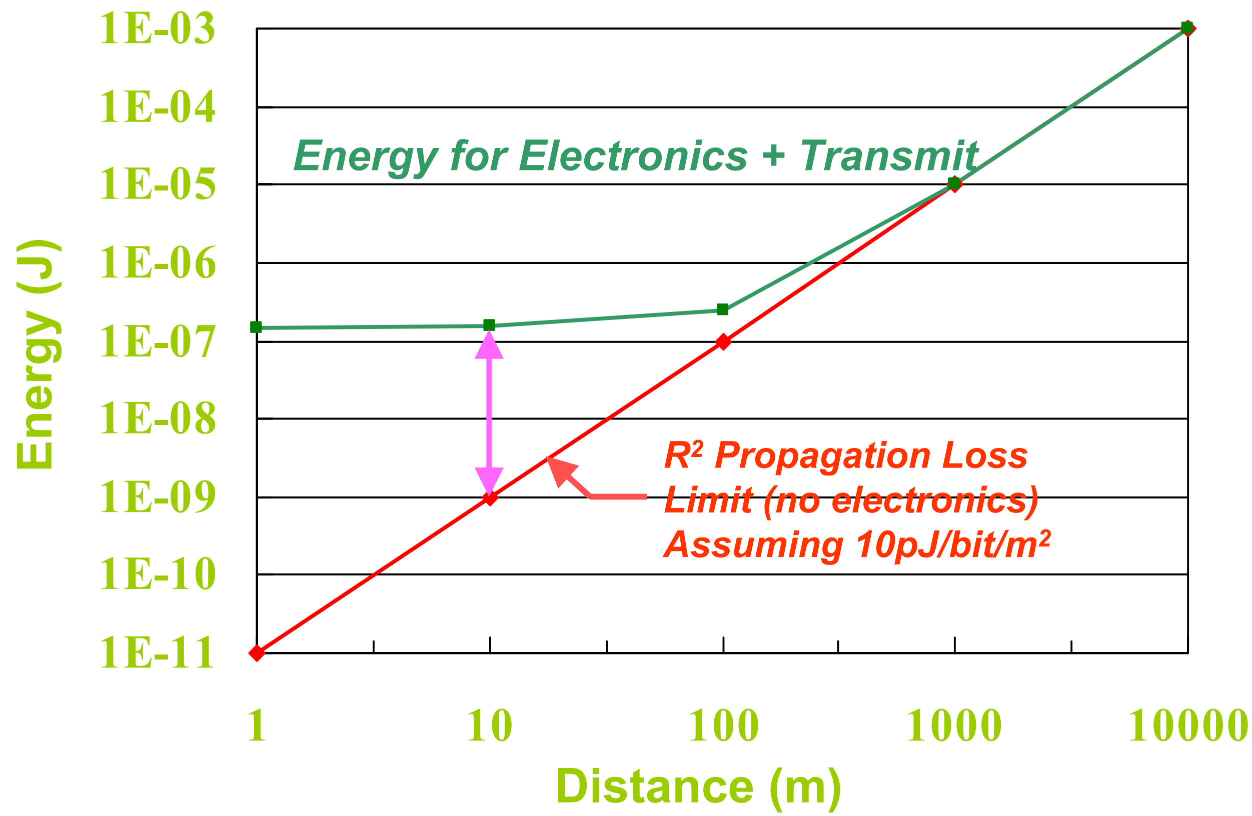
In the Idle Mode , with inputs drifting



[Kao, ESSCIRC '01]

- Use leakage to hold state in the flip-flop – very low leakage in sleep mode, with high-performance in active mode

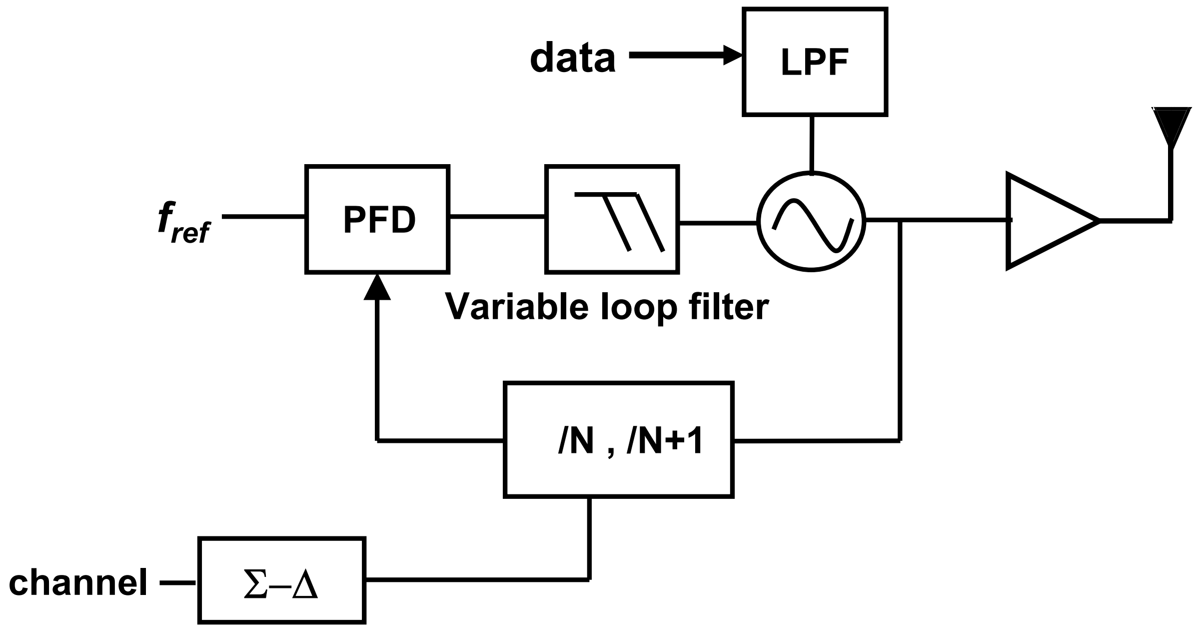
Computation vs. Communication

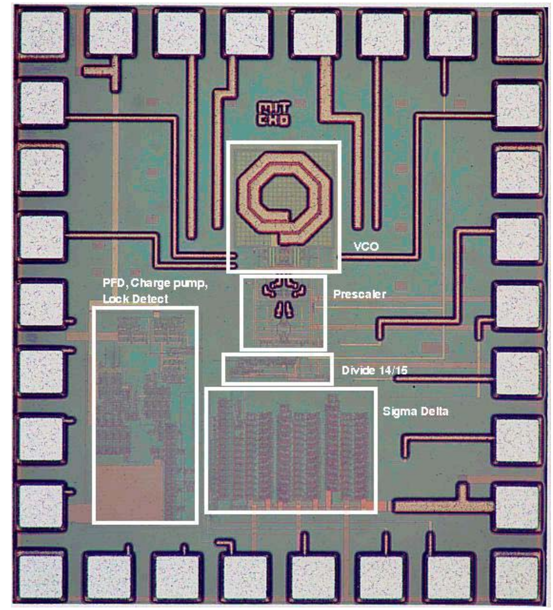


- Computation: 1nJ/op (μ-Processor) and Communication (@10m): 150nJ/bit
- @10 m: ~150 instructions/transmitted bit on a low-power processor
- @10m: > 1Million instructions/transmitted bit using dedicated hardware

