Physical Layer Driven Protocol and Algorithm Design for Energy-Efficient Wireless Sensor Networks

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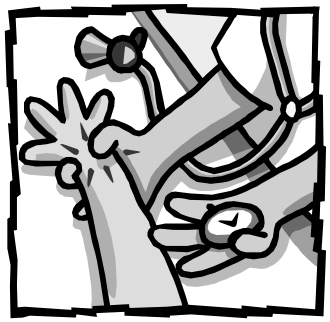
http://www-mtl.mit.edu/research/icsystems/uamps

Sensor Network Applications

Indoor Home Sensing

Equipment Monitoring

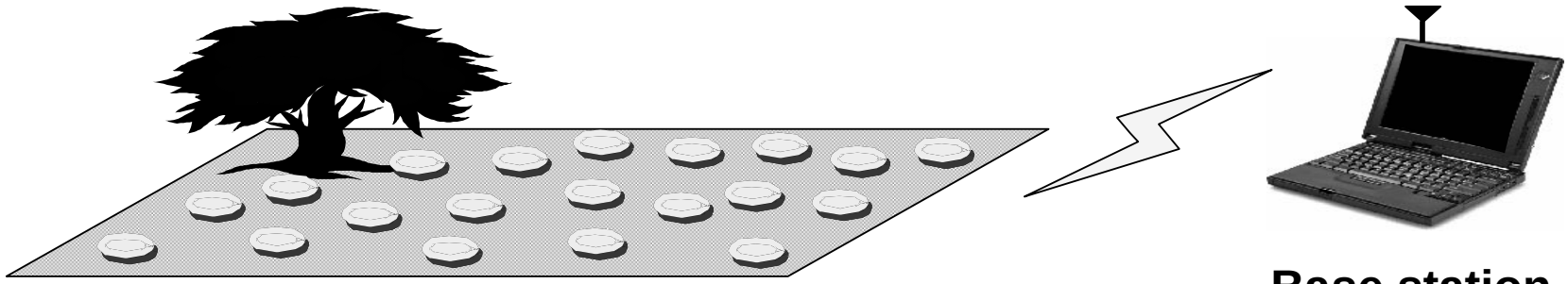
Medical Monitoring



Vehicle Tracking

Design a universal substrate for data gathering in a massively distributed wireless sensor network

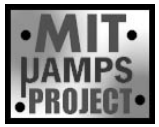
Domain Characteristics



- Node properties
  - Compact form factor (1 cm^3)
  - Low rate sensing (< 10 kbps)
  - Immobile
- Network properties
  - 100s to 1000s of nodes
  - Small inter-node distance
  - Network far from base station
  - Hard-to-access

