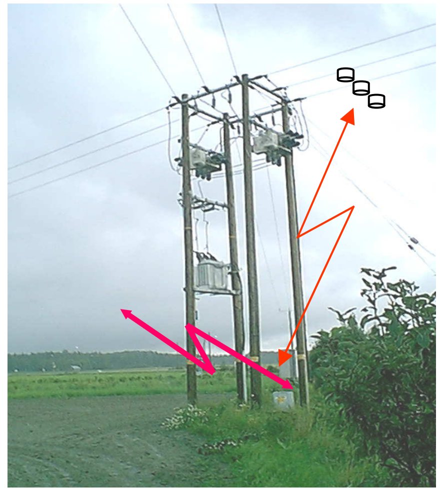
Design Considerations for Next Generation Wireless Power Aware Microsensor Nodes

D. Wentzloff, B. Calhoun, R. Min, A. Wang, N. Ickes, A. Chandrakasan

Massachusetts Institute of Technology

Emerging Microsensor Applications

Industrial Plants and Power Line Monitoring (courtesy ABB)

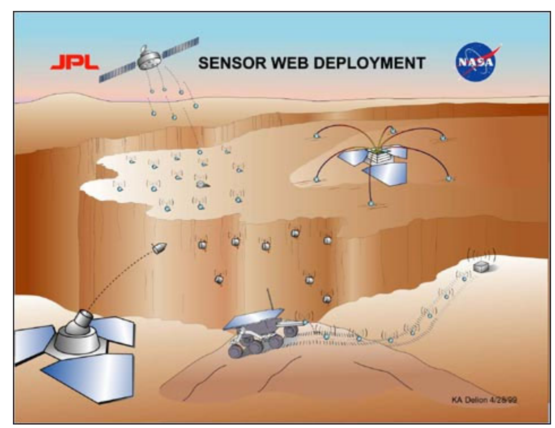


Operating Room of the Future (courtesy John Guttag)

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

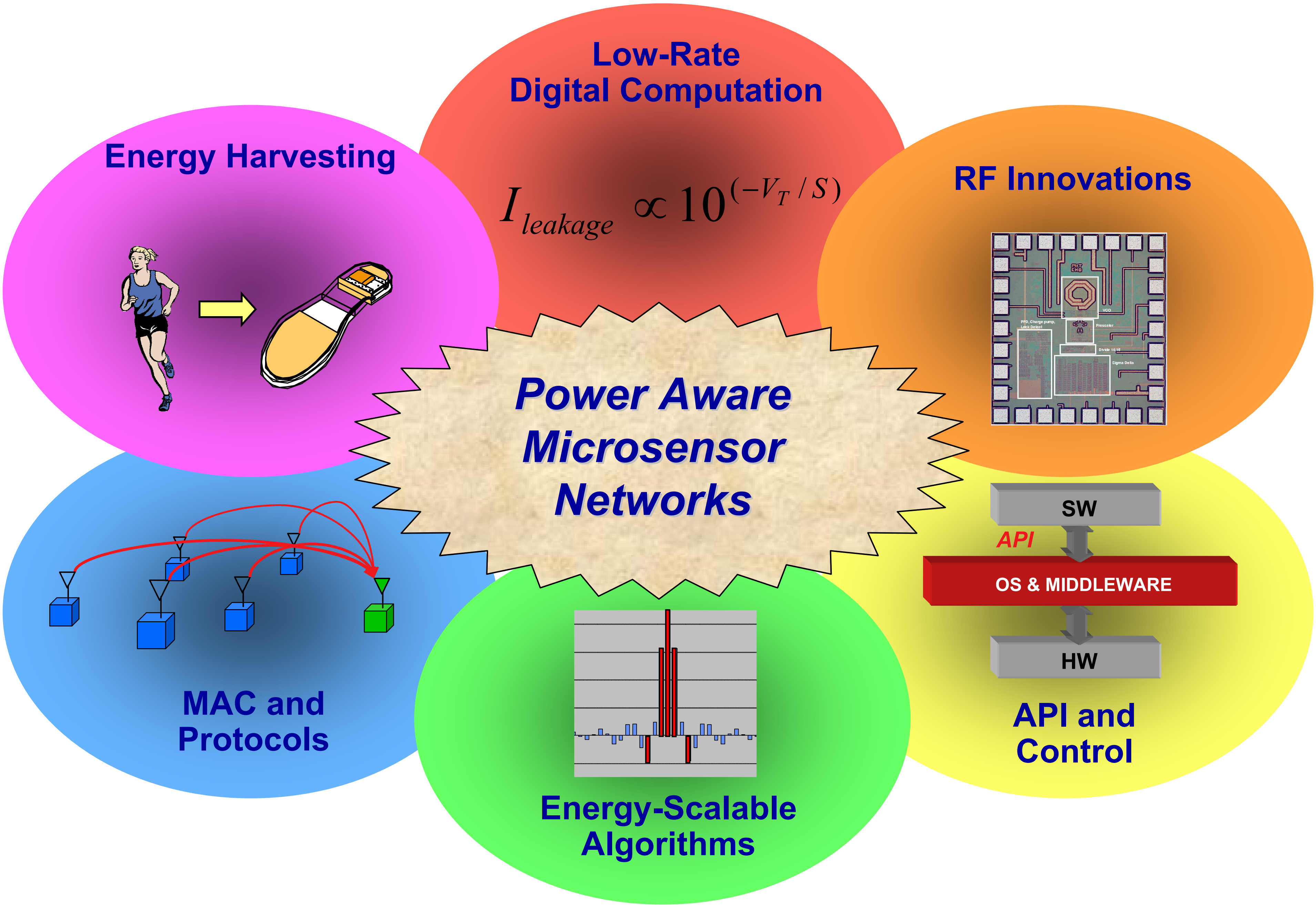
Application-specific designs provide energy efficient point solutions

Unpredictable Diversity

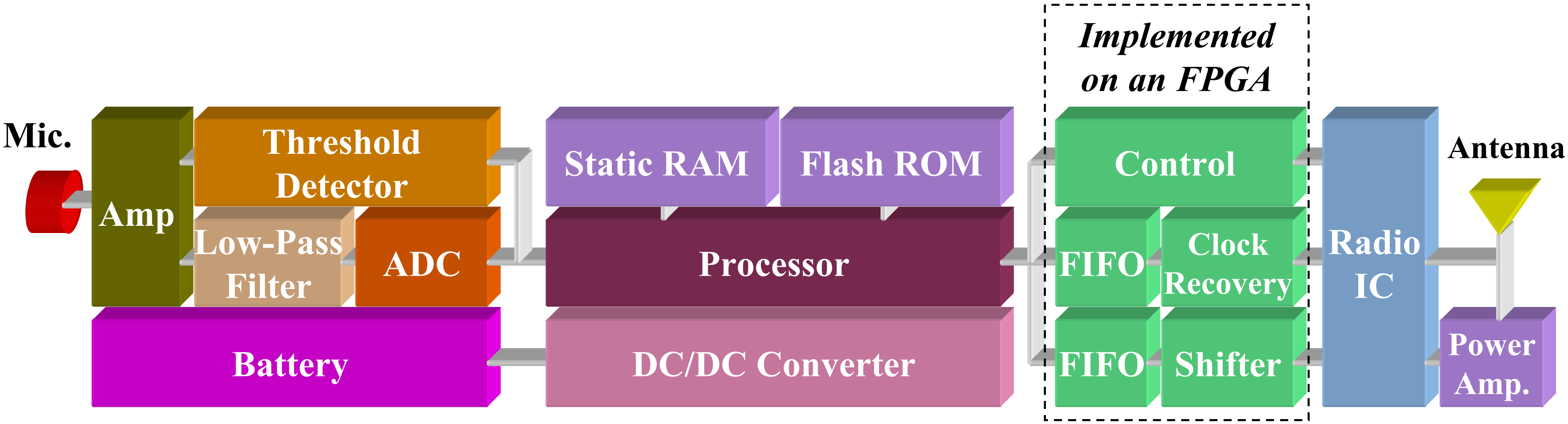
- ***Network roles:***
  relay, sensor, aggregator
- ***Environment:***
  event and signal statistics
- ***User/Application:***
  required latency, quality