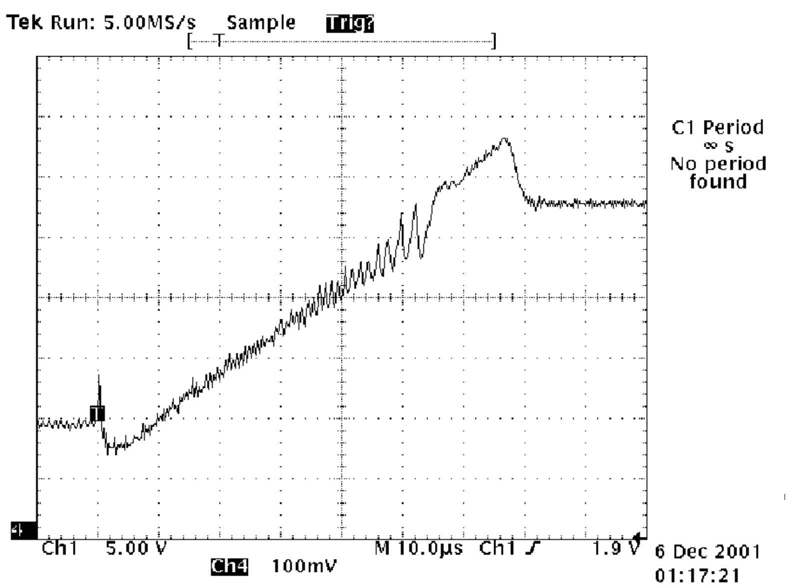
Compute, Don't Communicate

Fast Startup Transmitter

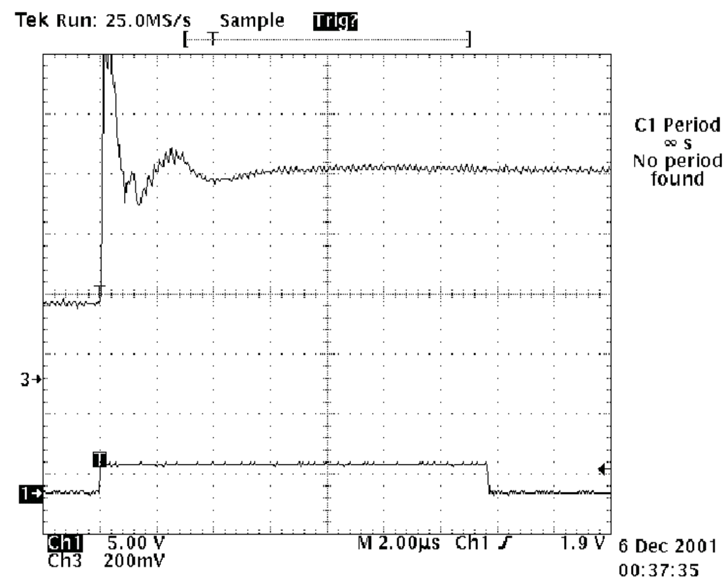




E/bit = 10nJ/bit

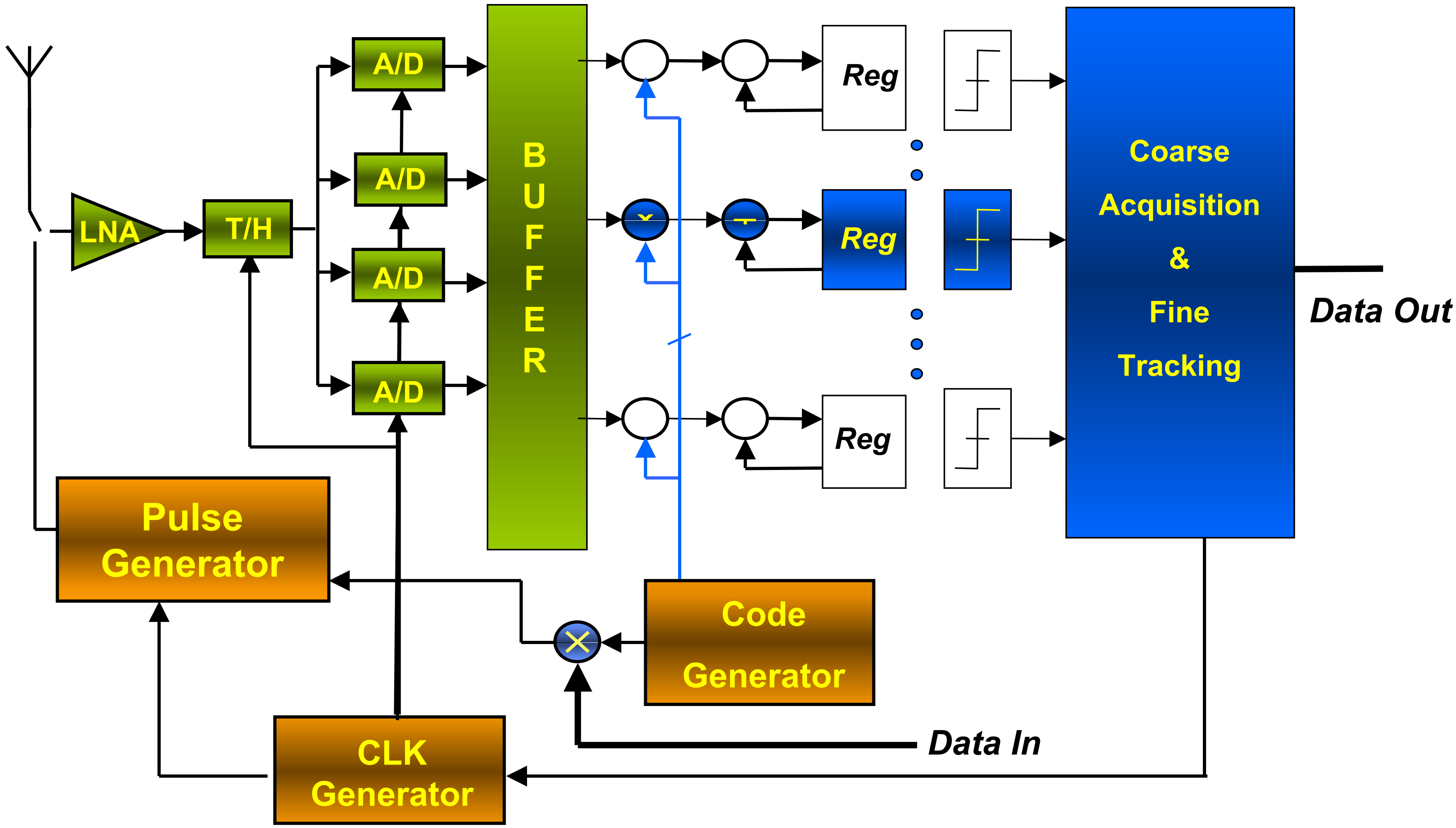


Fixed loop bandwidth



Variable loop bandwidth

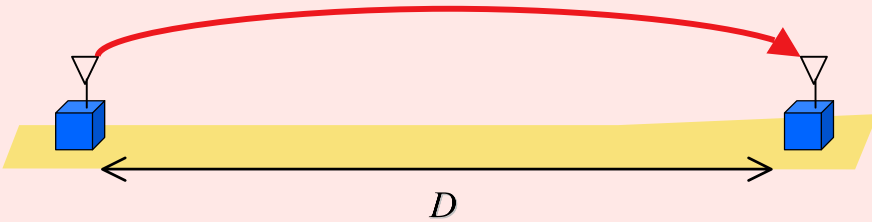
New Opportunities: "Digital" UWB Radio



- Minimal Front-end components: leverage low-power digital circuits
- 3-4 bits A/D sufficient (Newaskar, Blazquez, Chandrakasan, SIPS '02)