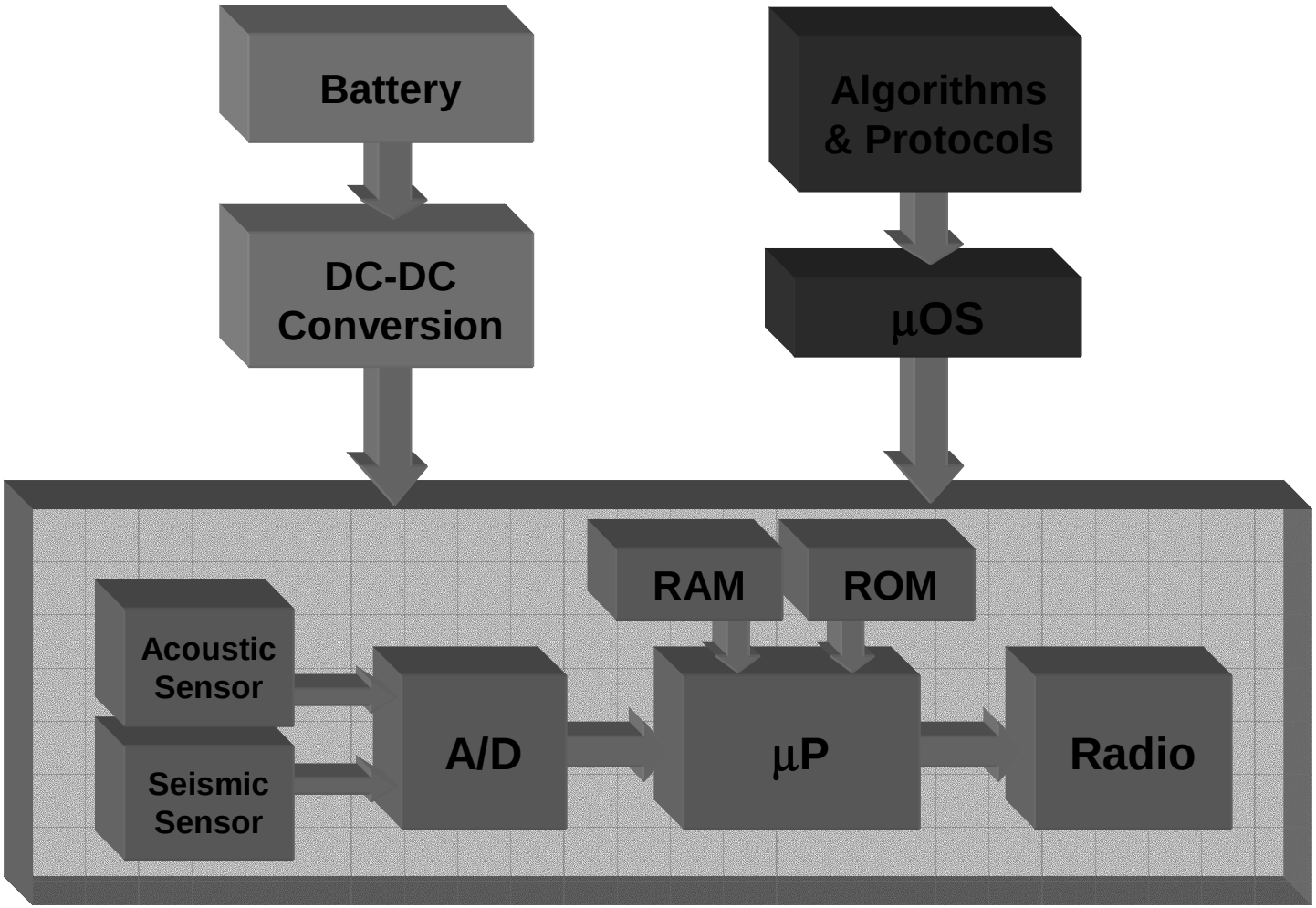
Compact form factor + Long lifetime $\rightarrow$
Need Energy-efficiency

Power-Aware Design



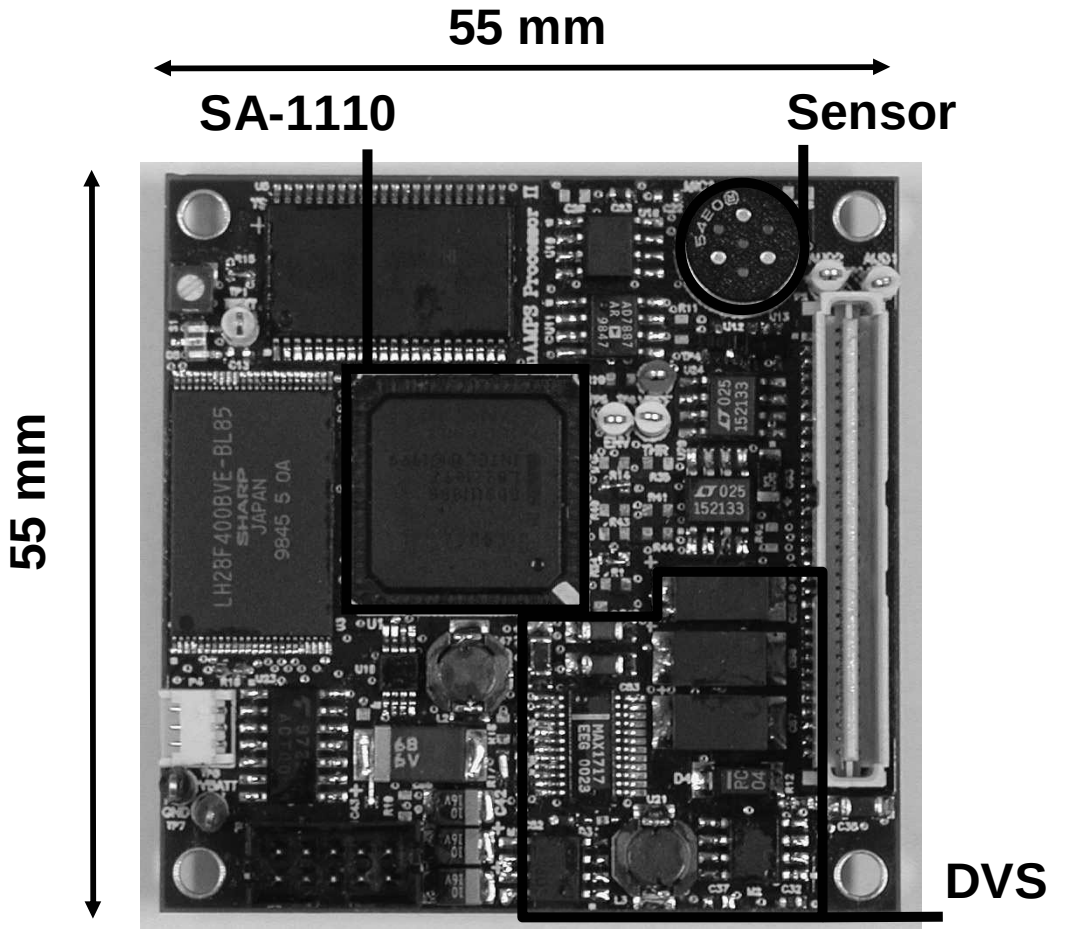
- Conditions and requirements are time-varying
  - Input statistics
  - Tolerable latency
  - Environment
- Power-aware design exploits these variations
  - But maintains application requirements
- Must pervade all system layers
  - Hardware hooks necessary
  - Upper layers utilize hooks