Power-aware designs adapt energy consumption to operating conditions

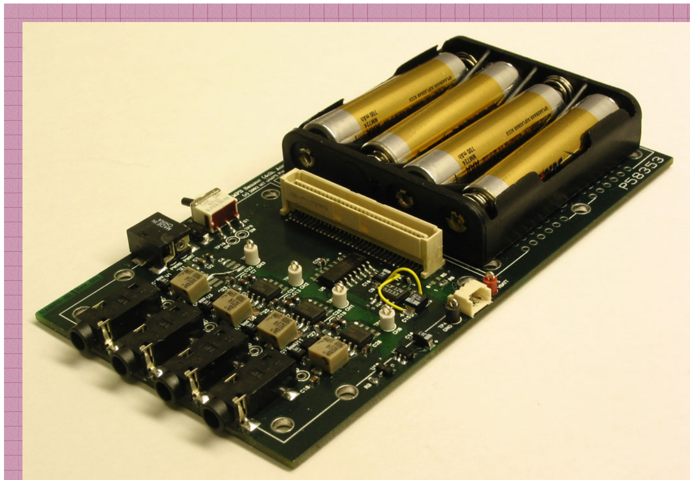
Power Aware Microsensor Considerations



First Generation Wireless Microsensor

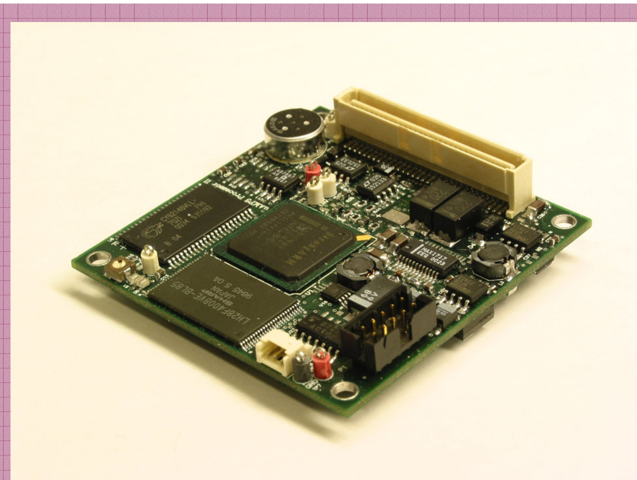


Sensor



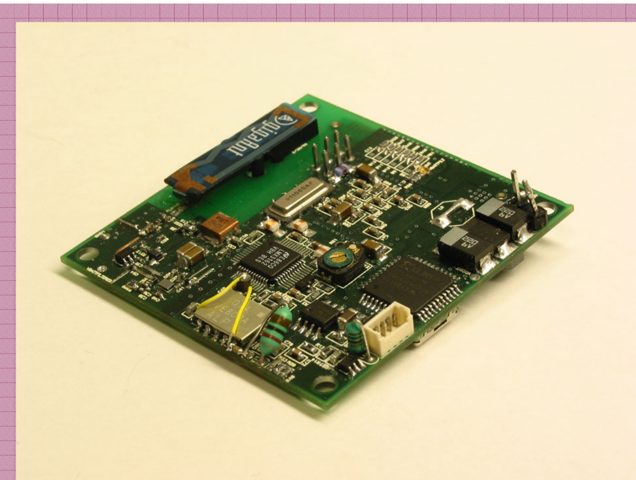
4-channel acoustic

Processor



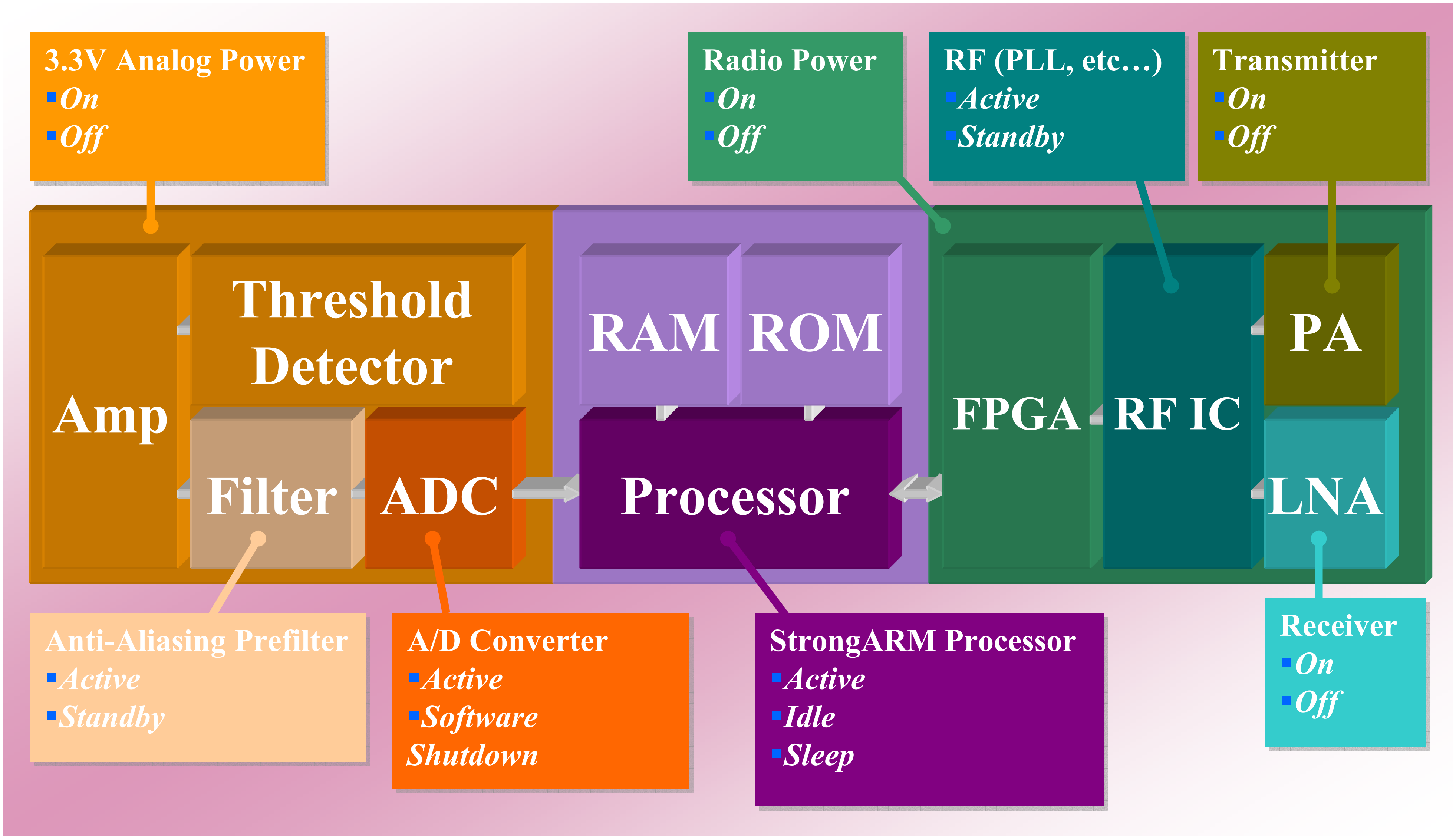
206MHz StrongARM

Radio



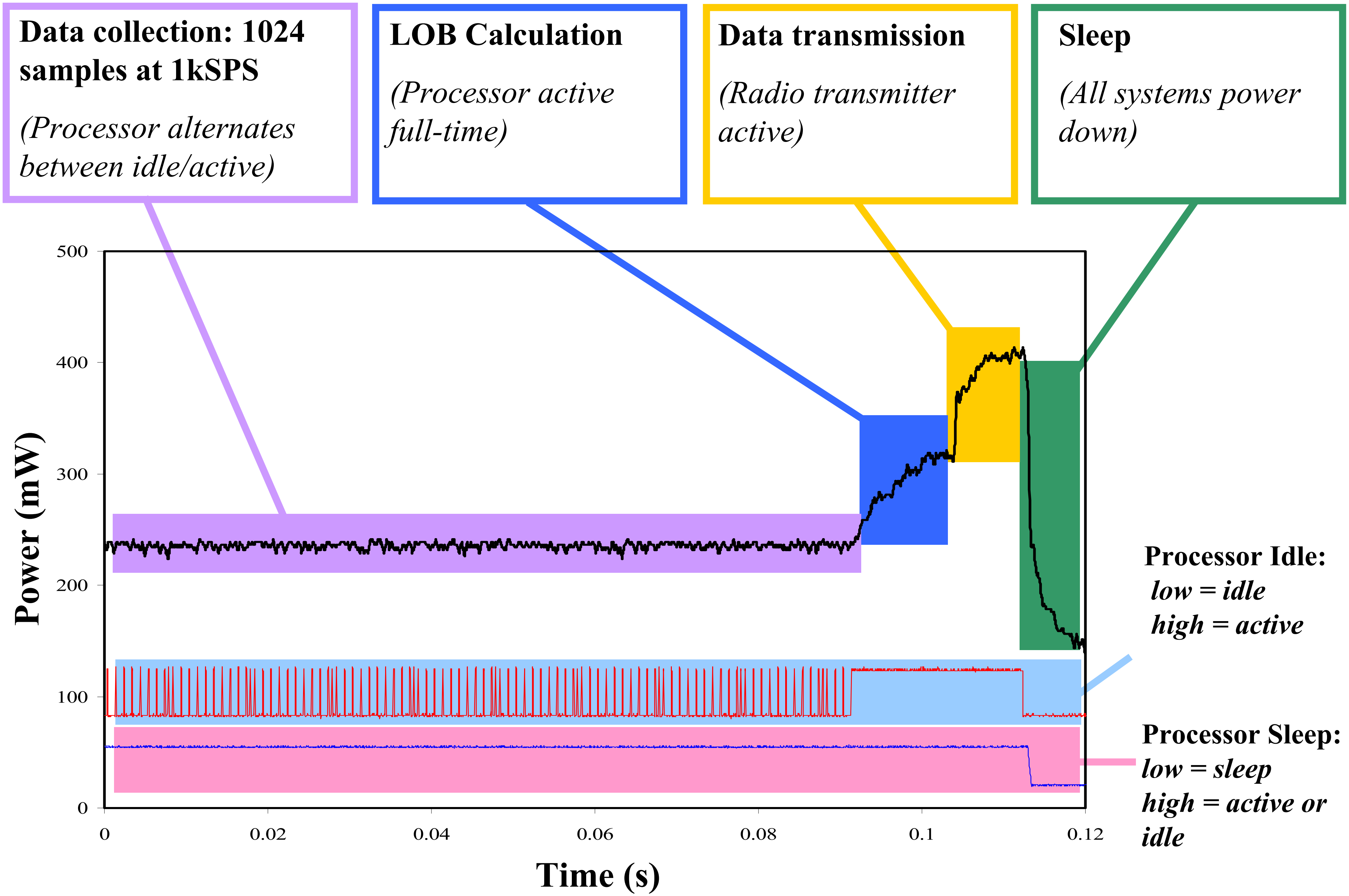
2.4GHz ISM band

Fine Grain Shut Down Control

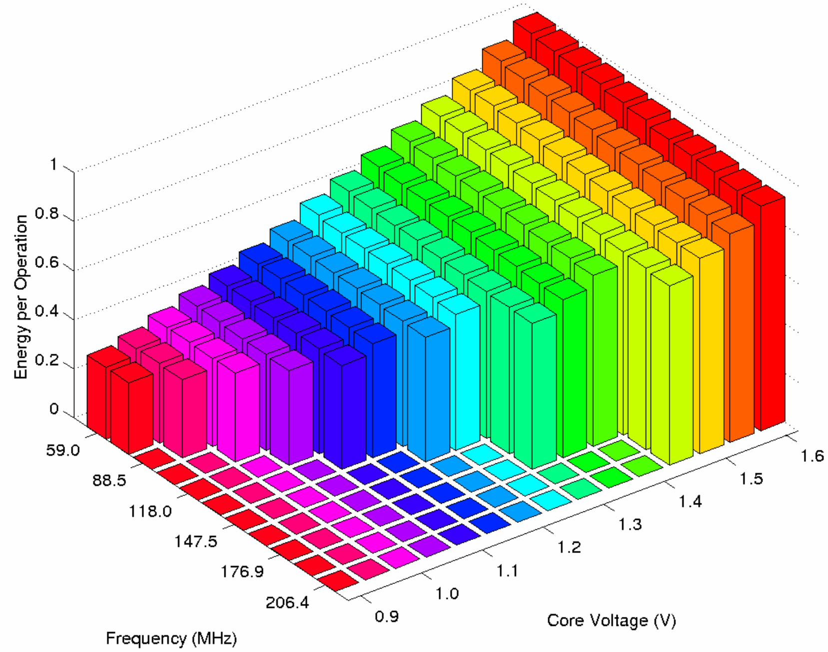


- **Active Power Management:** DVS, variable ECC and packet size, variable transmit power, agile algorithms

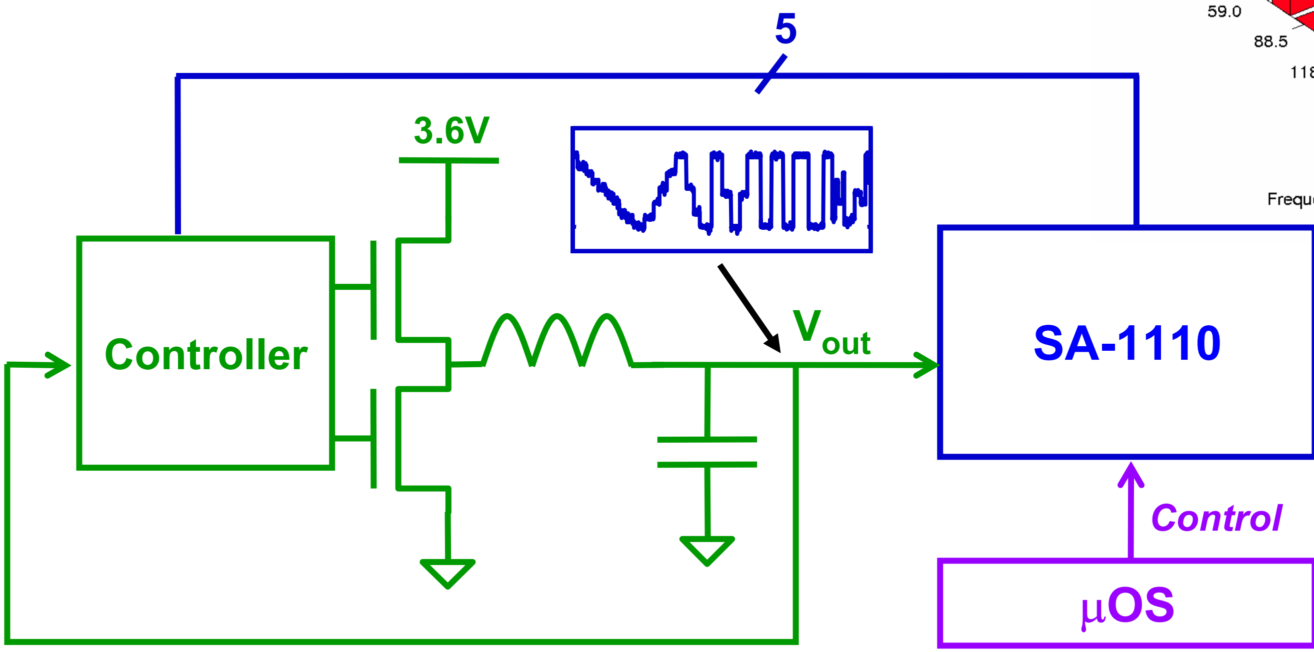
OS-Controlled Power Down Modes



Dynamic Voltage Scaling

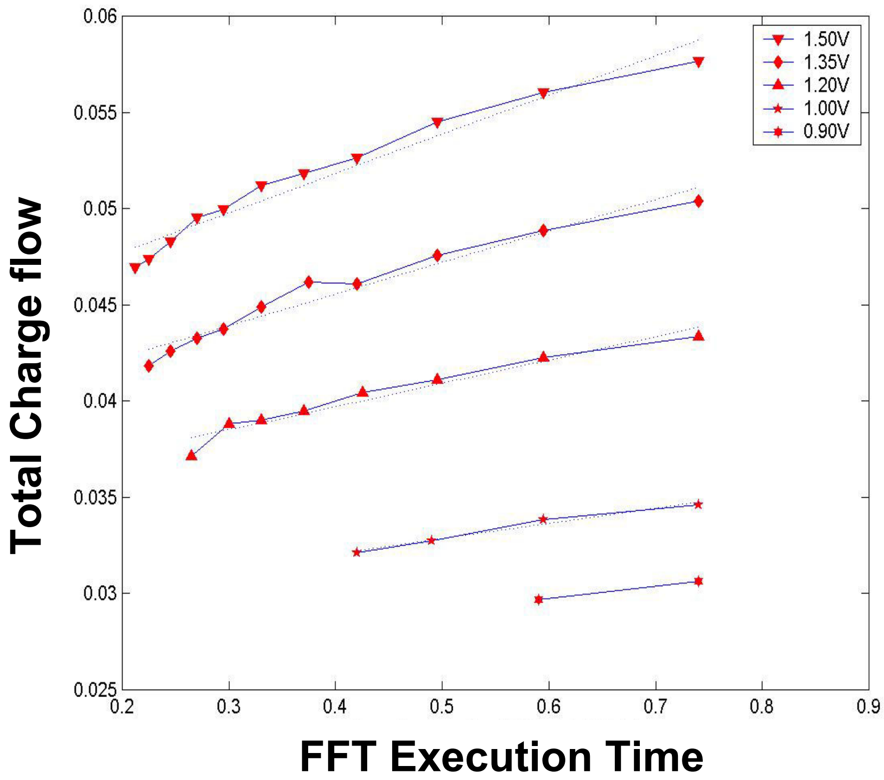


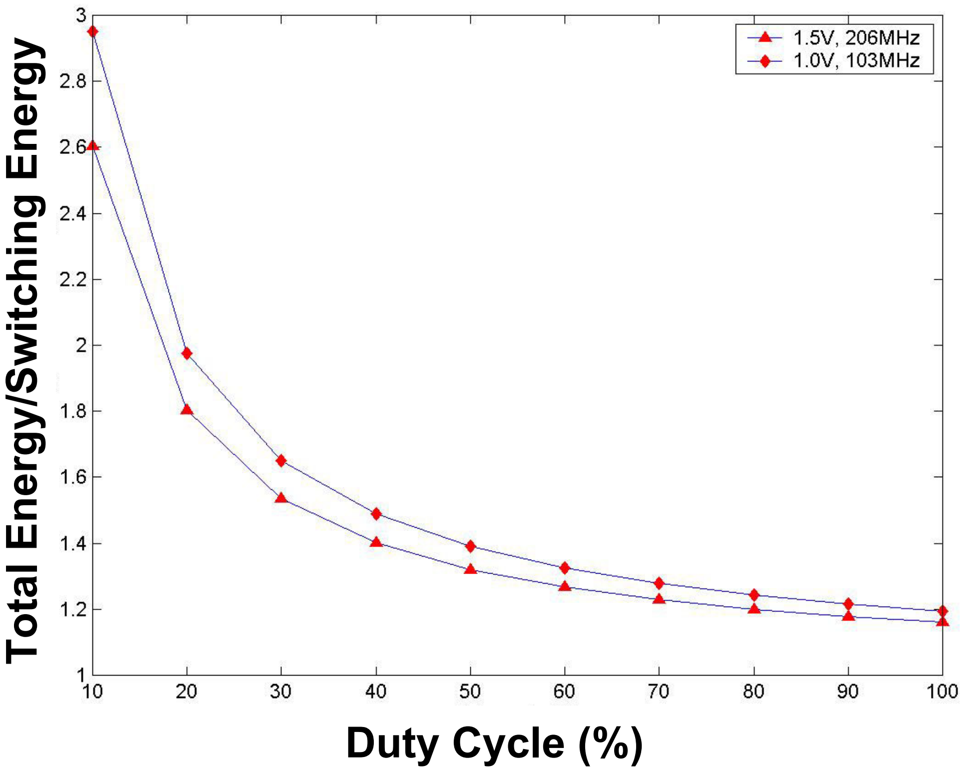
Digitally adjustable DC-DC converter powers SA-1110 core



μOS selects appropriate clock frequency based on workload and latency constraints