Multihop and the Characteristic Distance

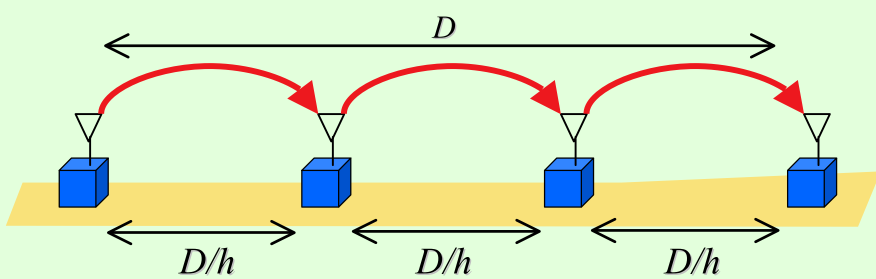
Direct Transmission



$$E = \alpha_1 + \alpha_2 D^2$$

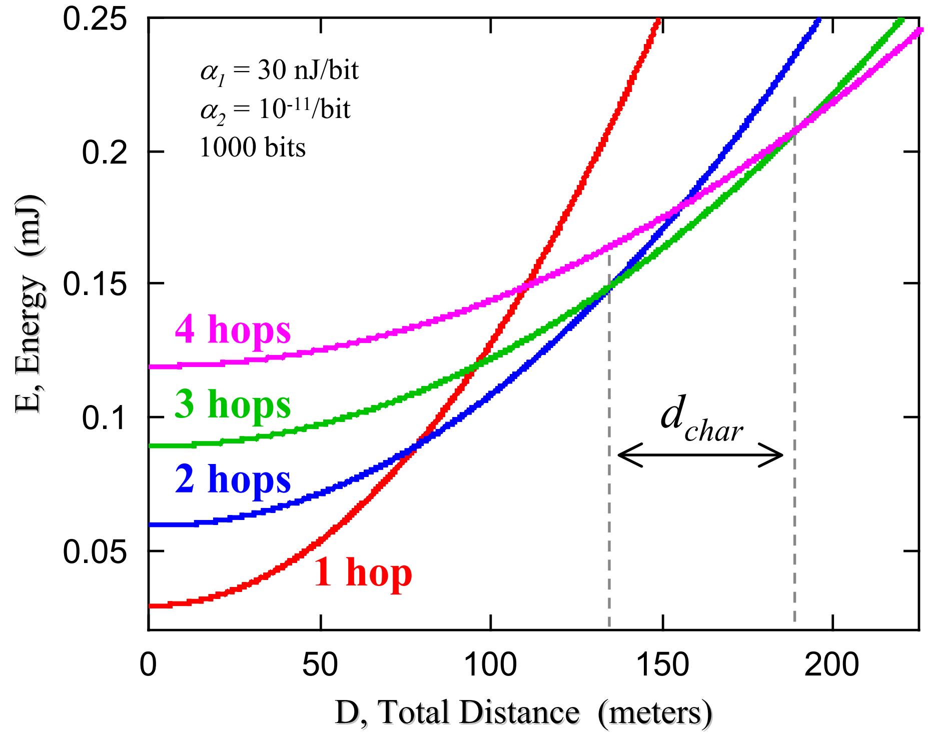
Tx &Rx Radio Electronics (α_1) · attenuation, power amp (α_2) · path loss exponent (2)

Multihop Transmission



$$E = h\left[\alpha_1 + \alpha_2 \left(D/h\right)^2\right]$$

number of hops (h) · per-hop distance (D/h)

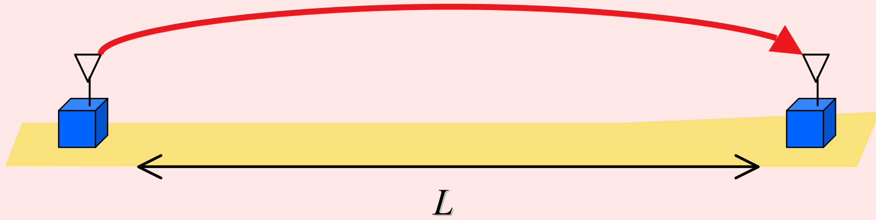


Characteristic Distance for Multihop Transmission

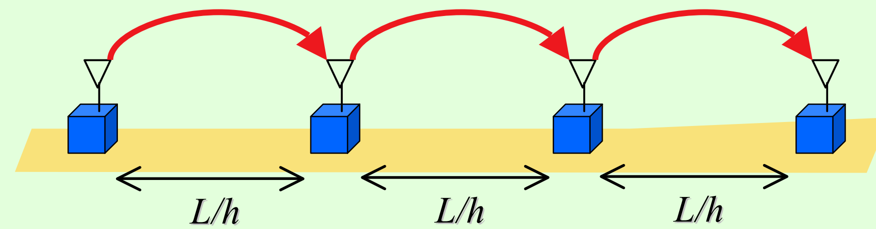
$$\min_h E = 2\alpha_1 \frac{D}{d_{char}}$$