µAMPS Node Architecture



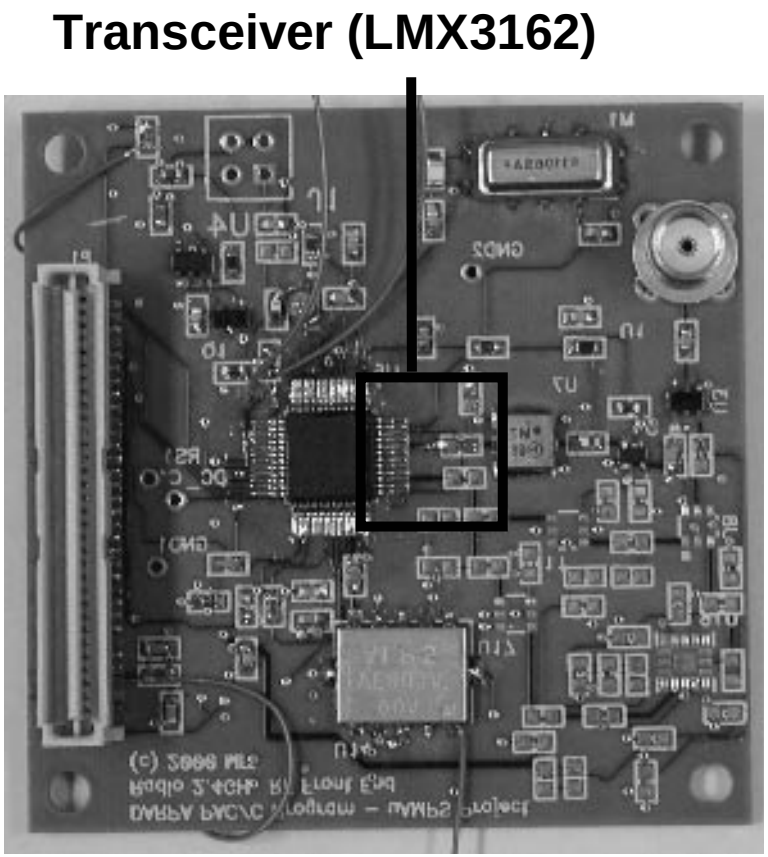
The µAMPS Node

µAMPS*: *micro-Adaptive Multi-Domain Power-Aware Sensors



Processor Board

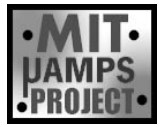
[Nathan Ickes]



Radio

[Fred S. Lee, Theodore Konstantakopoulos]

Dynamic Voltage Scaling



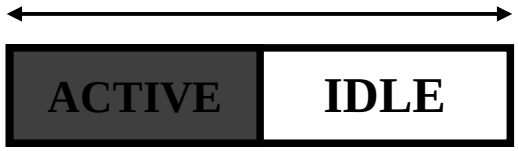
- Hardware hooks:
  - Voltage
  - Frequency
- Using the hooks:
  - Application has deadline for computation
  - Exploit conservative deadline to save energy