Leakage : Low Duty Cycle Concern

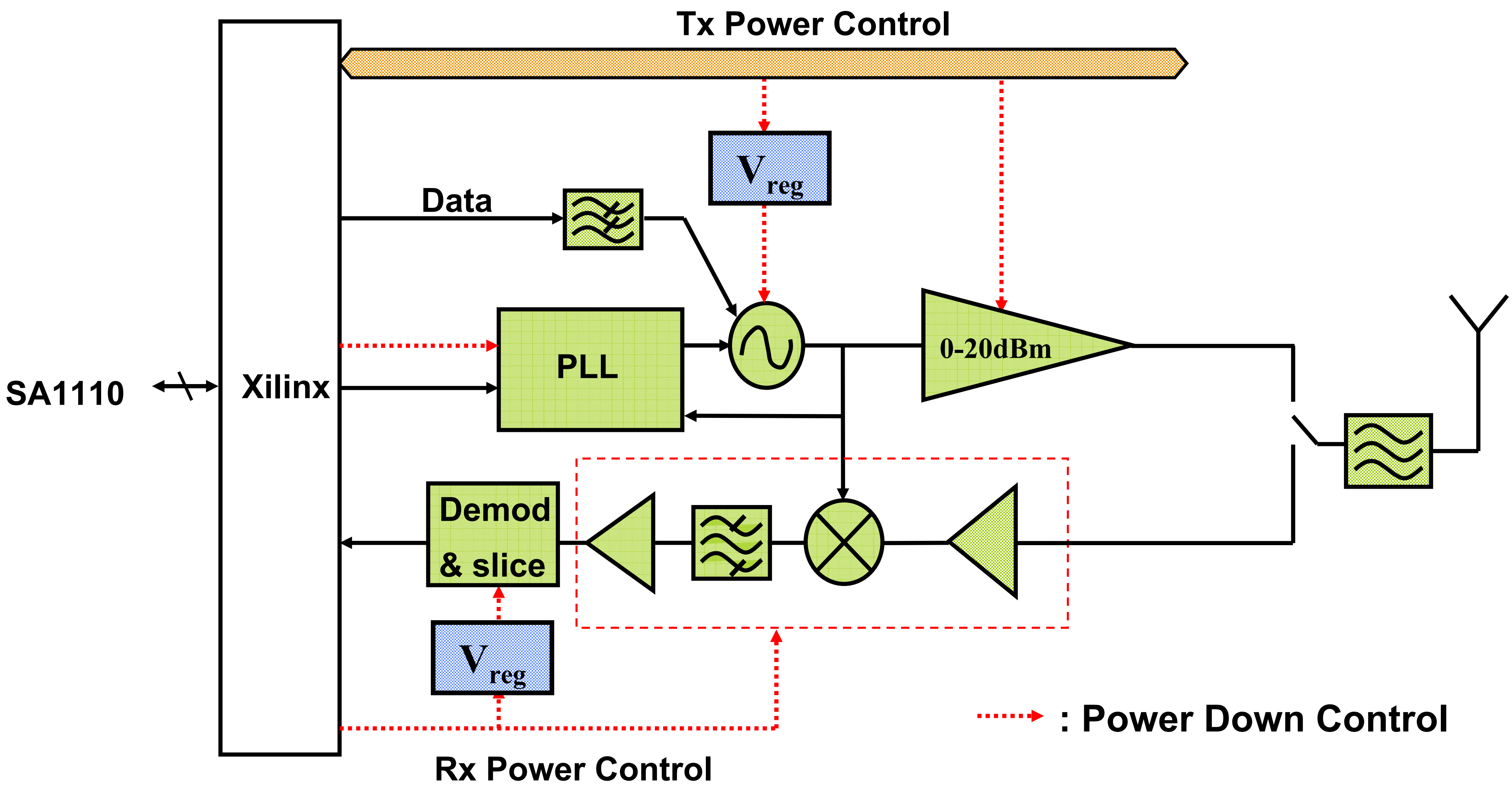




$$I_{leakage} \propto 10^{(-V_T / S)}$$

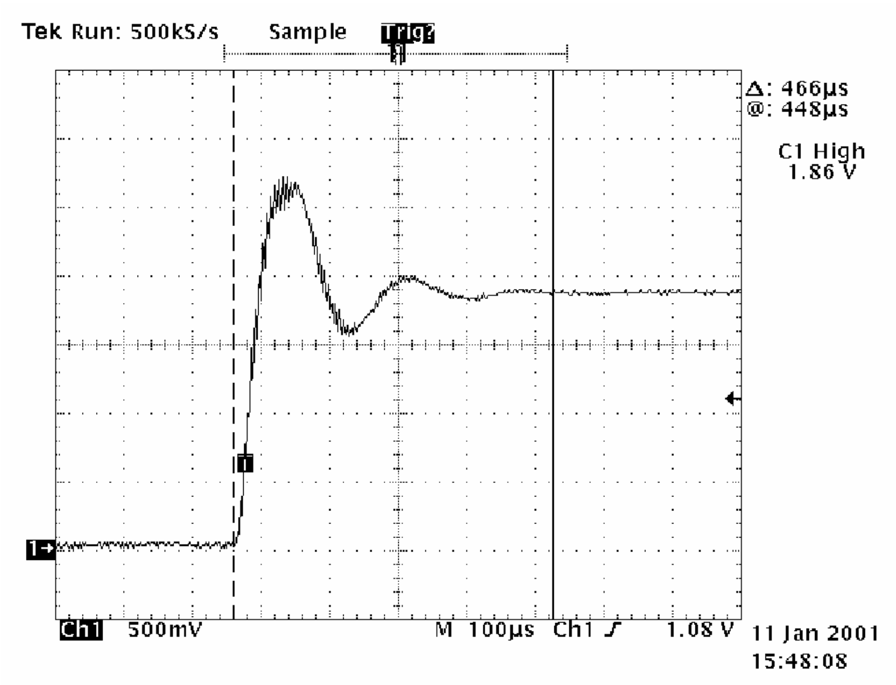
Leakage Dominates Switching Energy for Low Duty Cycles – "Off" State-centric Optimization

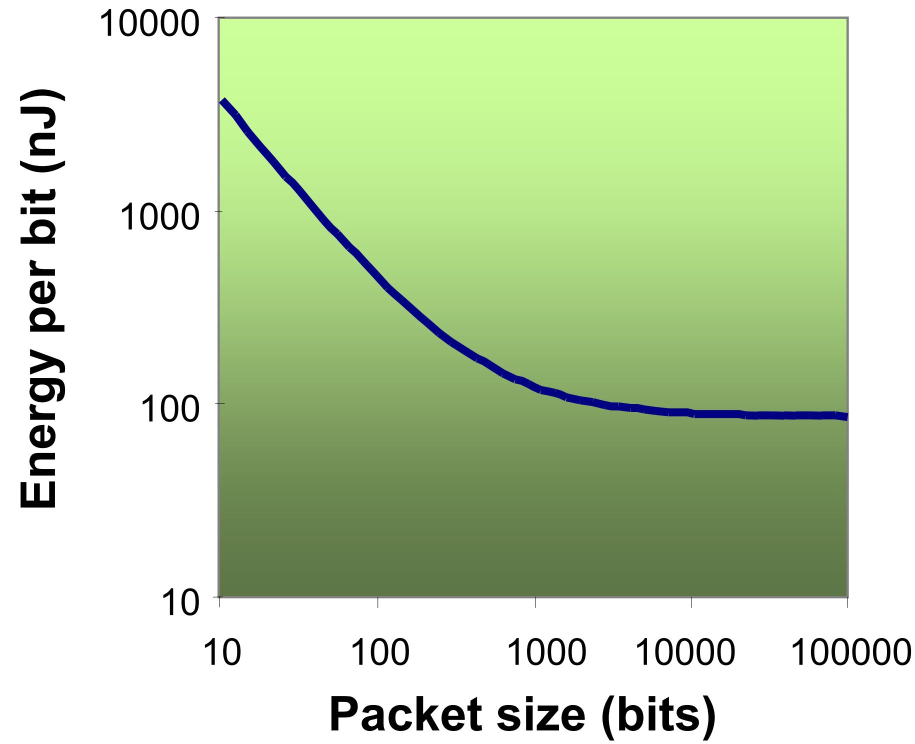
Power Aware Radio



- 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

Next Generation Sensor Nodes

Sensor System-on-a-Chip

Energy Source and Regulation

Sensor & A/D

Sensor Specific Cores (FFT, Matched Filters,etc.)

Low-End Sensor DSP Processor

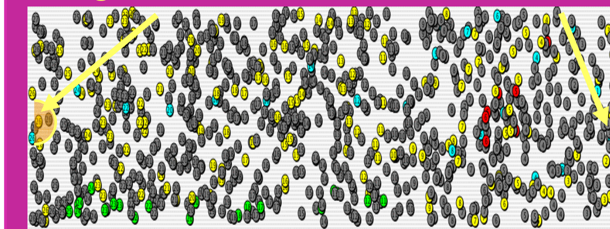
Protocol Processor (Basedband and MAC)

RF Transceiver

- Compact Form Factor (mm^3 – cm^3)
- Low Rate Radio link (10-100kbs)
- System Power < 100μW

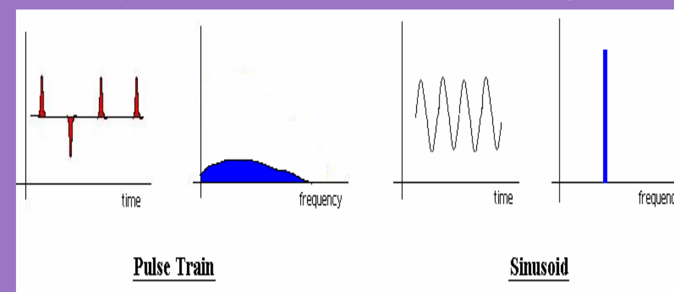
Network API/Simulation

Region of Observation   Base Station



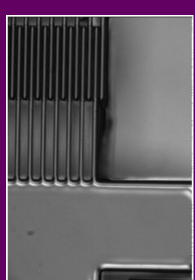
How to simulate 1000's nodes?

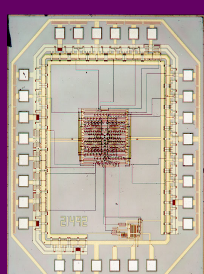
Ultra-Wideband Radio



High-speed & Low-power Time Domain Processing

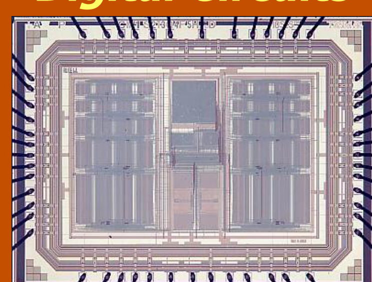
Energy Processing





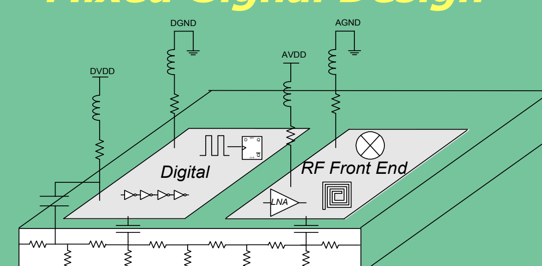
How to Scavenge 100μW?

Ultra Low-Voltage Digital Circuits



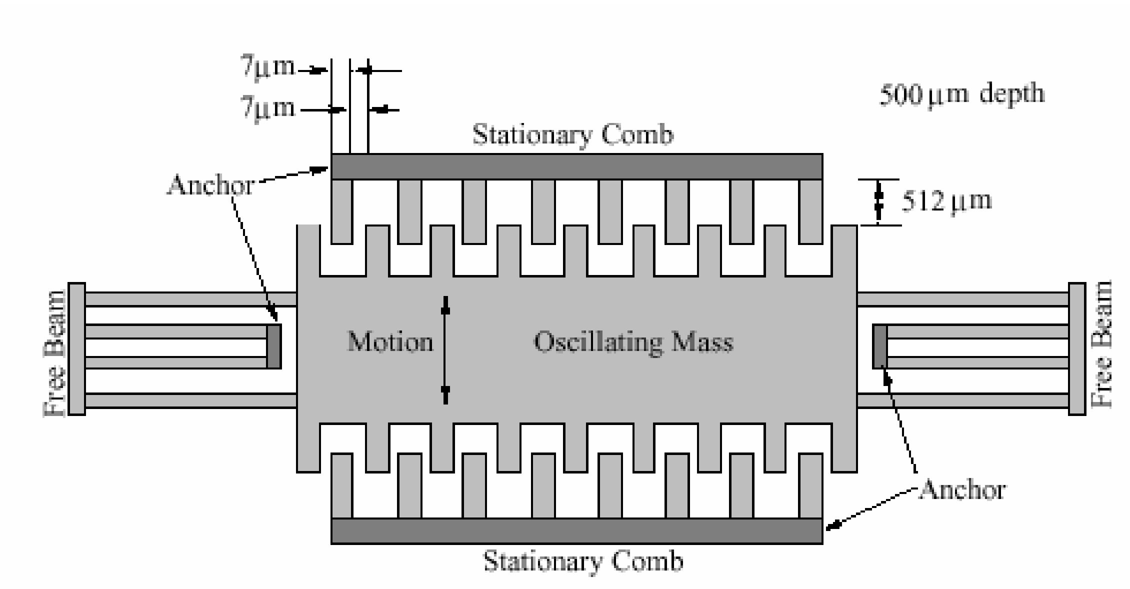
Design for 100mV Supply

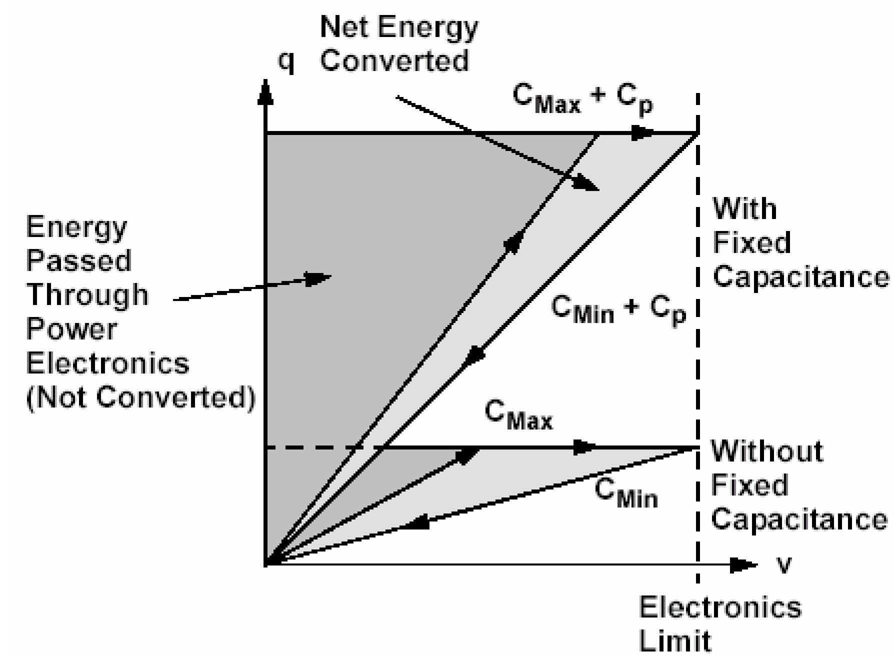
Mixed-Signal Design

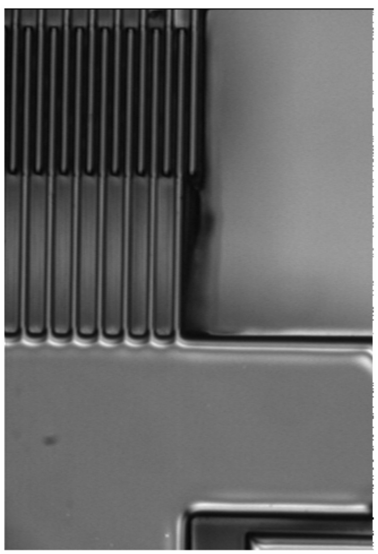


How to Integrate RF & Digital?