$$\text{where} \quad d_{char} = \sqrt{\alpha_1 / \alpha_2}$$

Analogy to Buffered Interconnect

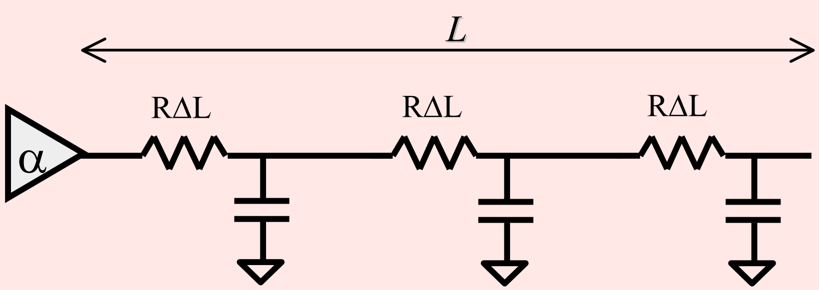


$$E = \alpha_1 + \alpha_2 L^2$$

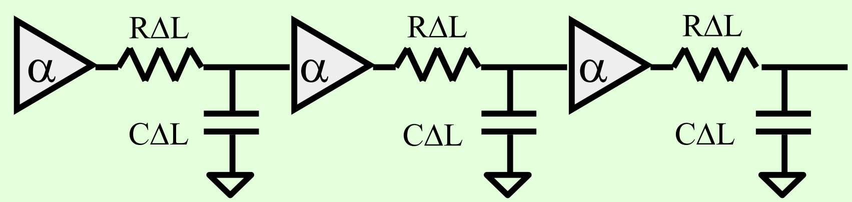


$$E = h\left[\alpha_1 + \alpha_2 \left(\frac{L}{h}\right)^2\right]$$

$$d_{char} = \sqrt{\frac{\alpha_1}{\alpha_2}}$$



$$T = \alpha + RCL^2$$

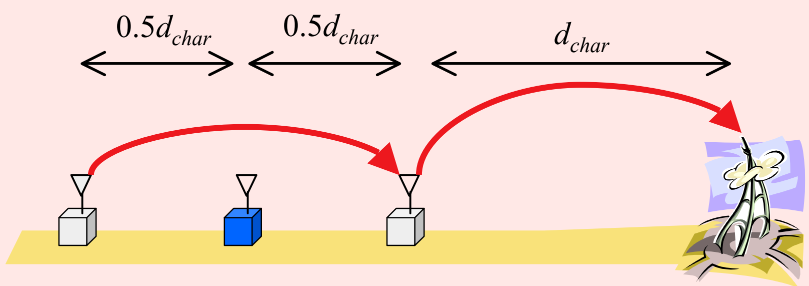


$$T = k\left[\alpha + RC\left(\frac{L}{k}\right)^2\right]$$

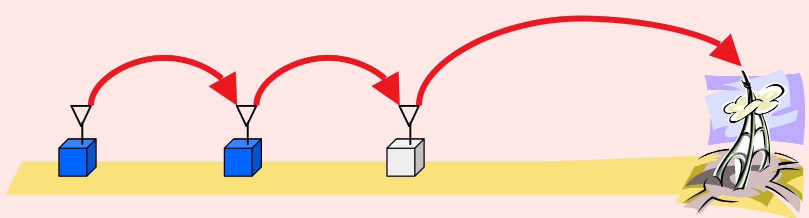
$$d_{char} = \sqrt{\frac{\alpha}{RC}}$$

Dithering of Characteristic Distance

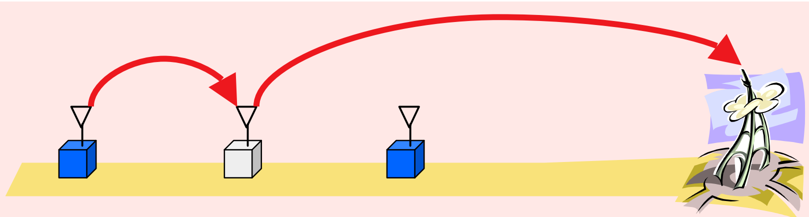
Fixed Multihop Routes



Lifetime = 77 days

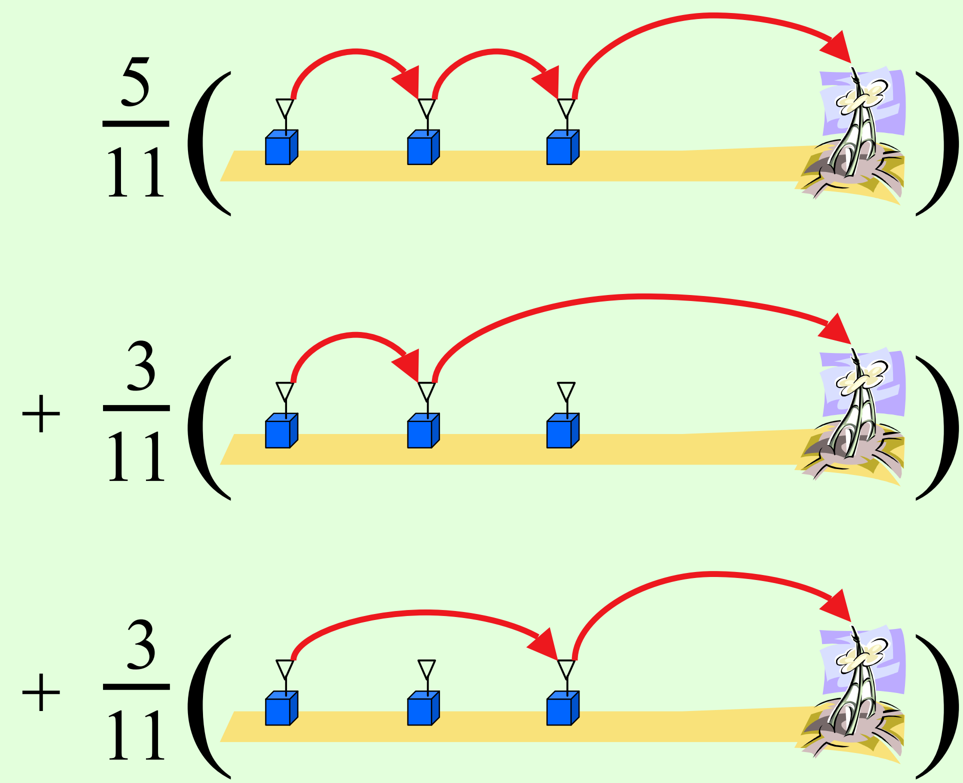


Lifetime = 77 days



Lifetime = 47 days

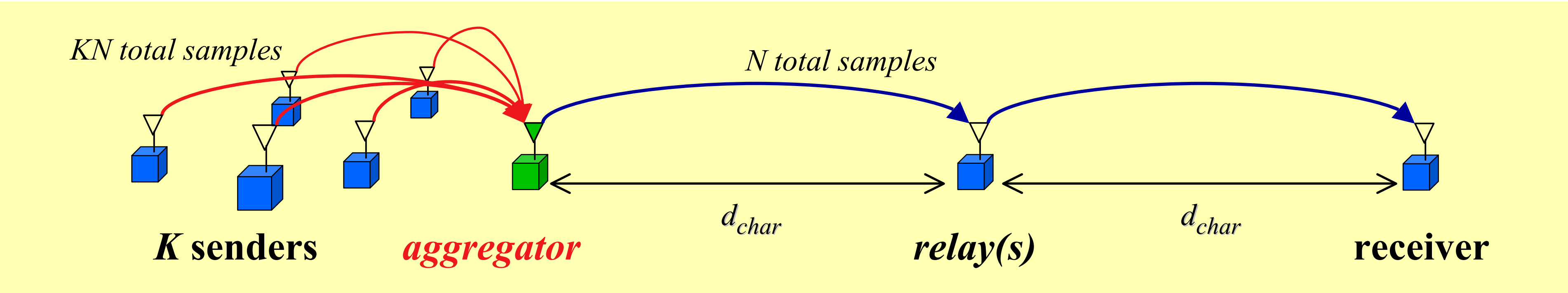
Rotated Routes

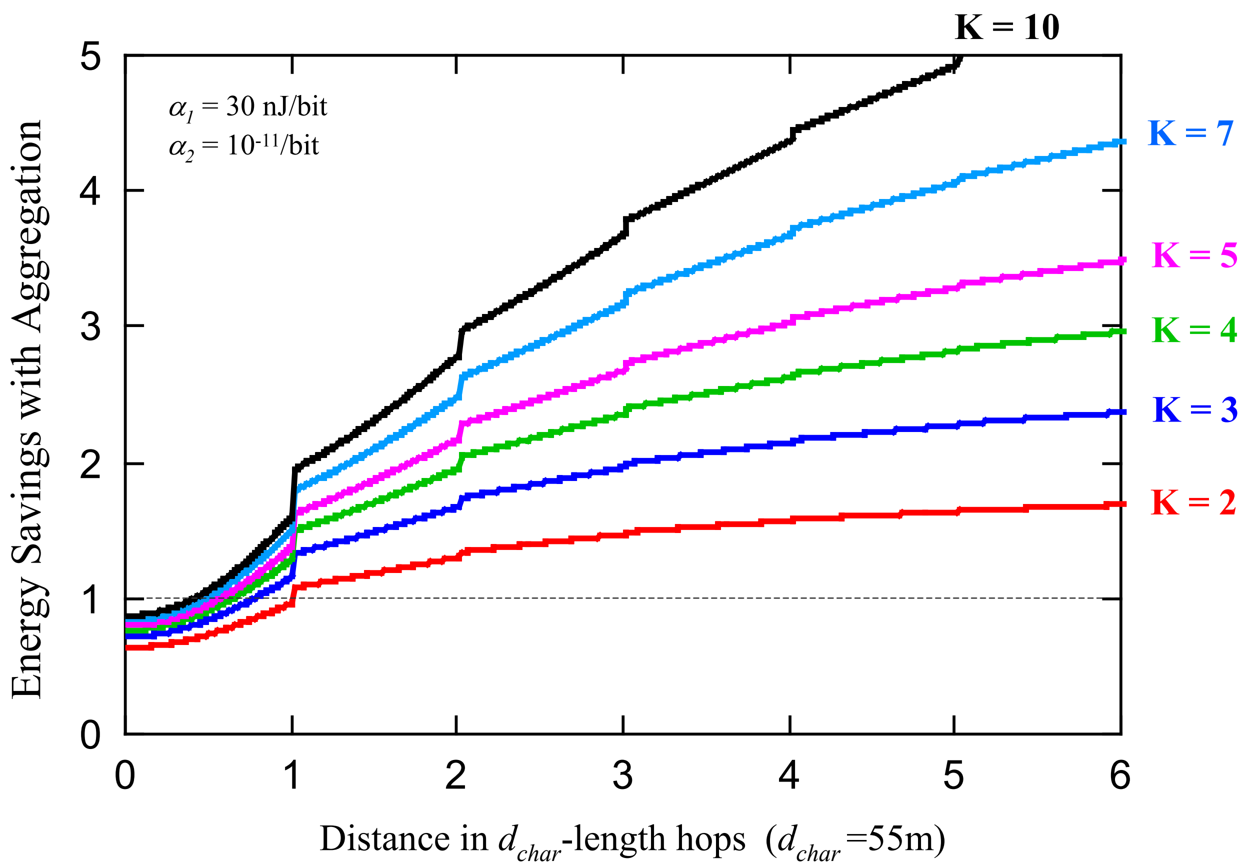


= **116 days of lifetime**

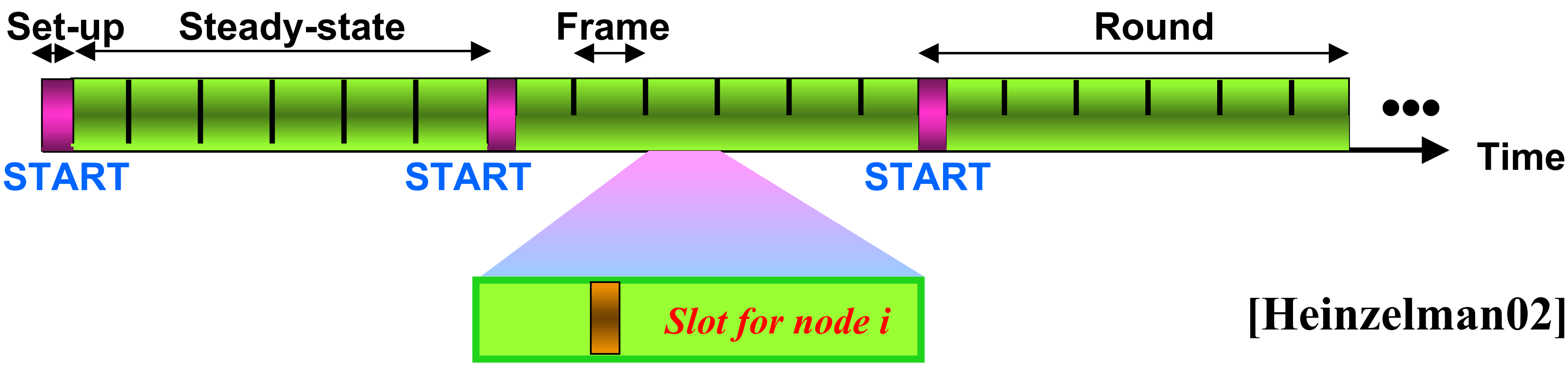
Even spatial distribution of energy burden