$$\textbf{Power} = \alpha\ \mathbf{C}\ \mathbf{V_{DD}}^2 f$$

$$\textbf{Energy} = \tfrac{1}{2}\ \mathbf{C}\ \mathbf{V_{DD}}^2$$

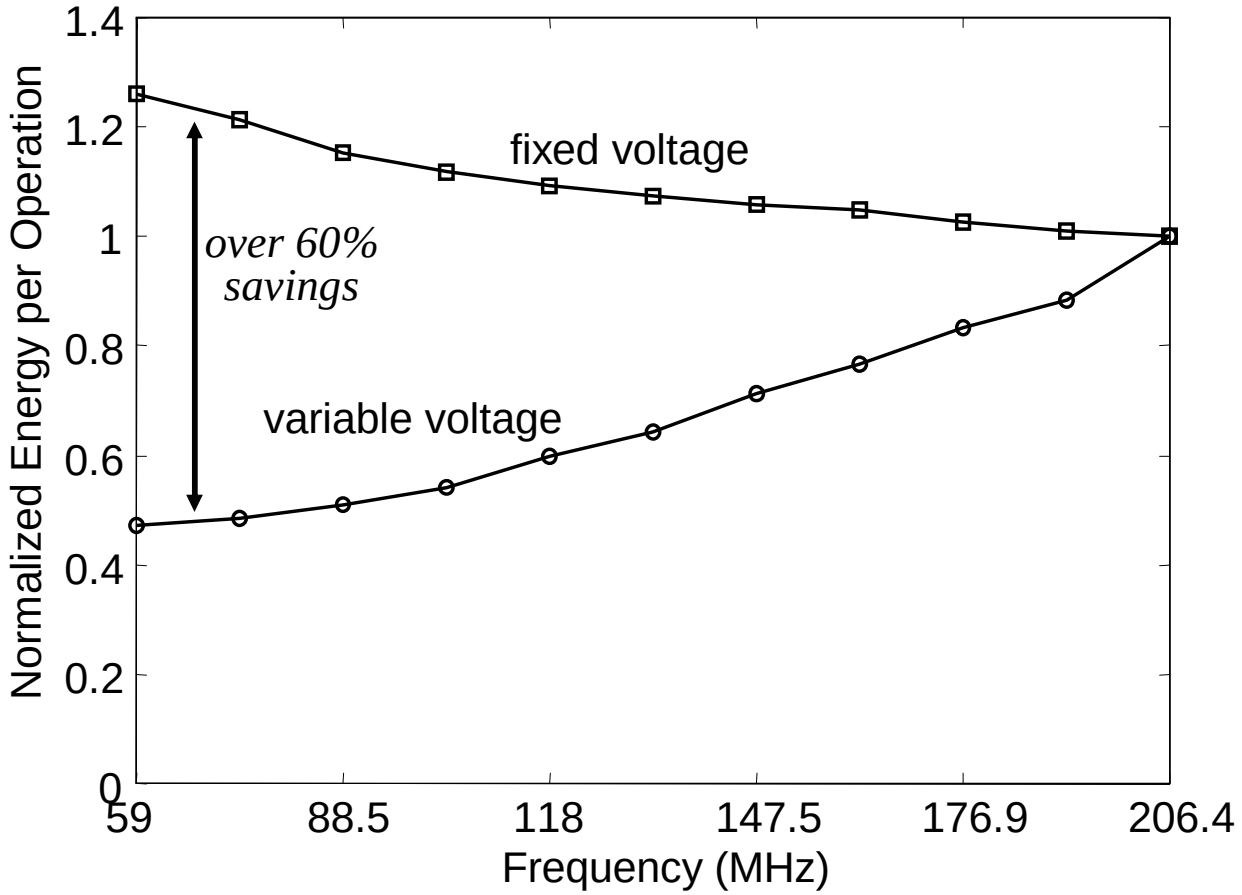
Latency-Awareness

Time required for operation

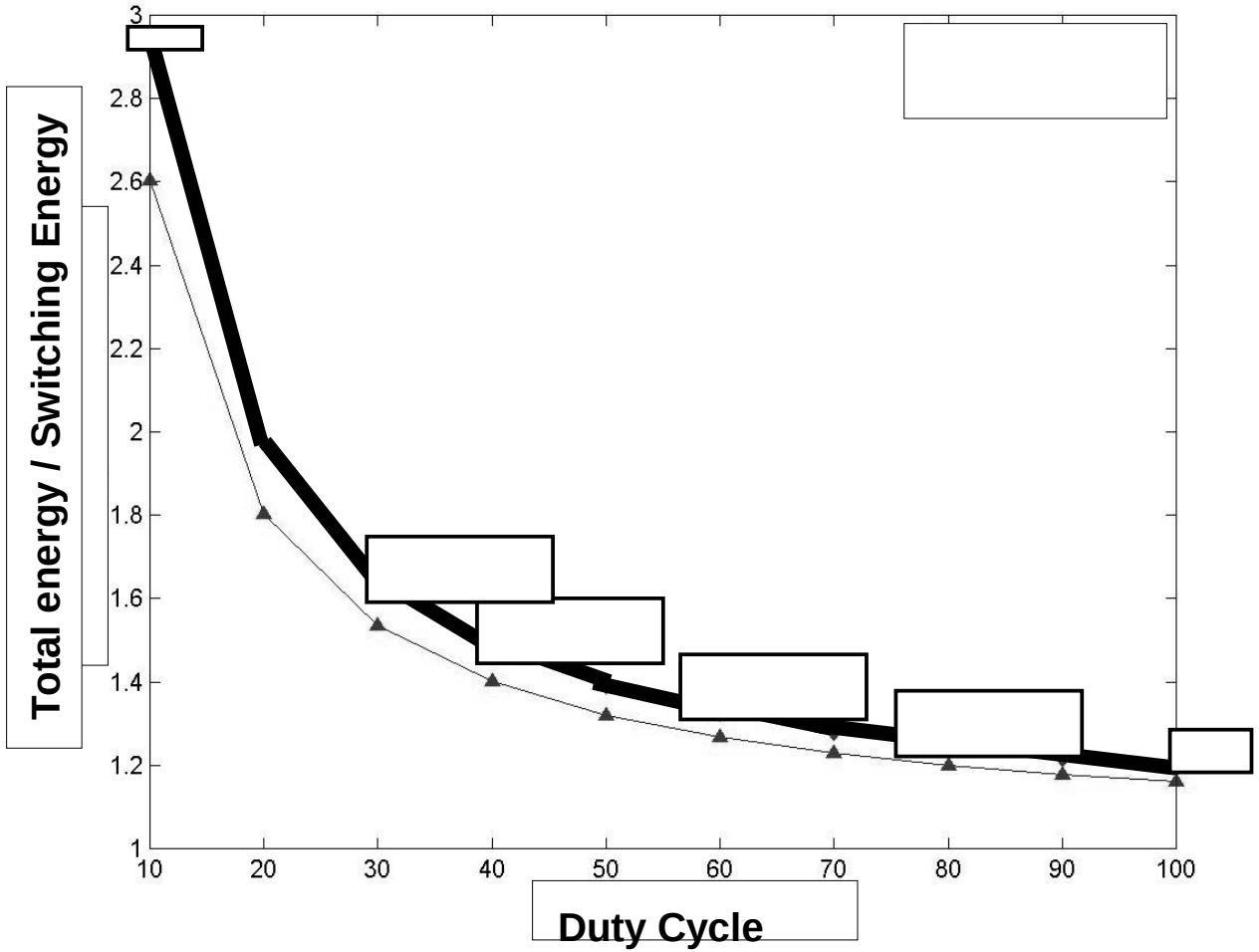