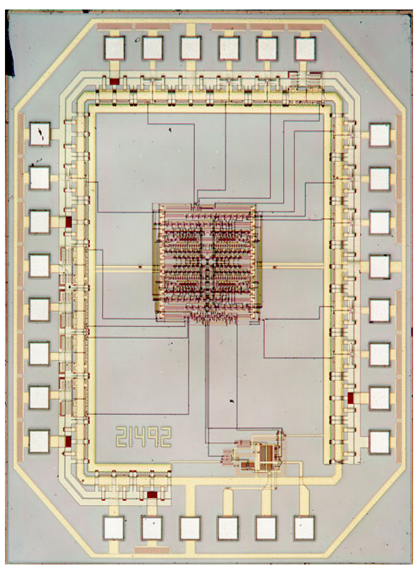
Energy Scavenging: Vibration-to-Electric Energy



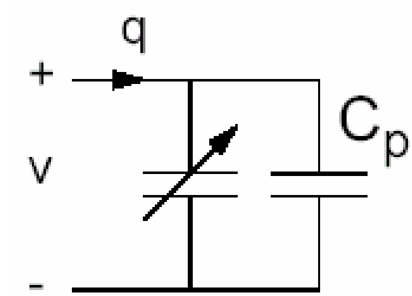




MEMS Generator



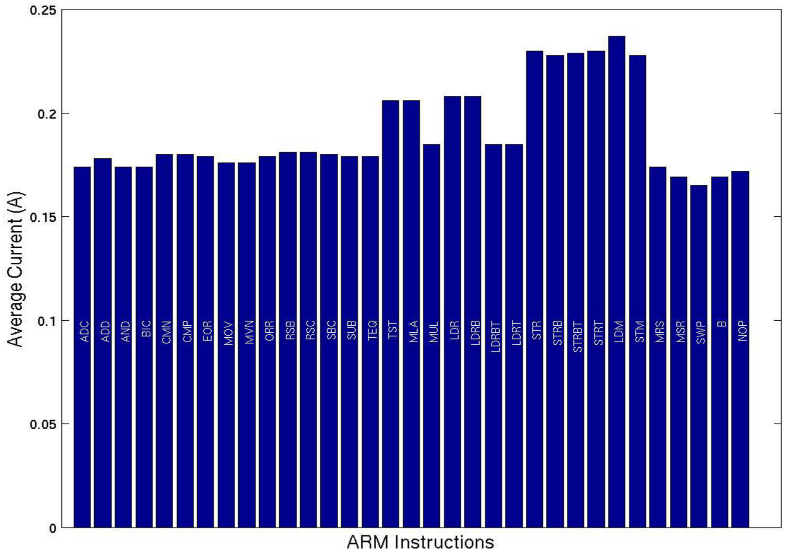
Controller

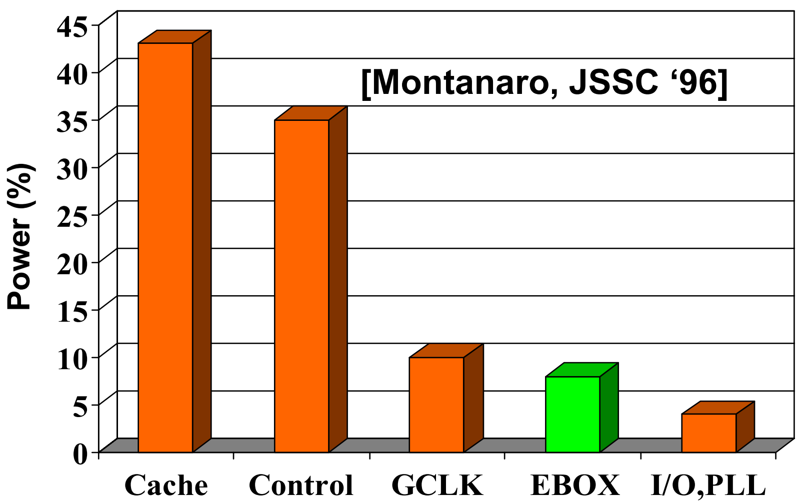


10μW from generator possible

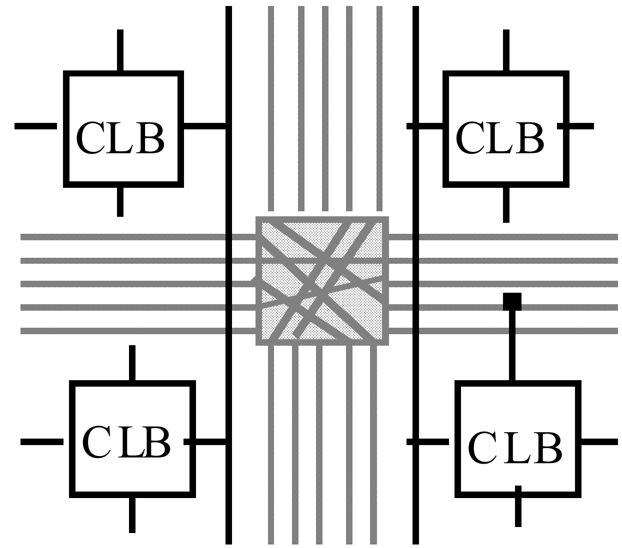
Programmable Software Fabrics

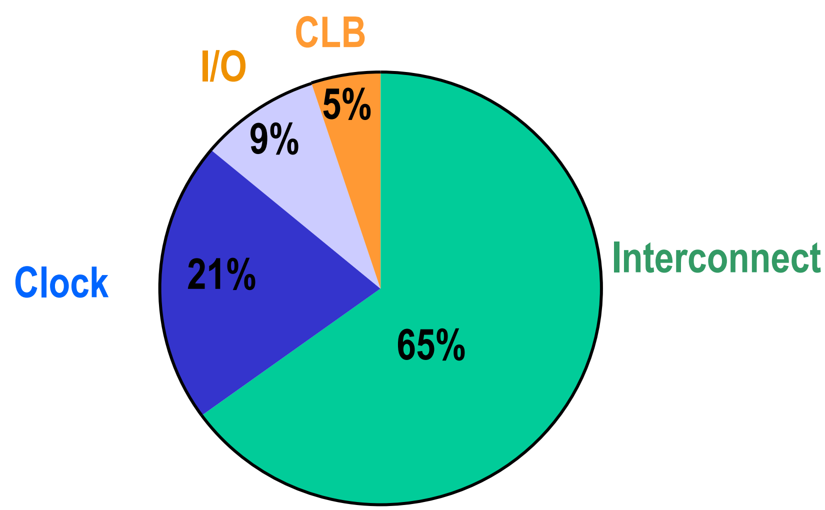
Processor (StrongARM-1100)





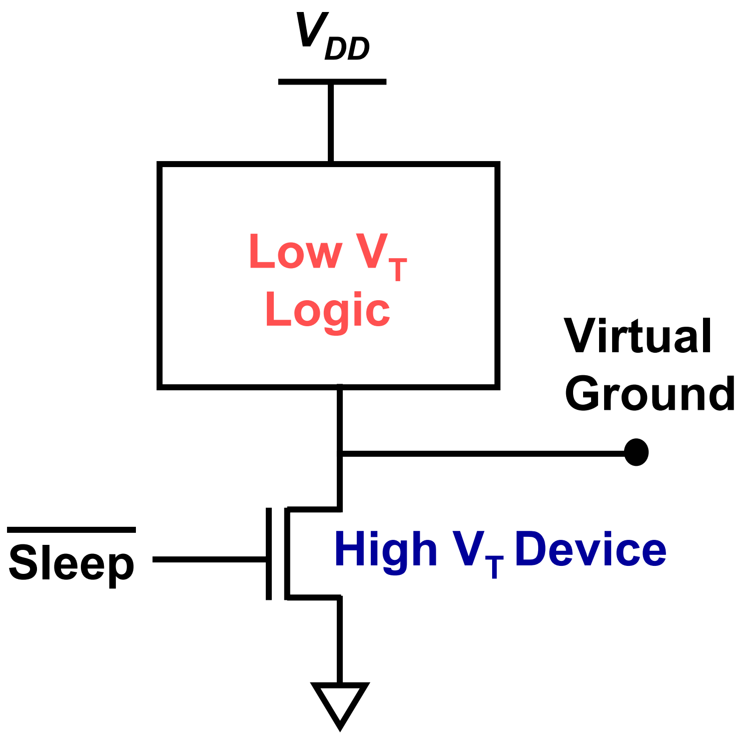
FPGA (Xilinx)