Signal Processing in the Network



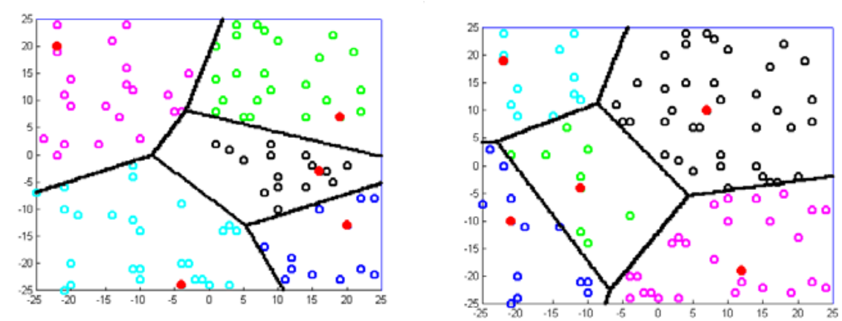


Clustering Protocols



[Heinzelman02]

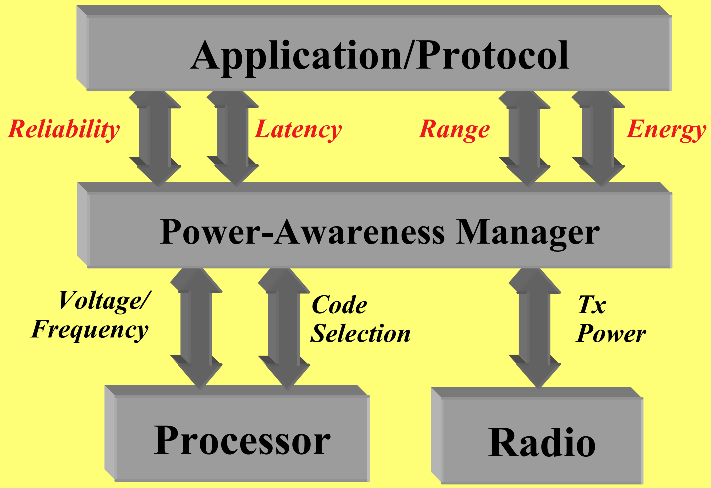
- **Clustering**
  - Localized control (through the "cluster head")
  - Local data aggregation
- **Randomized Rotation of cluster-heads**
  - Clusters formed during set-up
  - Data transfers during steady-state
- **TDMA in steady state**
  - Node *i* transmits once per frame
  - No collisions ⇨ low energy
  - Maximum sleep time



Round n　　*Round n+1*

Opportunity: Reactive Radios [Rabaey, ISSCC02]

API and Middleware Layer



Power Aware API: **<u>performance of communication</u> defined and exposed as a basis for trade-offs**

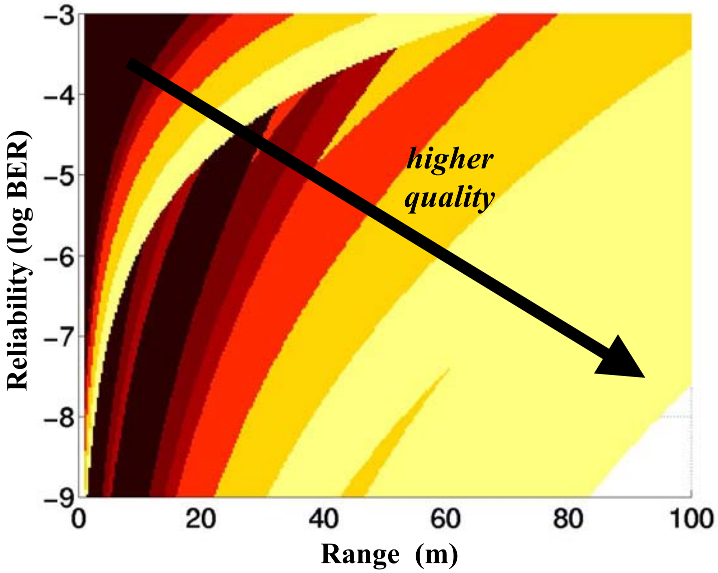
- **set_max_energy(Energy energy)**
- **set_max_latency(Time latency)**
- **set_min_reliability(Prob probReception)**
- **set_range(int nearestNodes, Node[] who, float meters)**

Quality of communication defined along four axes:

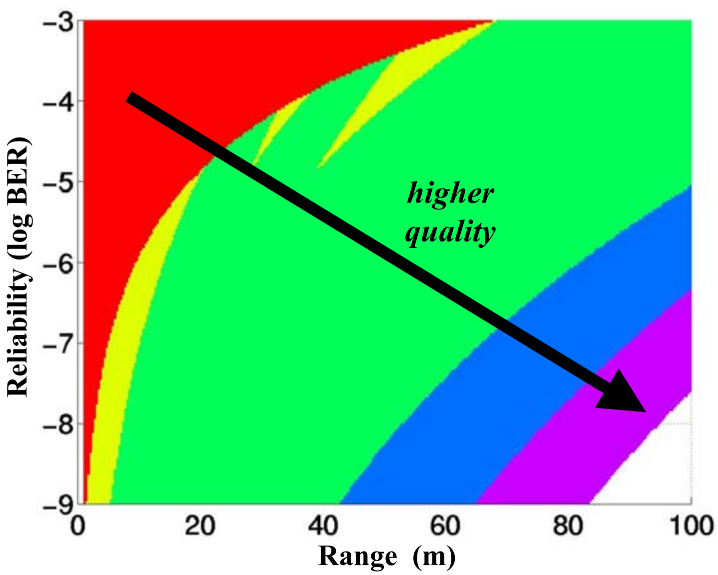
Concern	Metric
"To whom?"	**Range (m)**
"How soon?"	**Latency (ms)**
"How reliably?"	**Reliability (BER)**
"How much energy?"	**Energy (μJ)**