$E_{FIXED} = \frac{1}{2} C V_{DD}^2$

$E_{VARIABLE} = \frac{1}{2} C (V_{DD}/2)^2 = E_{FIXED} / 4$

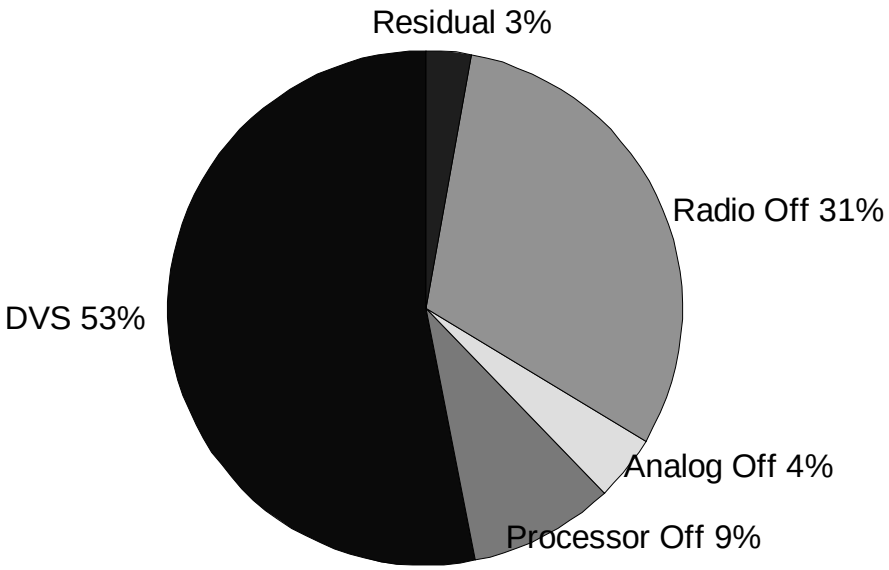


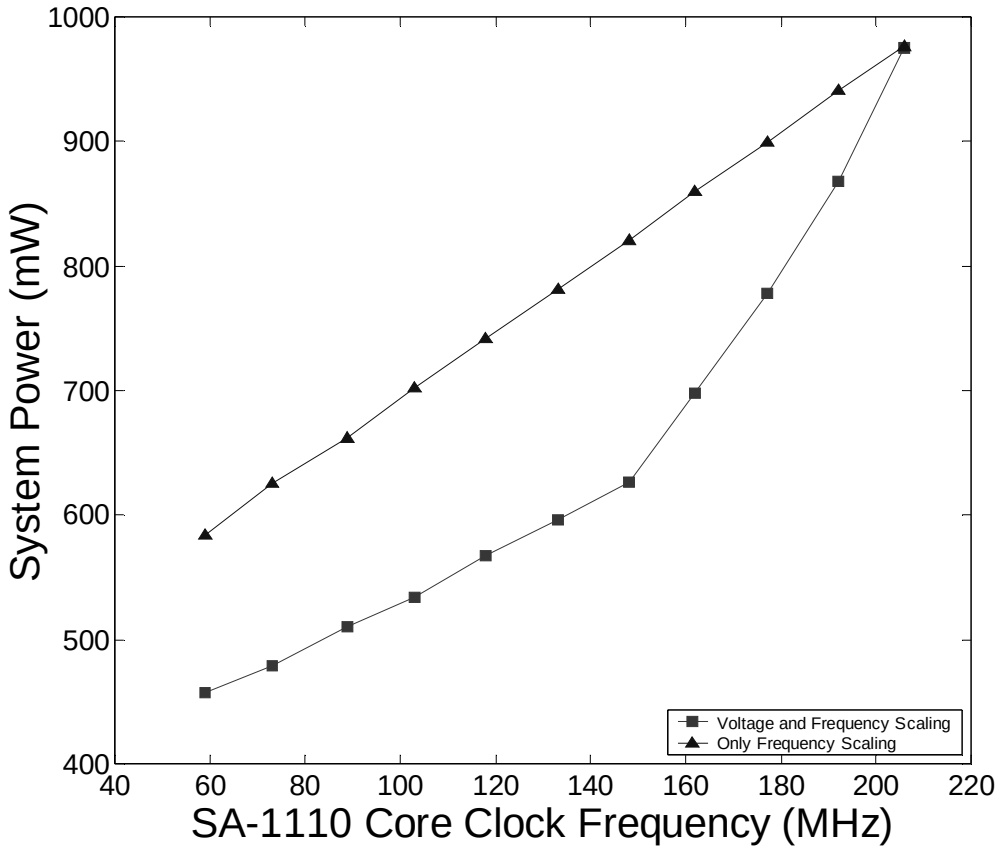
Leakage vs. Switching Energy



Leakage dominates switching energy at low duty cycles