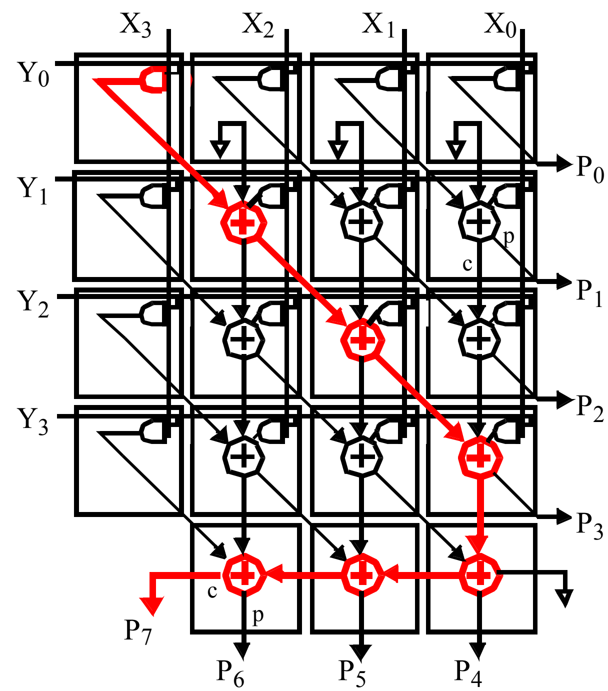


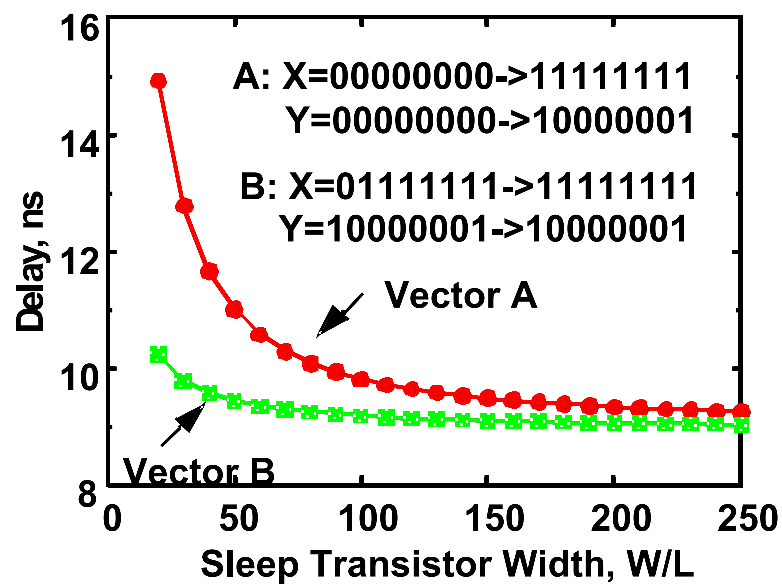


"Software" Energy Dissipation is Dominated by Overhead and NOT by Useful Work

Leakage Mitigation Using MTCMOS



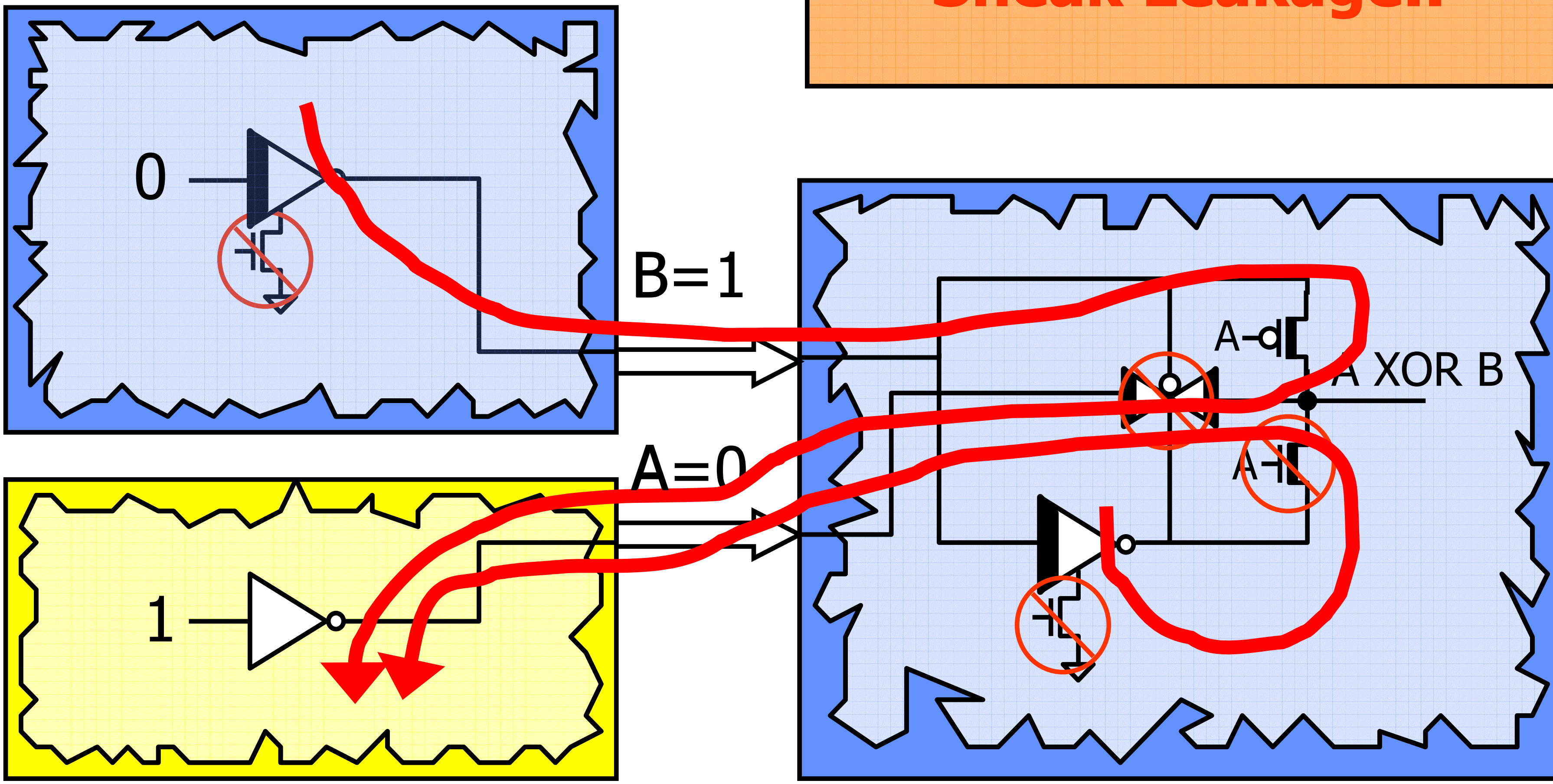




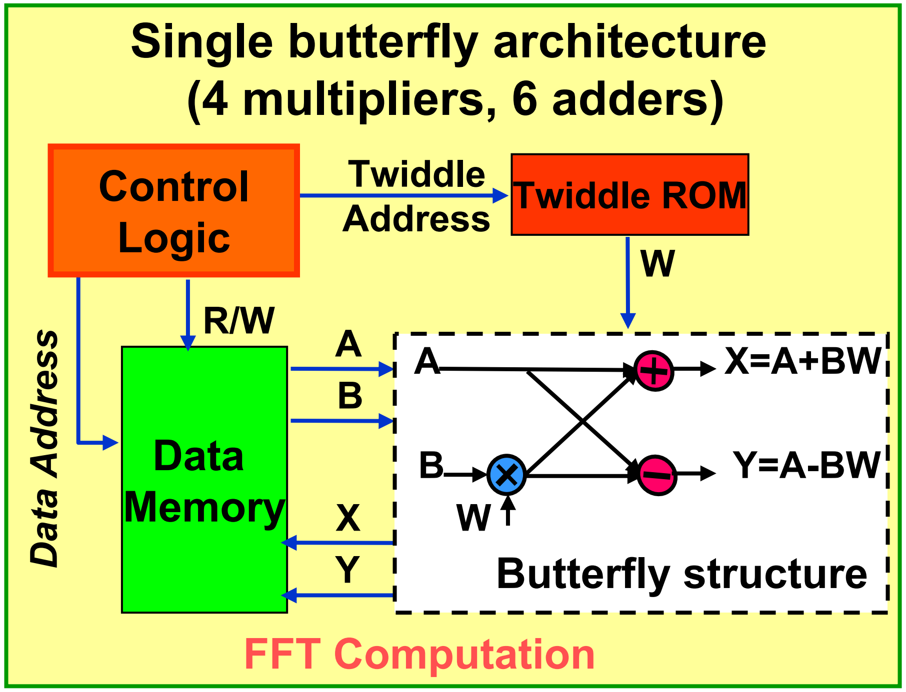
Device Sizing is a Major Concern in Multiple Threshold CMOS

Leakage Reduction Using MTCMOS

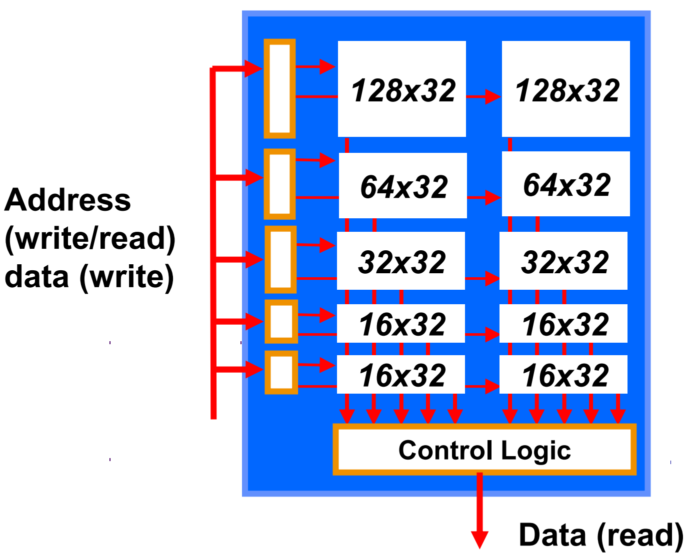
Look at A=0 and B=1.
Sneak Leakage!!



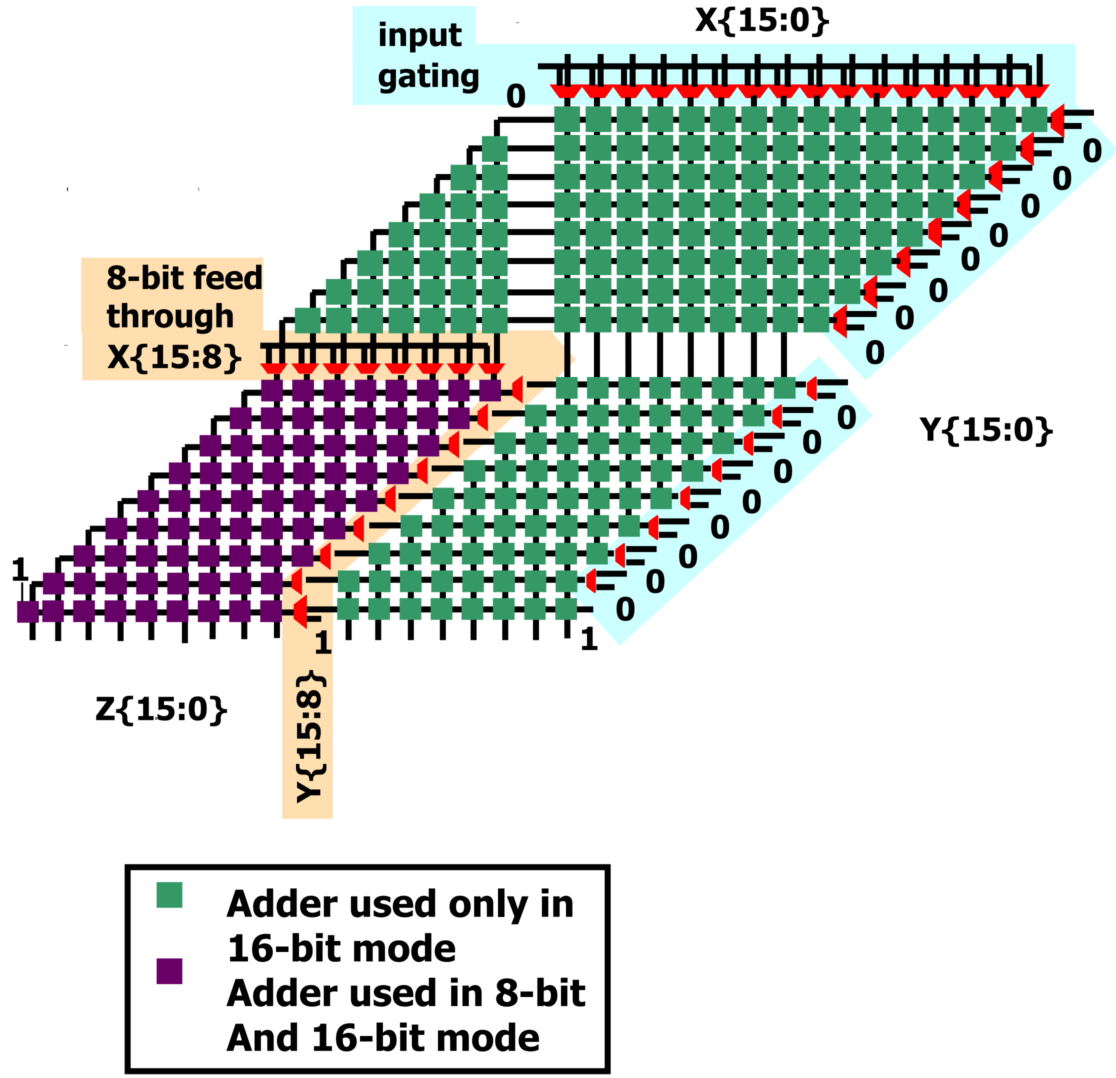
Power Aware Architectures



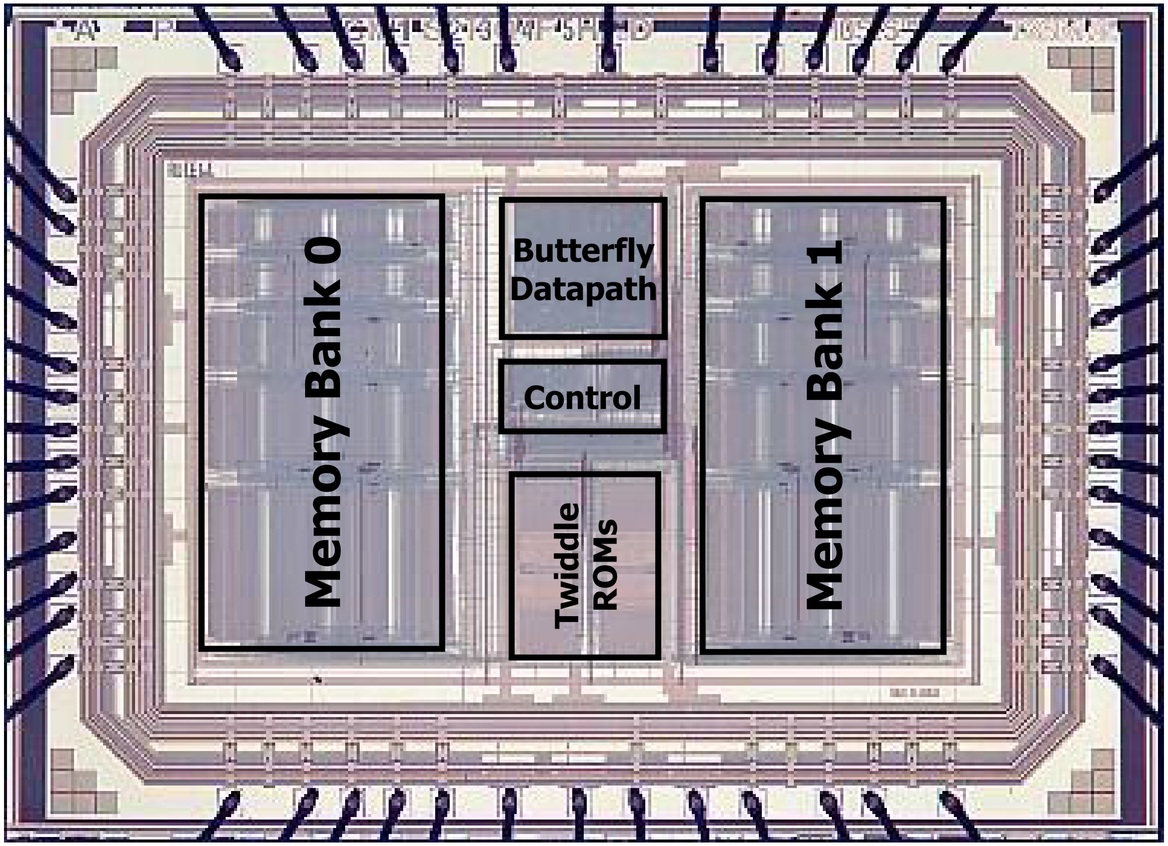
Power Scalable Memory



Power Scalable Multiplier (modified Baugh-Wooley)



First Generation Power Aware FFT



Technology Parameters

- **0.18μm process**
- **2.1mm x 3mm**
- **V_{T0n} = 0.45V, V_{T0p} = -0.44V**
- **V_{dd} = 1.8V**