API-Controlled Operational Policy

Radiated Power



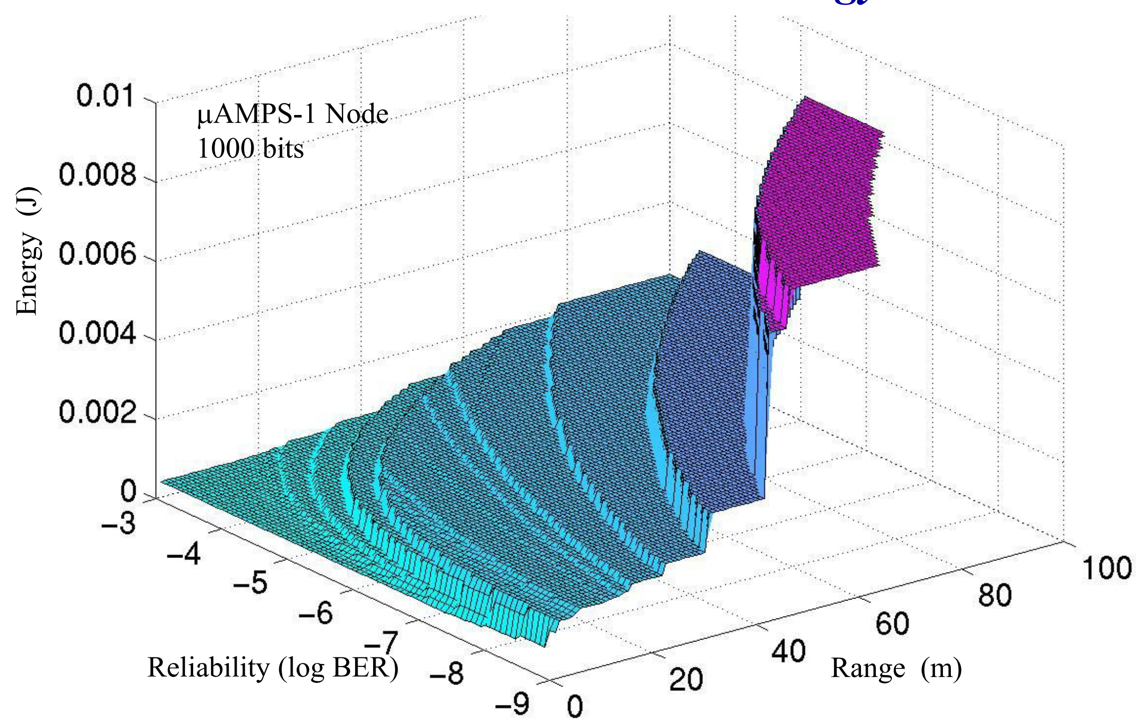
Convolutional Code



Operational Policies

Radiated Power	Convolutional Code
+0 dBm	Uncoded
+3 dBm	R=2/3, K=3
+5 dBm	R=1/2, K=3
+10 dBm	R=1/2, K=5
+15 dBm	R=1/2, K=7
+20 dBm	

Total Communication Energy



Energy scales gracefully with communication quality

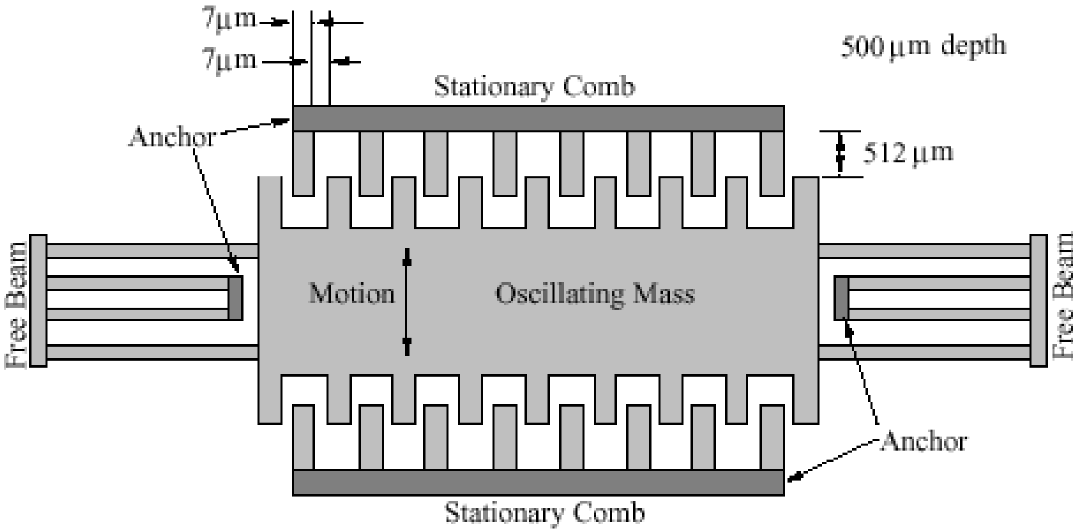
Energy Scavenging

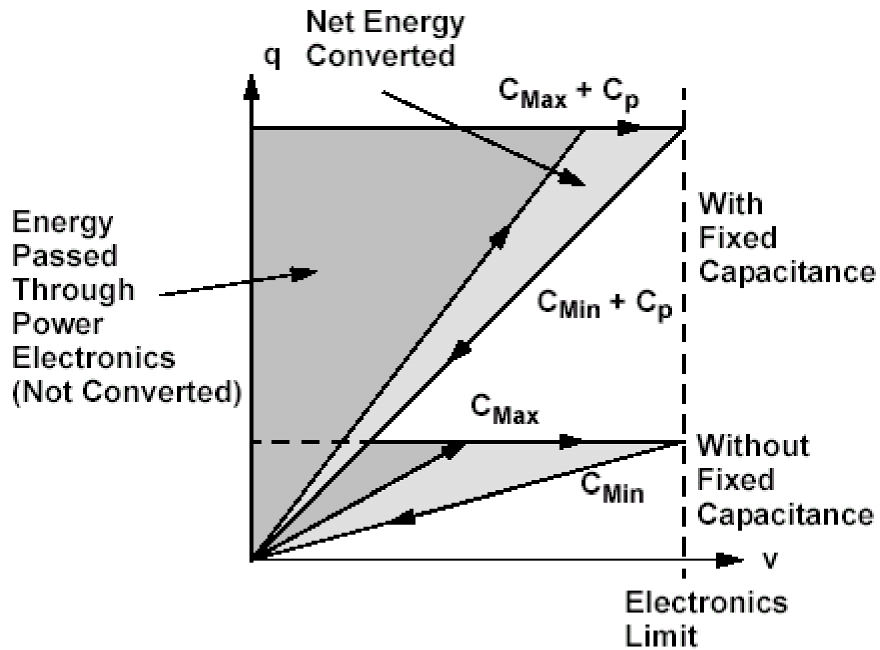
- Self-powered operation is a real option if the power dissipation can be scaled to 10's - 100's of μW
  - Mechanical vibration (e.g., machine mounted sensors)
  - Electromagnetic fields (RF)

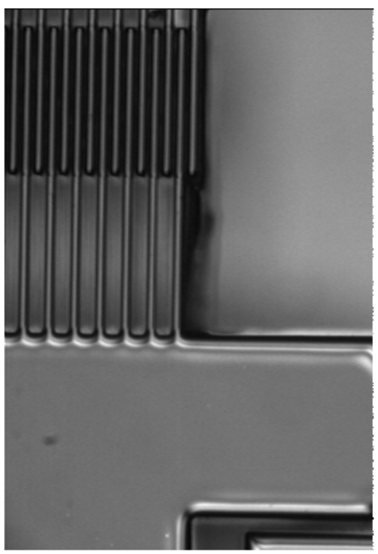
  ⋮

- A major opportunity exists in developing energy scavengers (generator and associated electronics) for extracting useful energy from ambient sources