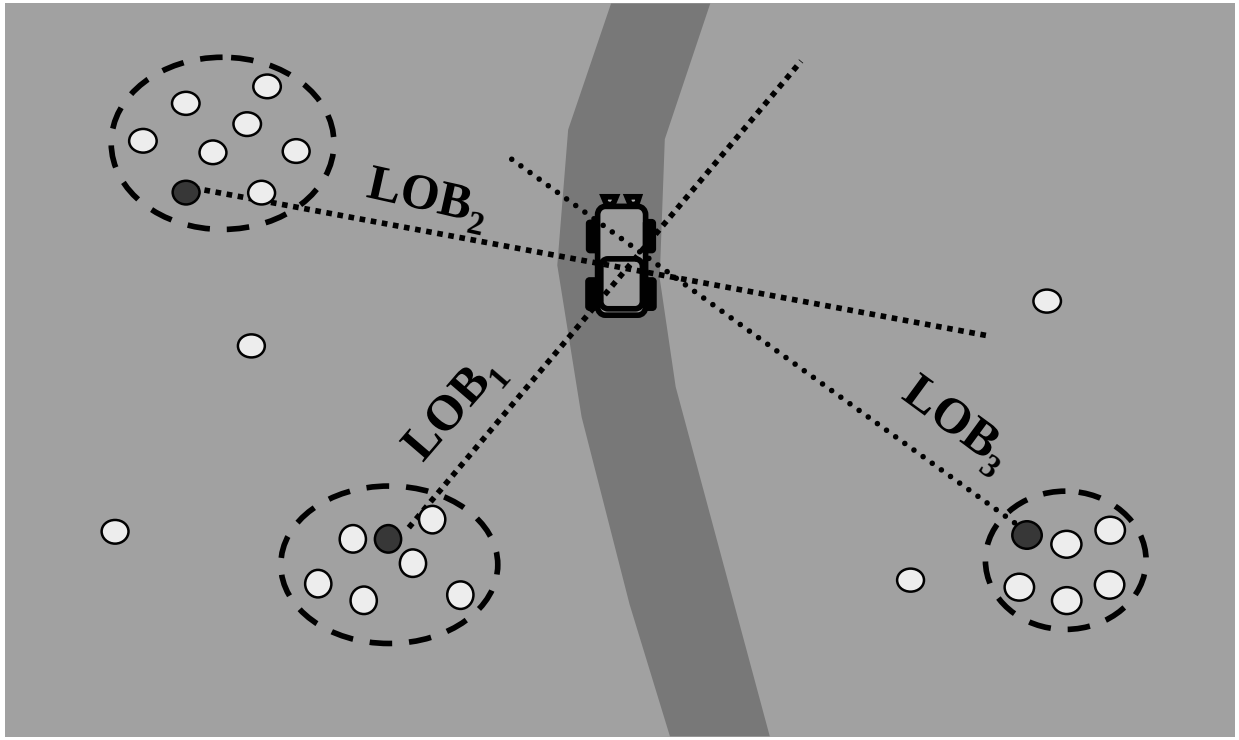
Shutdown Modes on µAMPS node





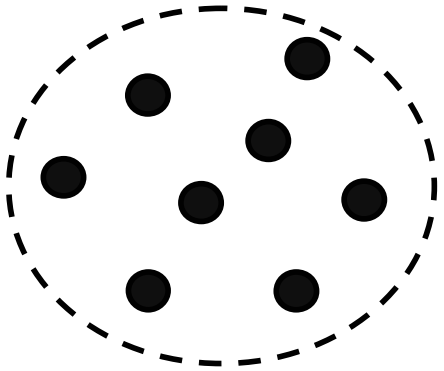
- Total power = 975.6 mW (Radio power approximated)
- Duty Cycle of 1% → 27x lifetime improvement

Energy-Efficient Signal Processing



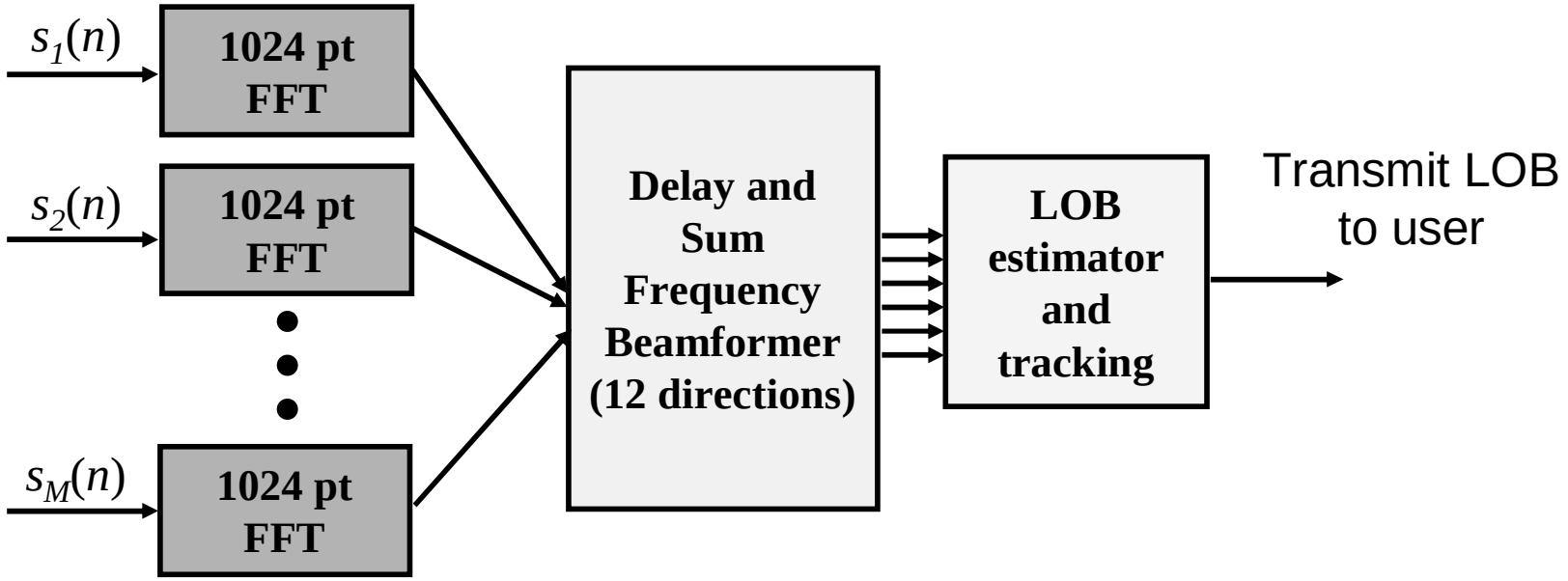
- Vehicle tracking application
  - Sensors used to form cluster
  - Multiple clusters used to estimate line of bearing (LOB)
  - Cluster sends data to remote user where tracking is performed
- Goal: Devise energy-efficient technique for LOB estimation and vehicle tracking