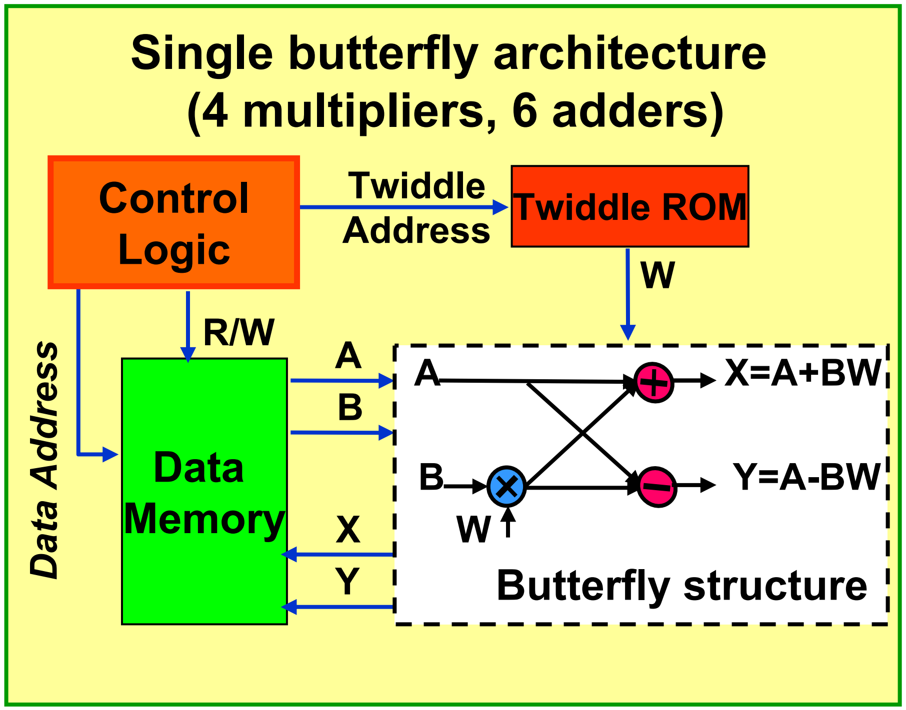
Measured energy dissipation

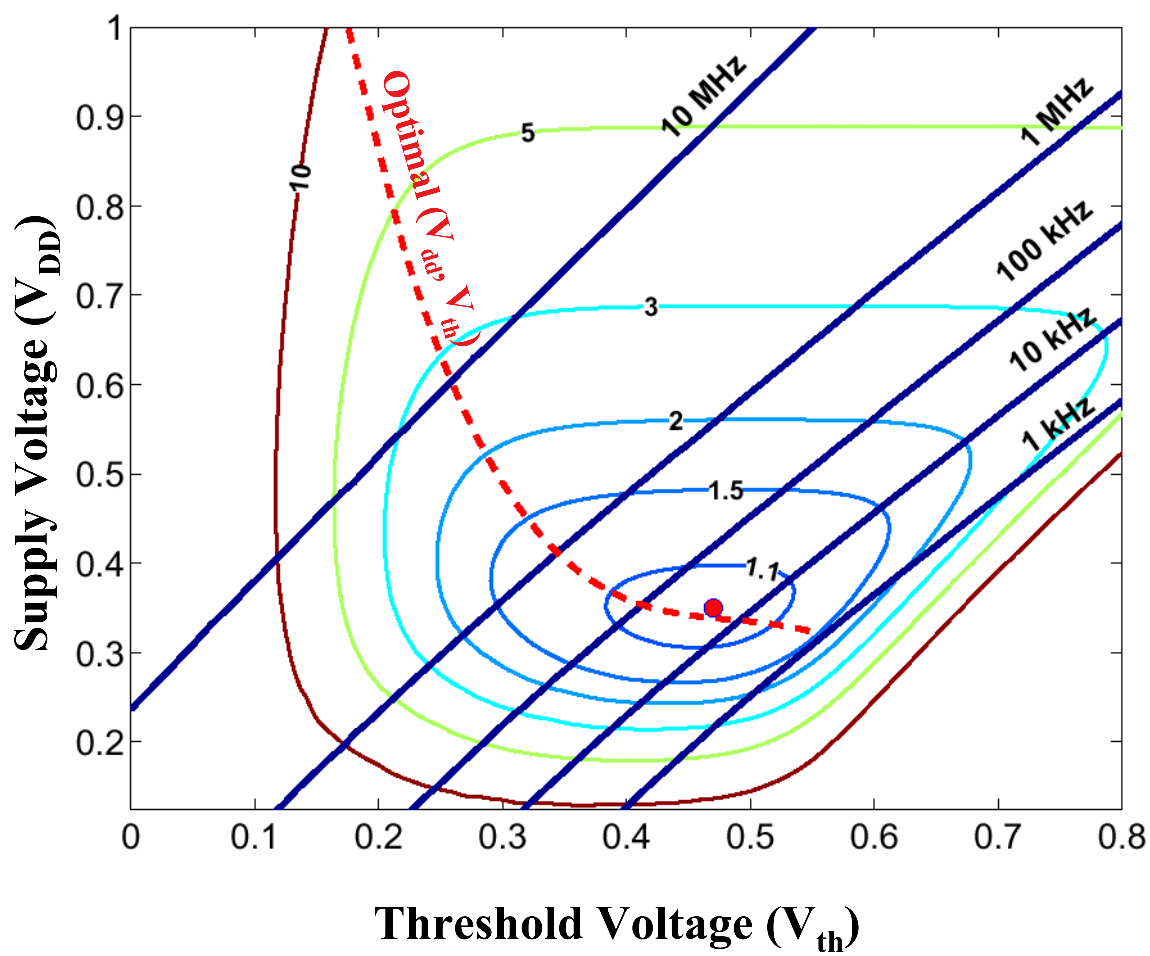
	8-bit	16-bit
128 pt.	46 nJ	81 nJ
256 pt.	121 nJ	216 nJ
512 pt.	304 nJ	564 nJ

Power programmable from 128pts to 512pts and 8 bits and 16 bits

Energy Efficiency of Digital Computation

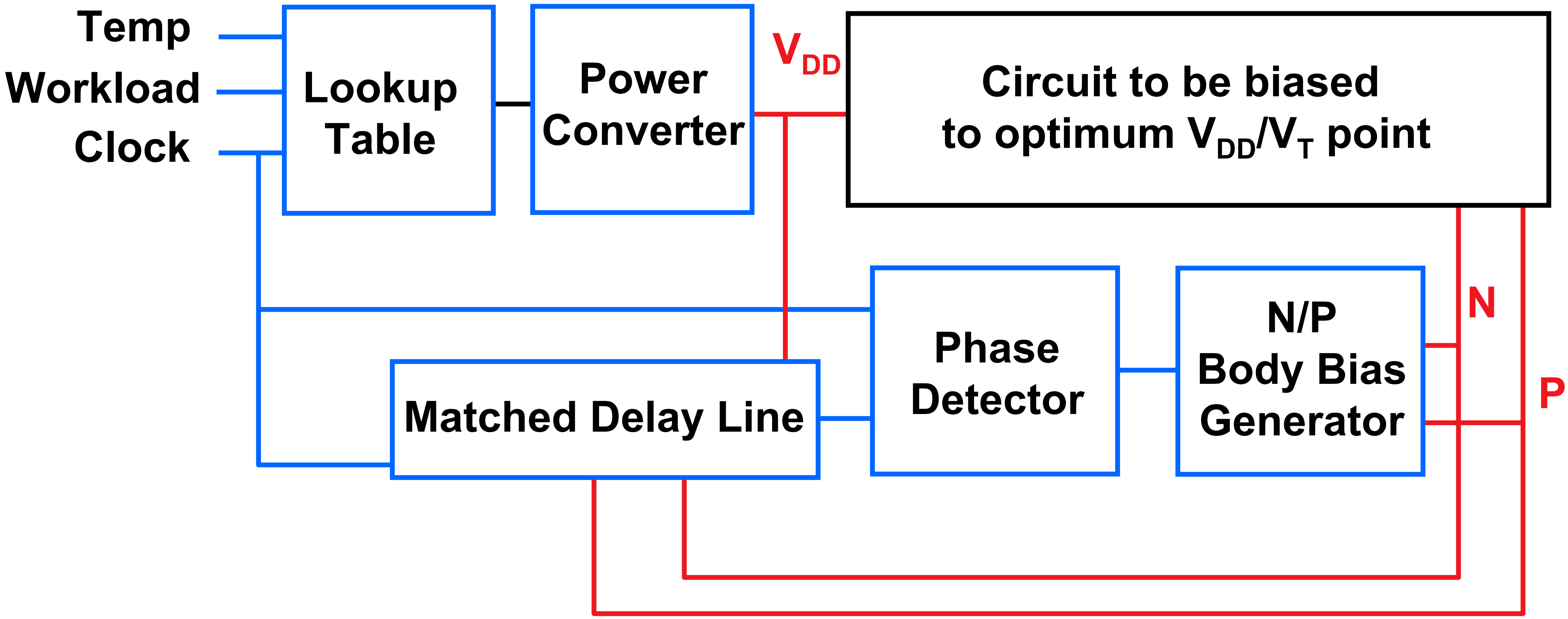
FFT Computation

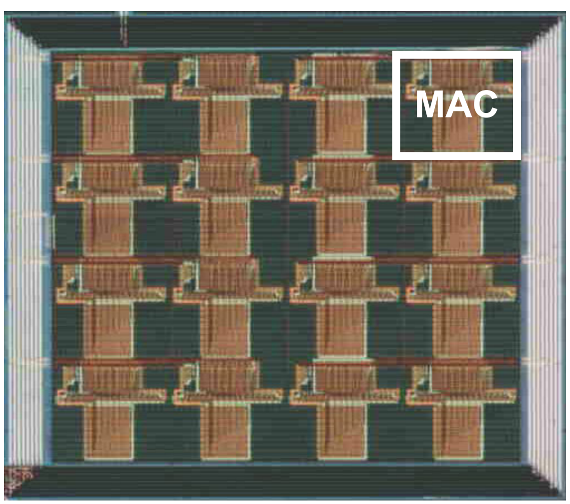


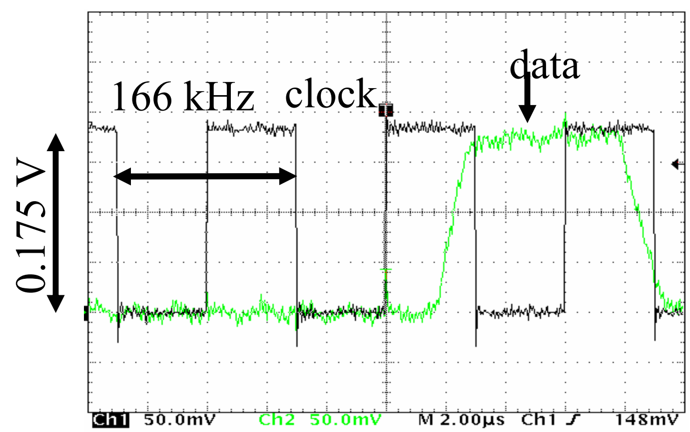


Exploit Sub-threshold Operation for Sensor Circuits

Adaptive V_{DD}/V_T Architecture

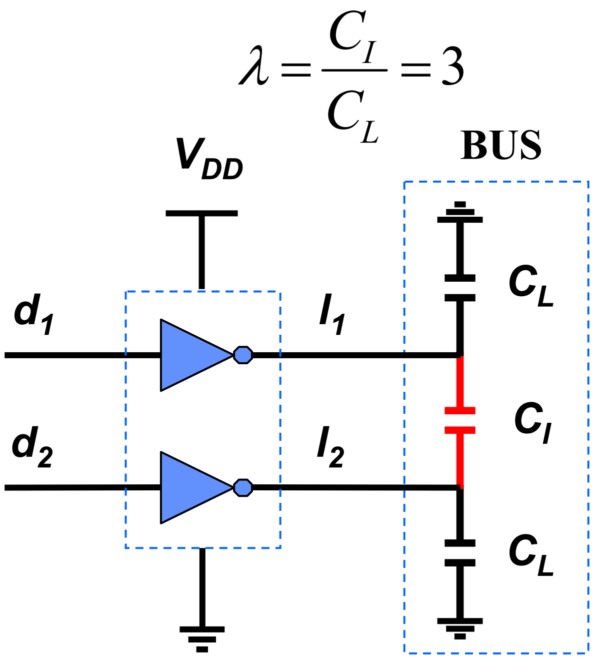


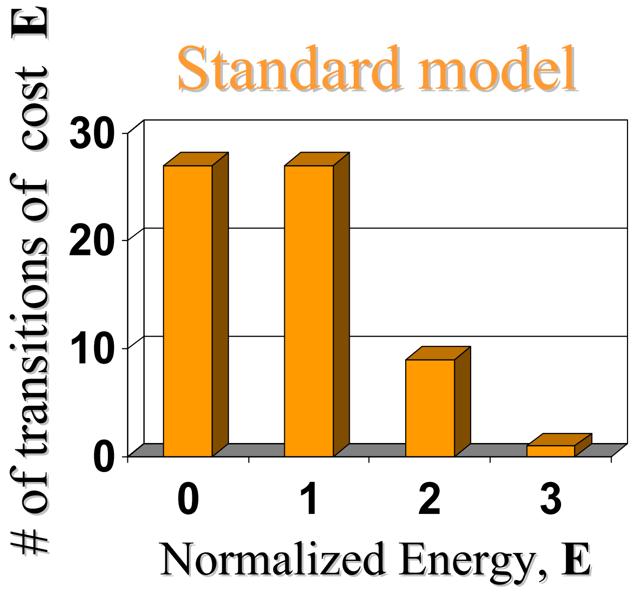


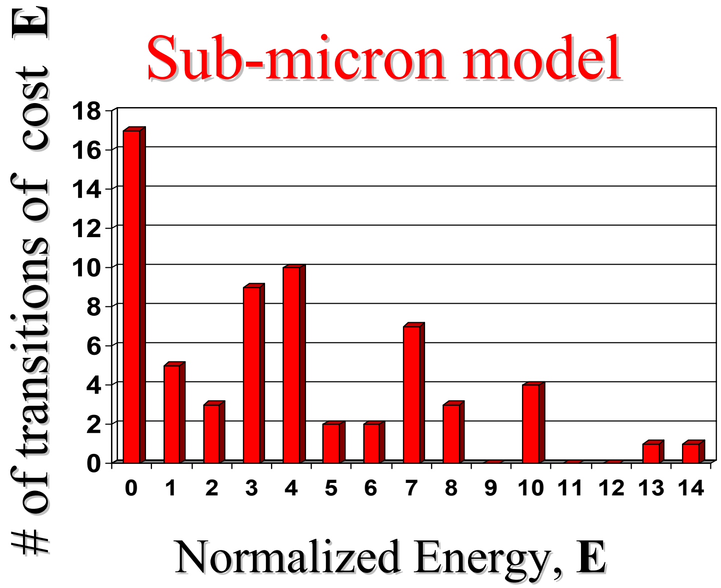


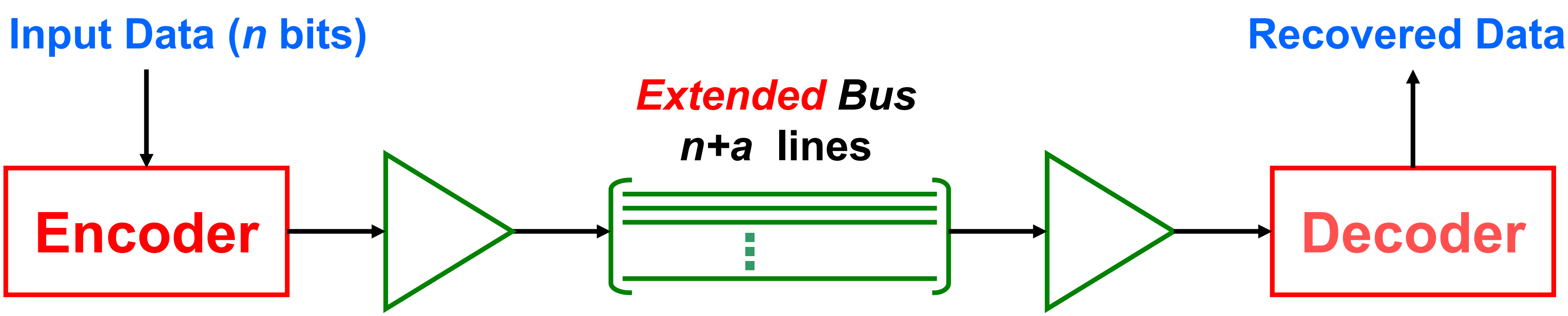
[Miyazaki, ISSCC ’02]