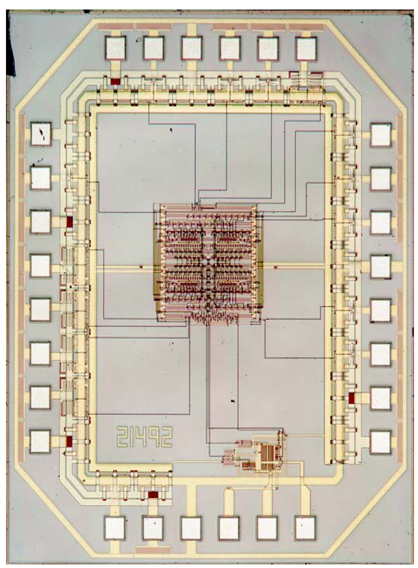
Vibration-to-Electric Energy



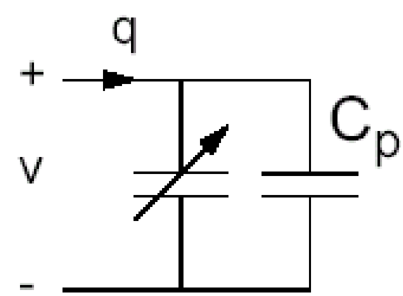




MEMS Generator

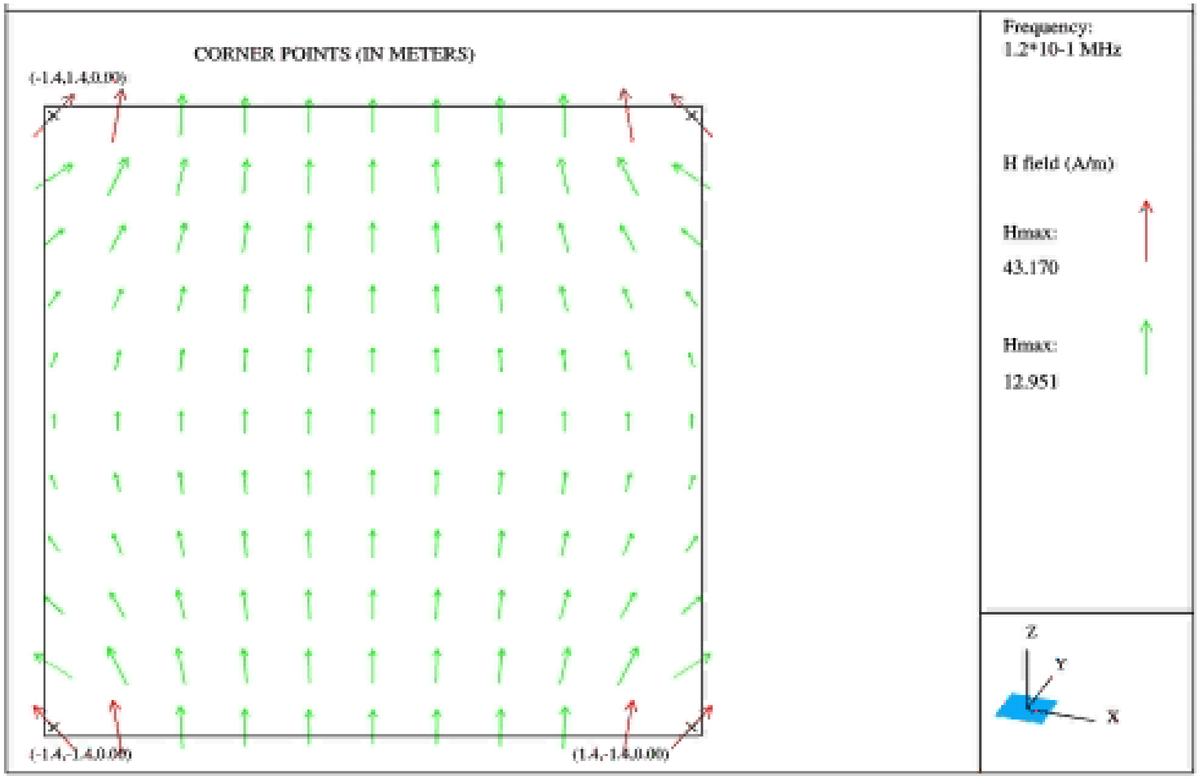


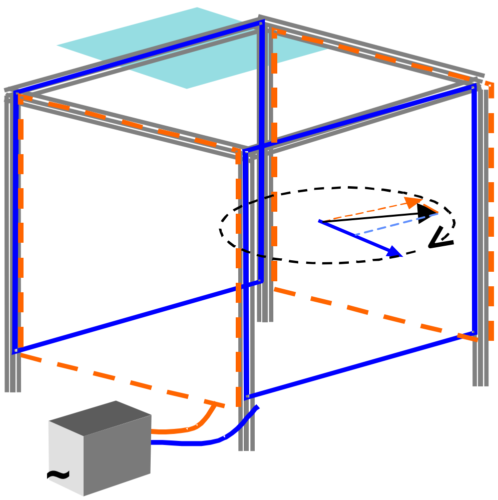
Controller



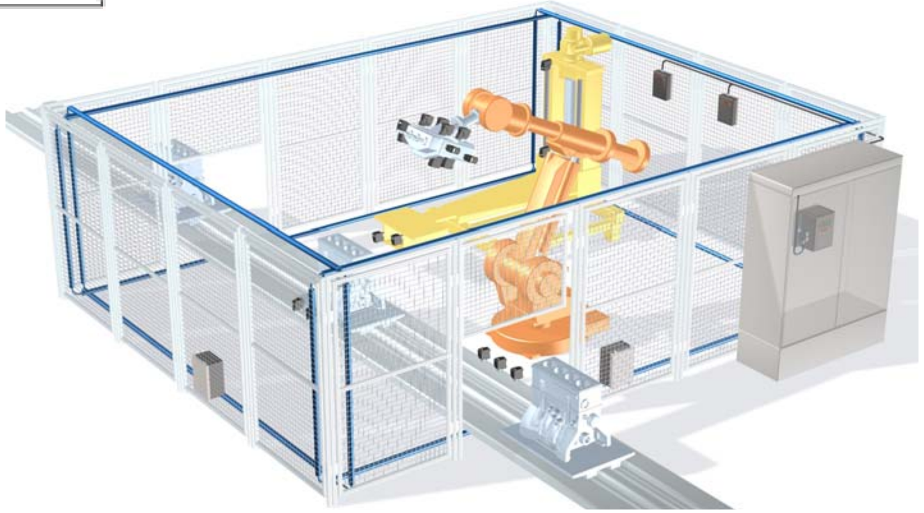
Hardwired Fabrics enable No Power Signal Processing (10μW from generator)

Proximity Sensor: Wireless Power Supply





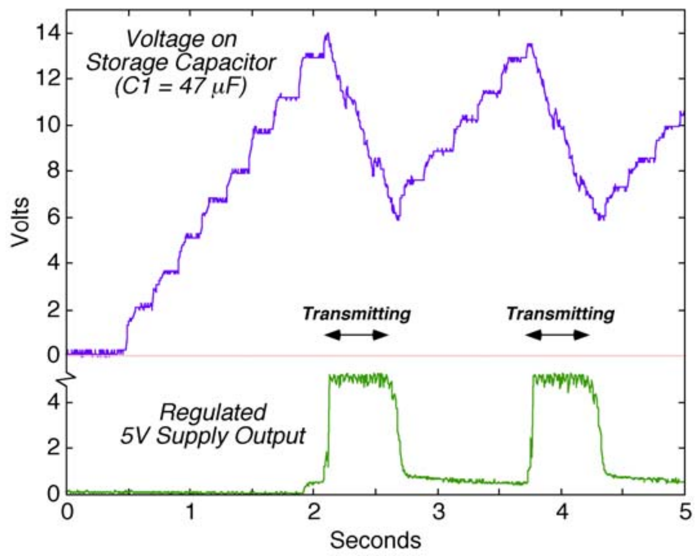
Simulation of rotating field over one period at 120kHz (in middle of 2D arrangement and supplied plane xy)