New Energy Metrics in DSM Interconnect



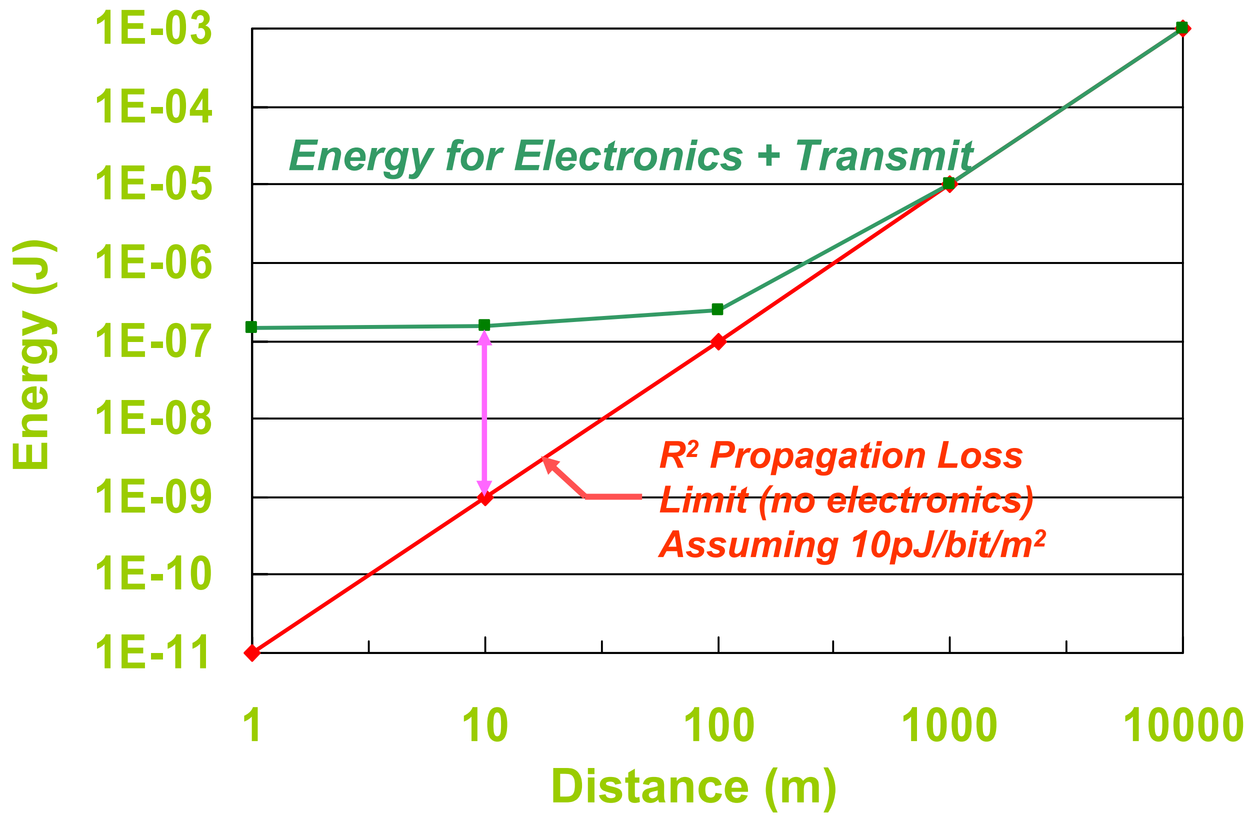






Minimizing Transition Activity is not the Right approach to Minimize Power

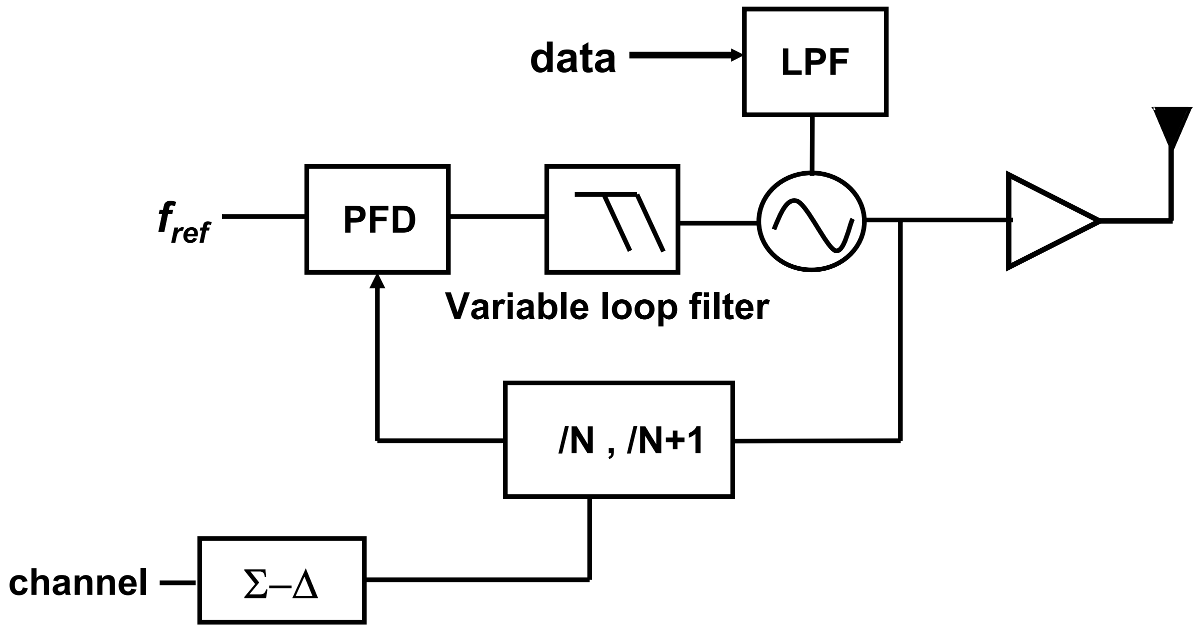
Computation vs. Communication

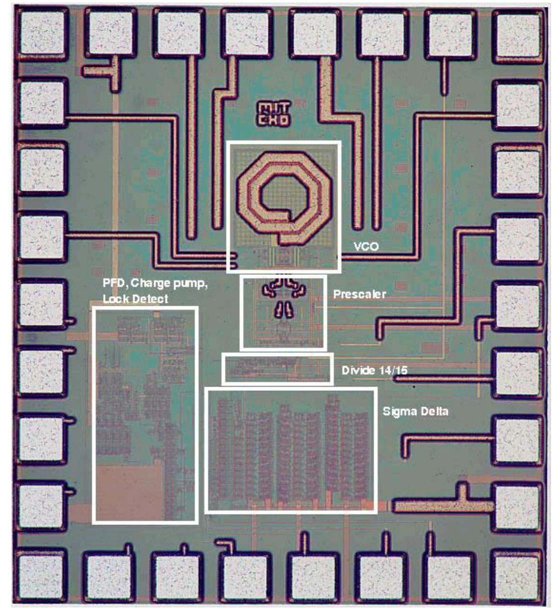


- **Computation: 1nJ/op (μ-Processor) and Communication (@10m): 150nJ/bit**
- **@10 m: ~150 instructions/transmitted bit on a low-power processor**
- **@10m: > 1Million instructions/transmitted bit using dedicated hardware**

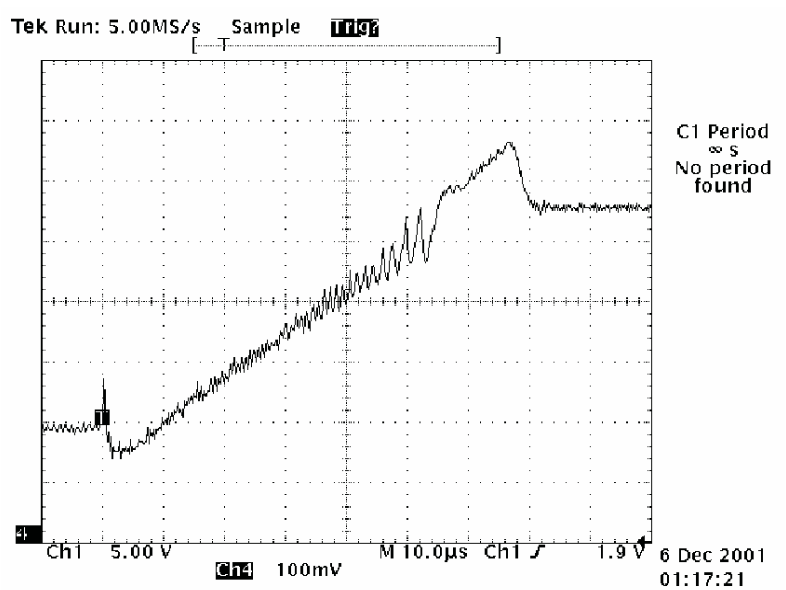
Compute, Don't Communicate

Fast Startup Transmitter

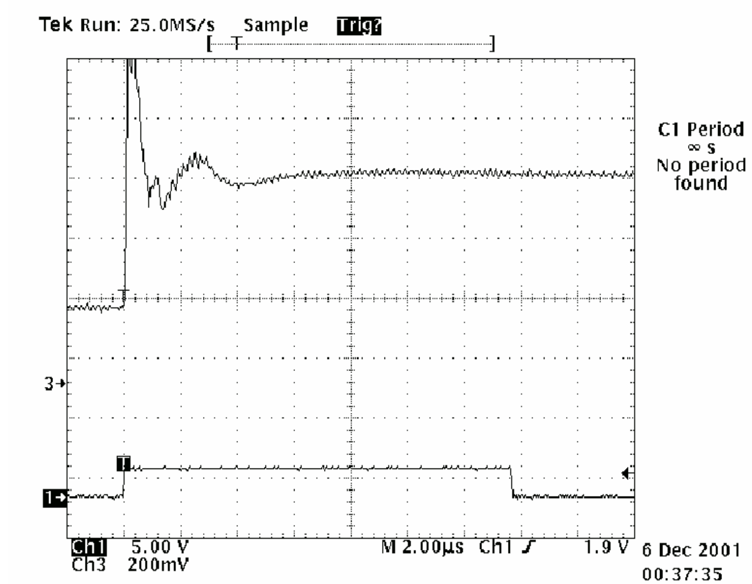




E/bit = 10nJ/bit

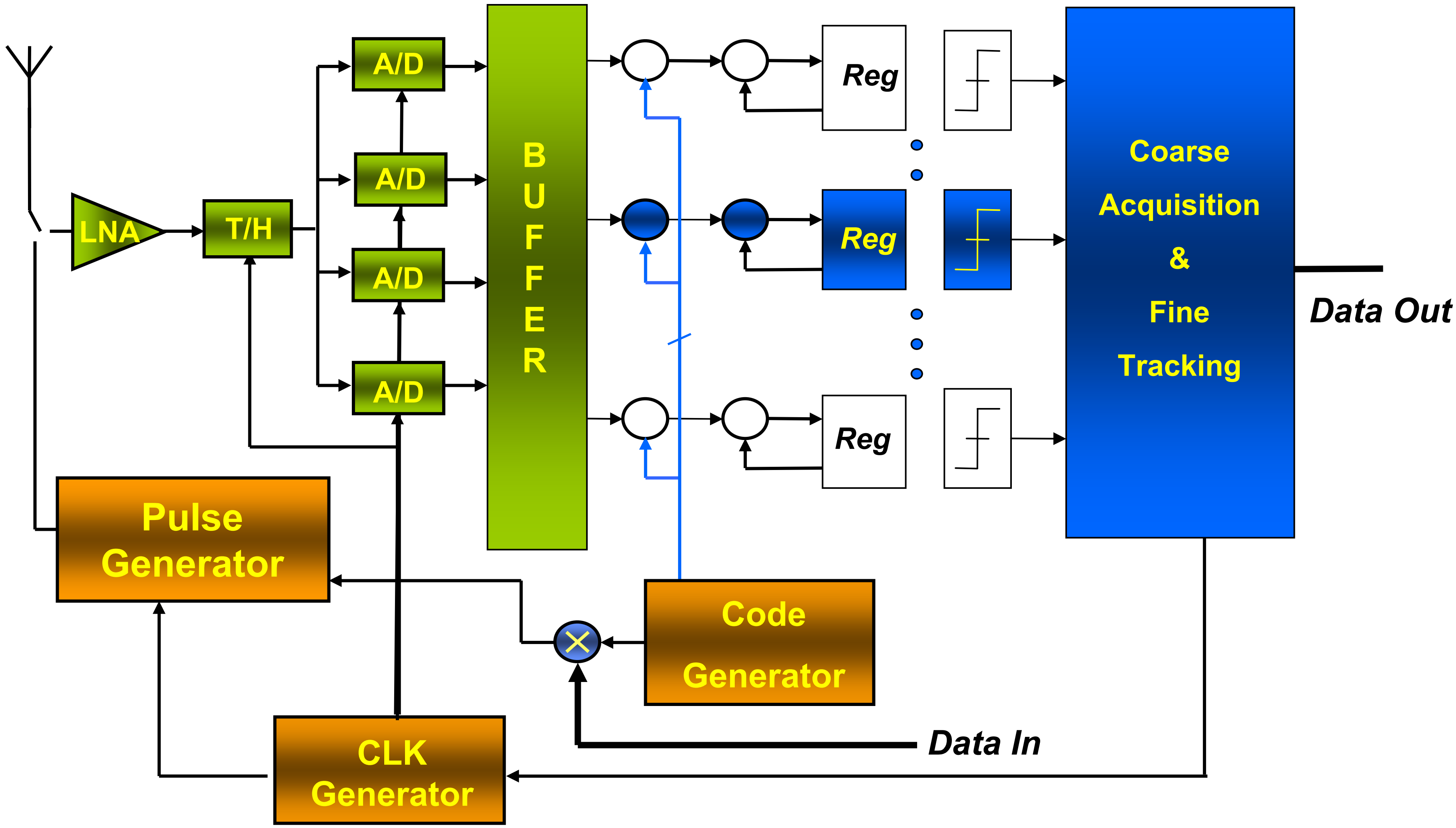


Fixed loop bandwidth



Variable loop bandwidth

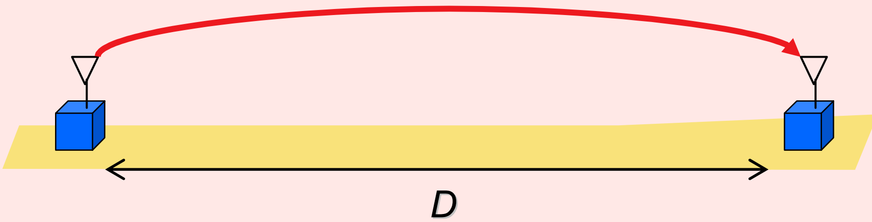
New Opportunities: "Digital" UWB Radio



- 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



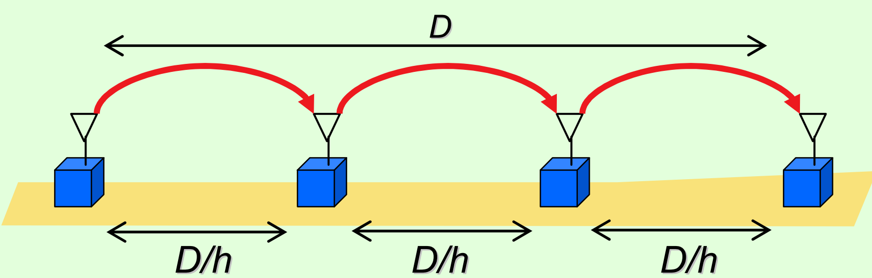
$$E = \alpha_1 + \alpha_2 D^2$$

Tx &Rx Radio Electronics

attenuation, power amp

path loss exponent

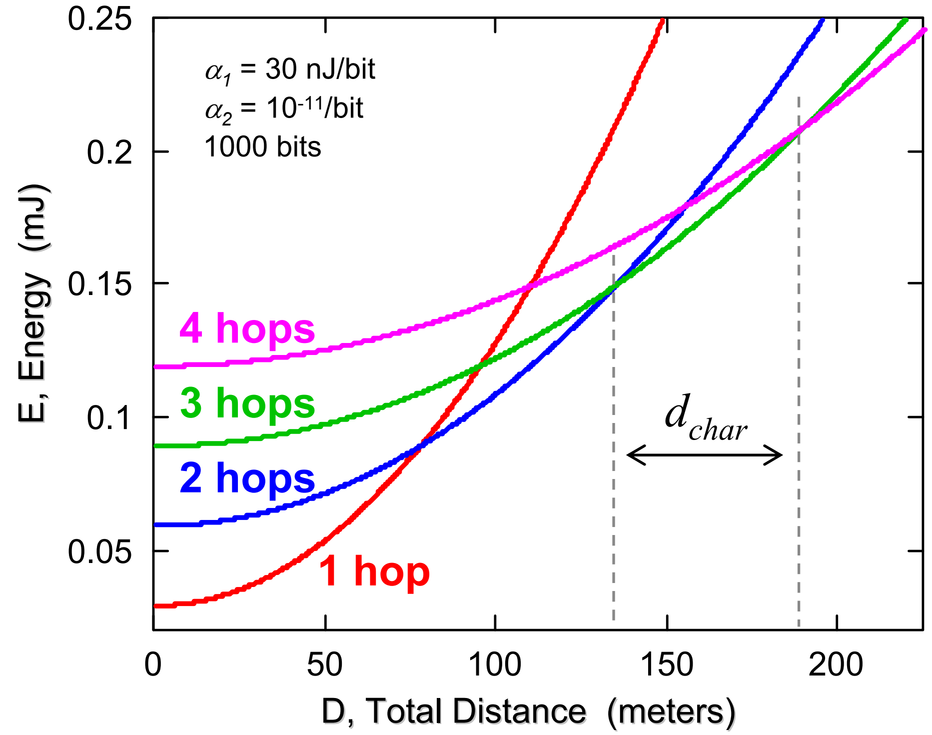
Multihop Transmission



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

number of hops

per-hop distance



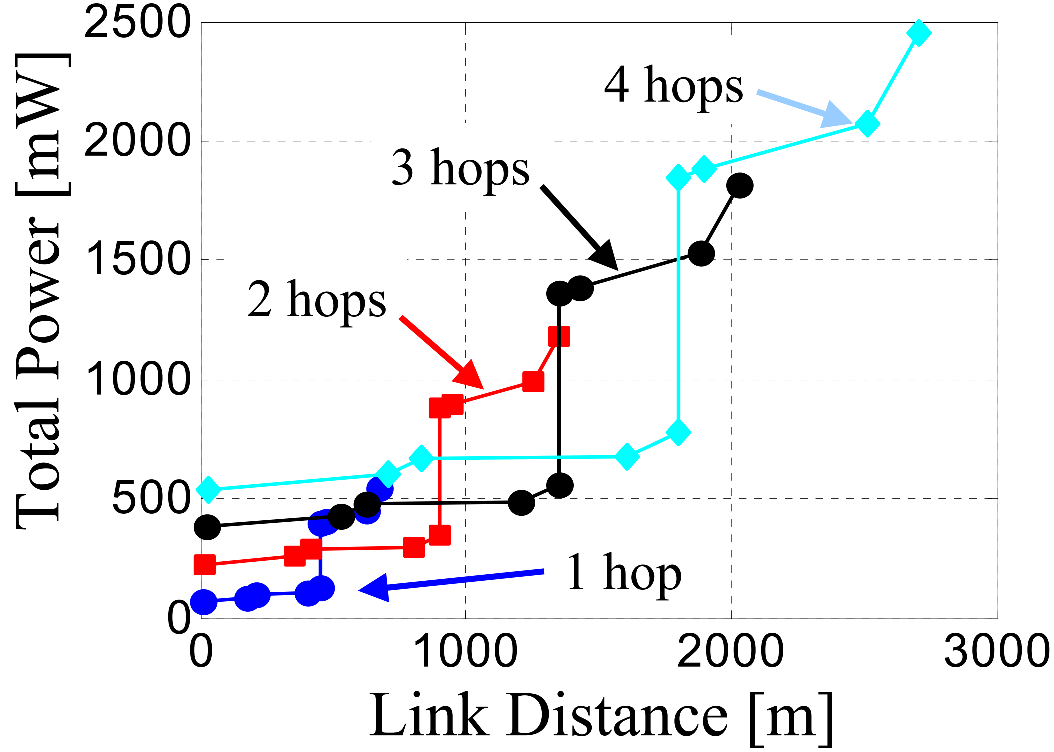
Characteristic Distance for Multihop Transmission

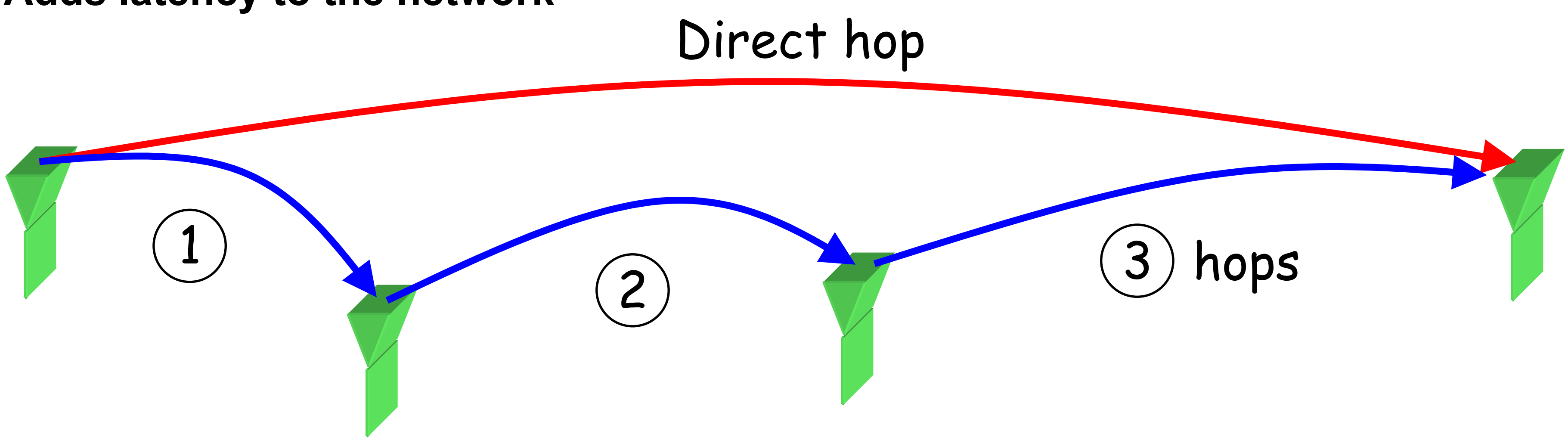
$$\min_h E = 2\alpha_1 \frac{D}{d_{char}}$$

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

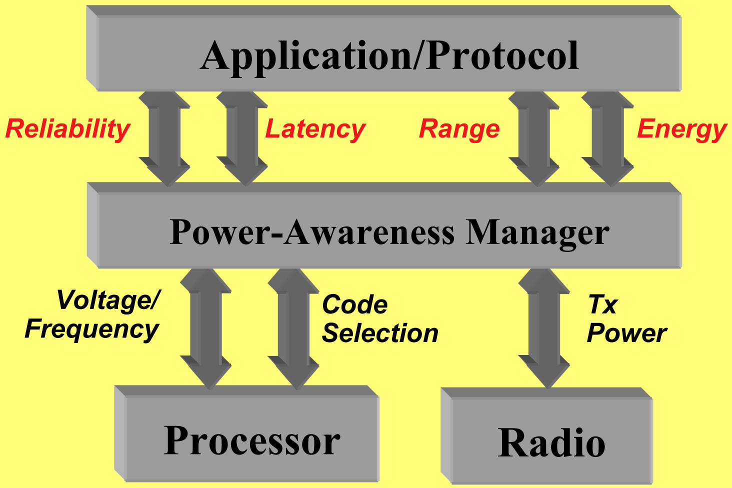
Multi-Hop Routing Analysis

- Take advantage of dense sensor networks by using several shorter hops to transmit long distances
- Plot of total power used to transmit a given distance for 1, 2, 3, and 4 hops
  - Large power step in each trace from turning on external PA
  - Trace out lowest curve for energy efficiency (i.e. use 3 hops @ 1000 m)
- Multi-hop routing is more energy efficient for this particular radio
  - Adds overhead to the protocol
  - Adds latency to the network





API and Middleware Layer



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

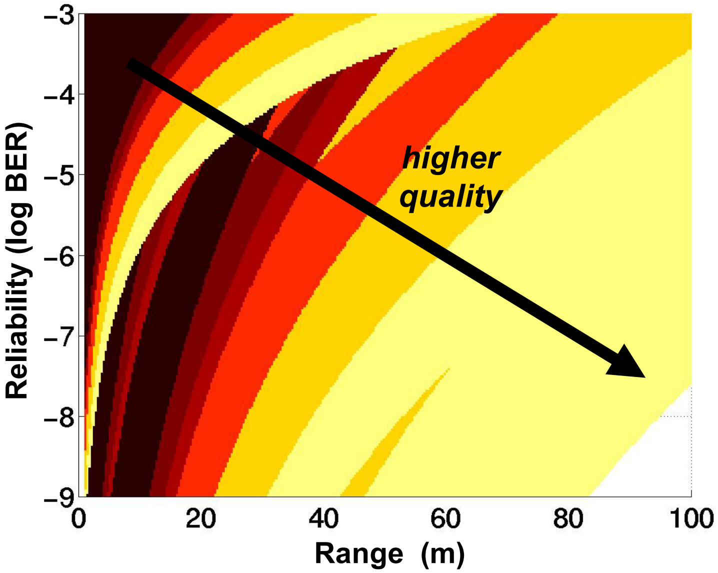
- **set_max_energy(Energy energy)**
- **set_max_latency(Time latency)**
- **set_min_reliability(Prob probReception)**
- **set_range(int nearestNodes, Node[] who, float meters)**

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

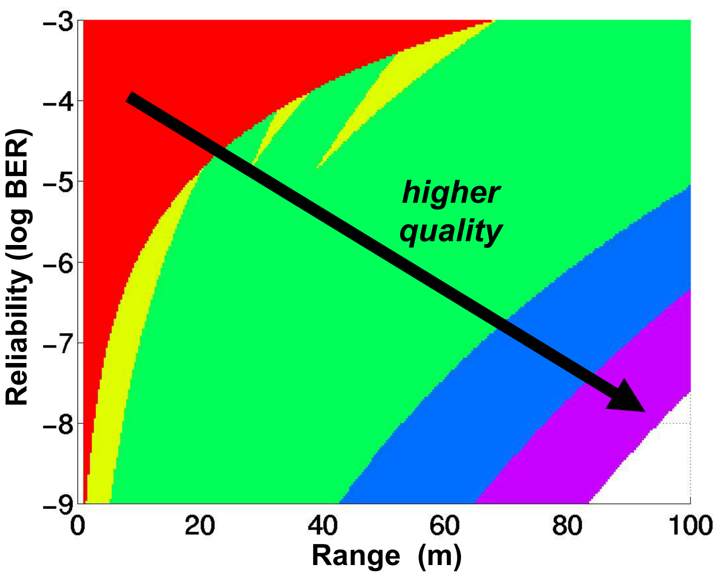
Radiated Power



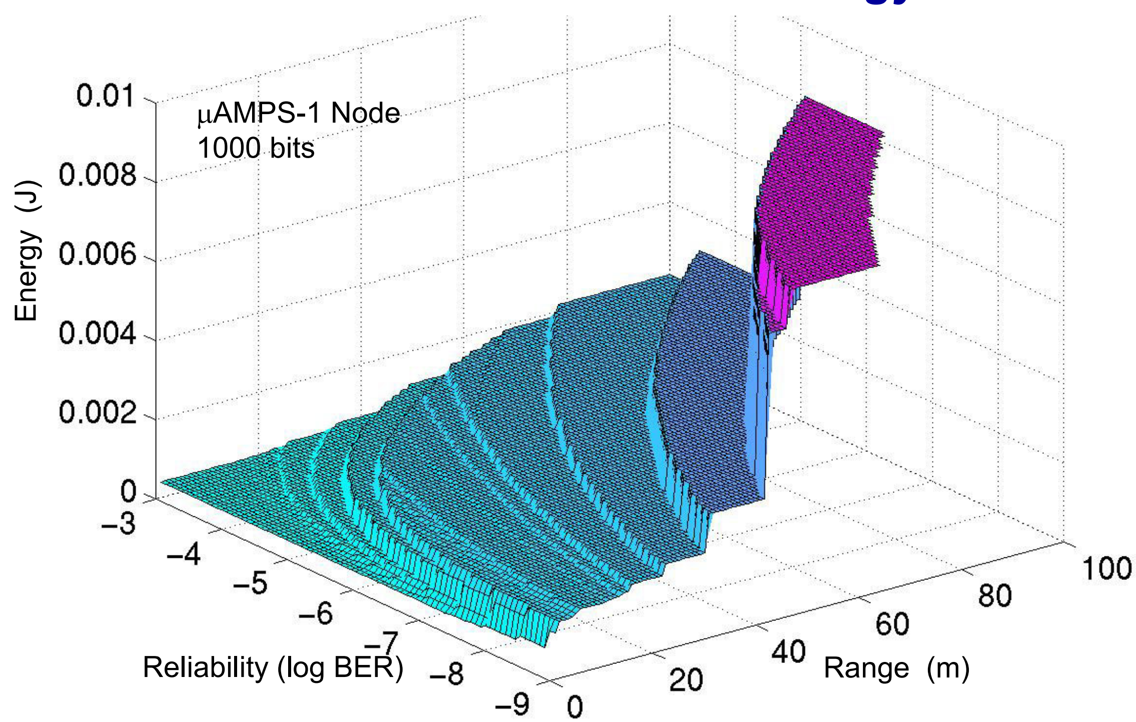
Operational Policies

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	

Convolutional Code



Total Communication Energy



Energy scales gracefully with communication quality

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