Courtesy of Snorre Kjesbu, ABB

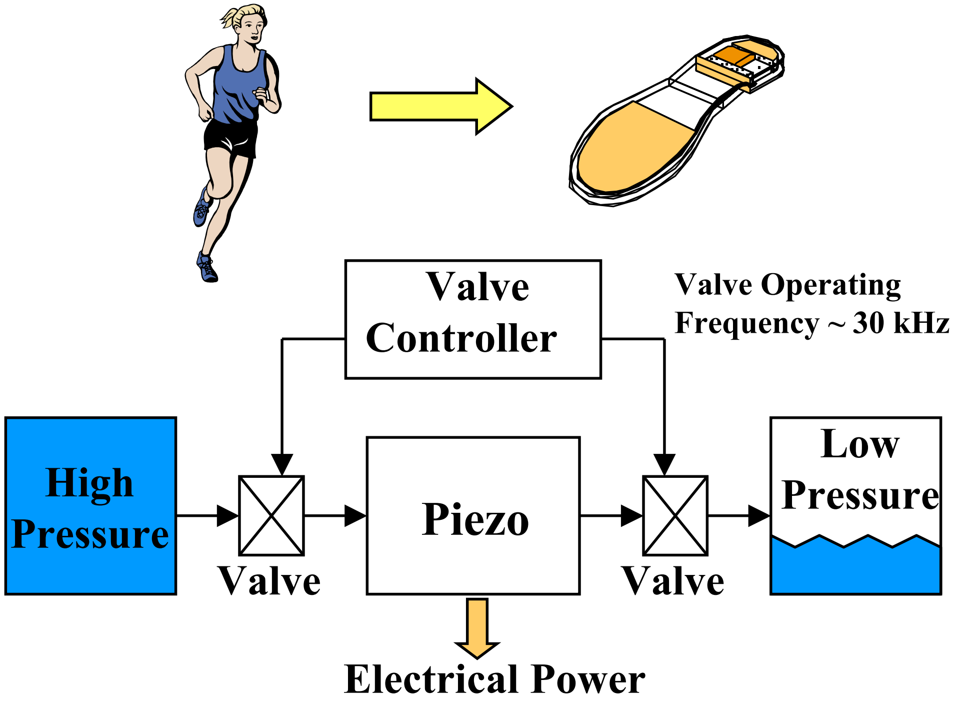
Heel-Strike Energy Harvesting

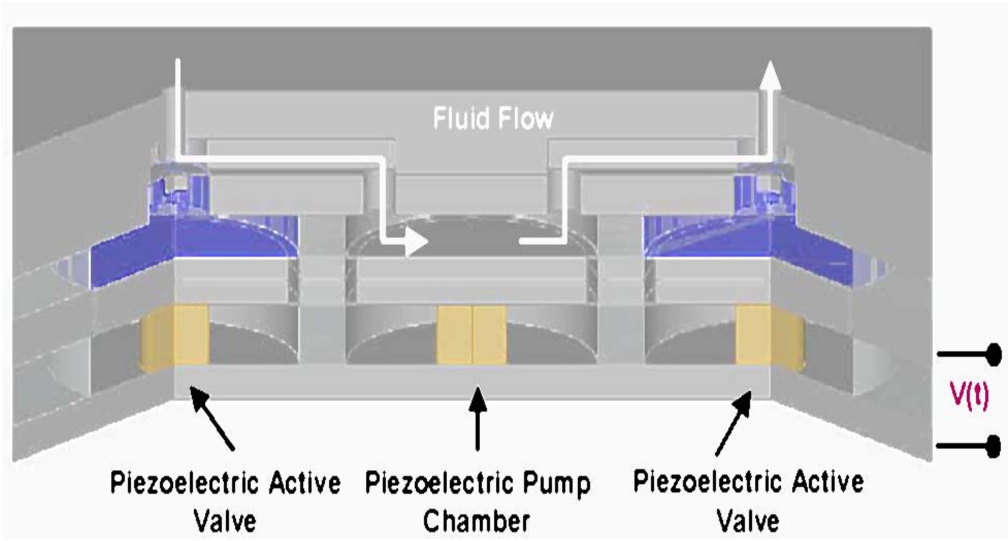
Joe Paradiso (MIT Media Lab)



After 3-6 steps, it provides 3 mA for 0.5 sec ~10mW

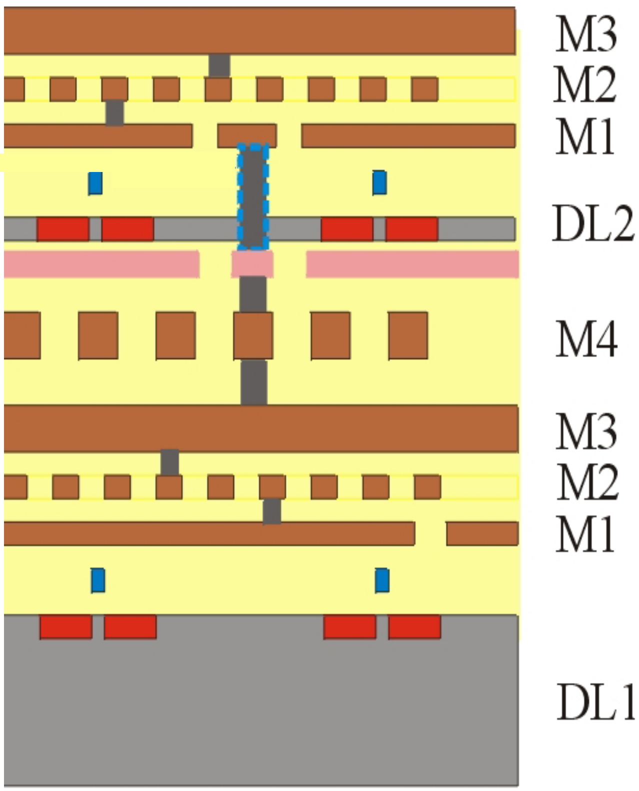
Hagood, Spearing, Schmidt (MIT)



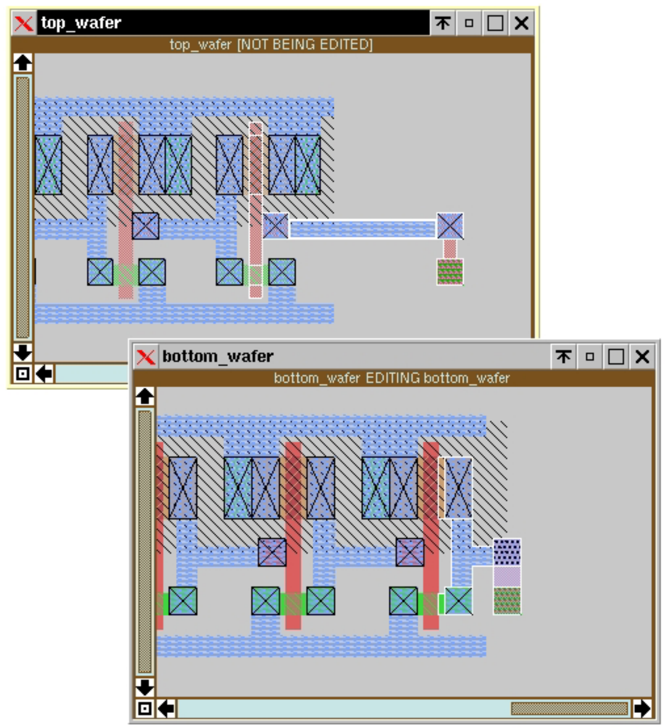


3D Integration

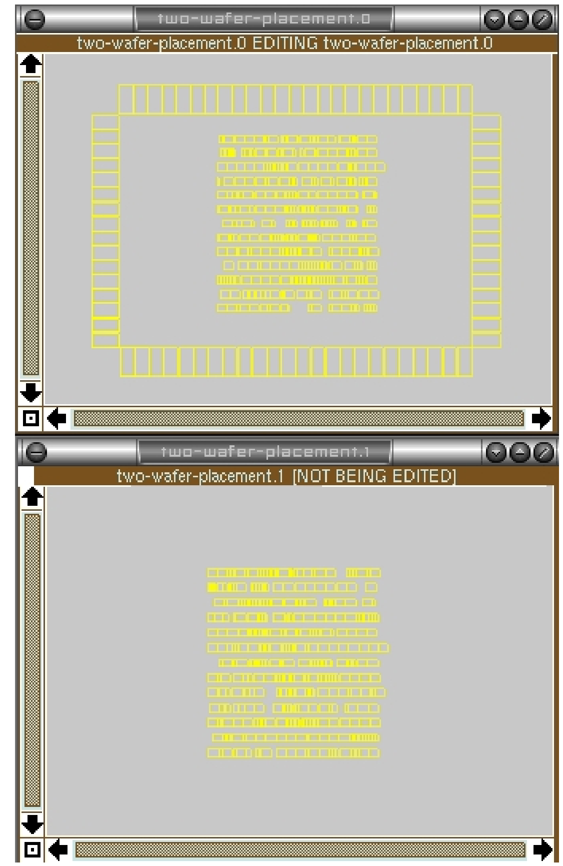
3-D Integration



3-D Layout Editor



3-D Standard Cell Placement and Routing



Compact Interconnection of Heterogeneous Technologies

Conclusions

- Exciting new applications enabled by a network of low-power wireless sensing devices
- Power Aware Design Methodology supersedes Energy Efficient Design
- *Slower is Better* – exploit sub-threshold operation as fastest switching speed is not needed
- *Communication-centric design*
  - Energy per operation (mW/MIPS) will scale with technology
  - Communication costs (nJ/bit) will not scale at the same rate

Low Energy Sensor Design Requires a System-level Approach – Tight Coupling Between Fabrics, Algorithms and Protocols