Line of Bearing Algorithm



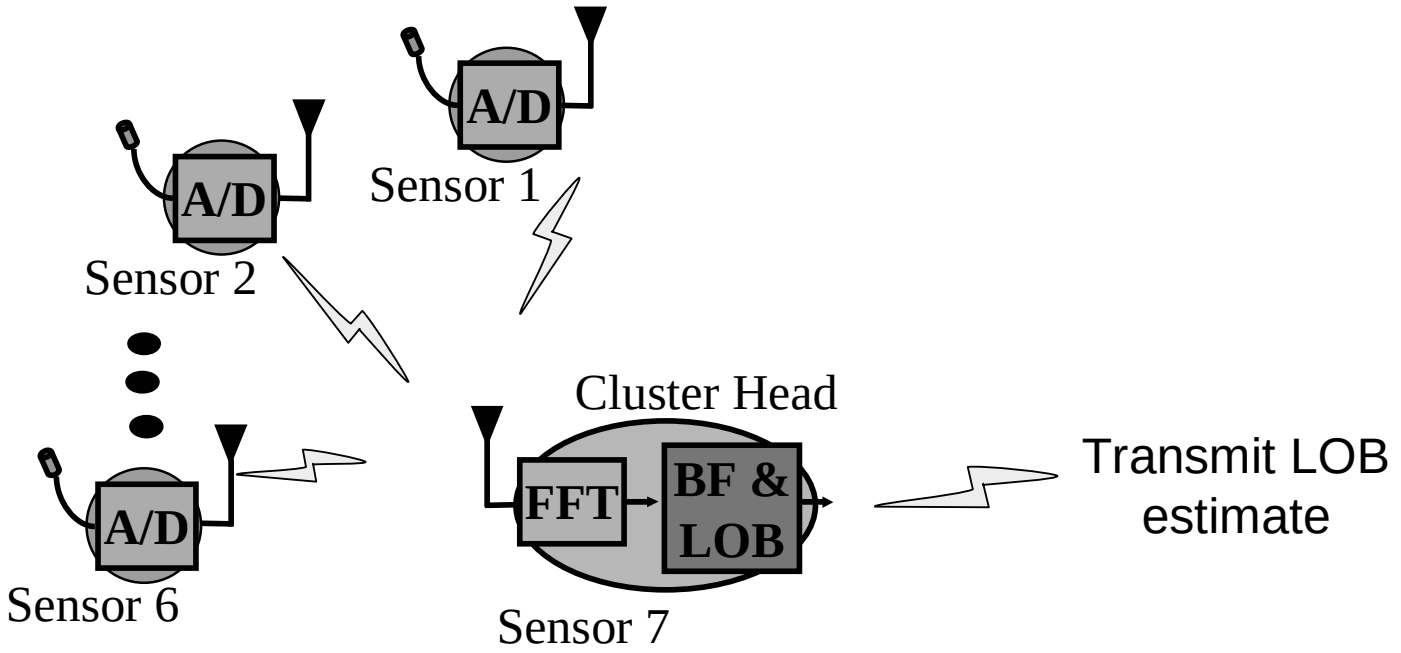
M sensor array

- LOB estimated by delay-and-sum beamforming algorithm
- Direction with strongest signal forms LOB estimate
- Algorithm performed in frequency domain



[Courtesy N. Srour (Army Research Laboratories)]

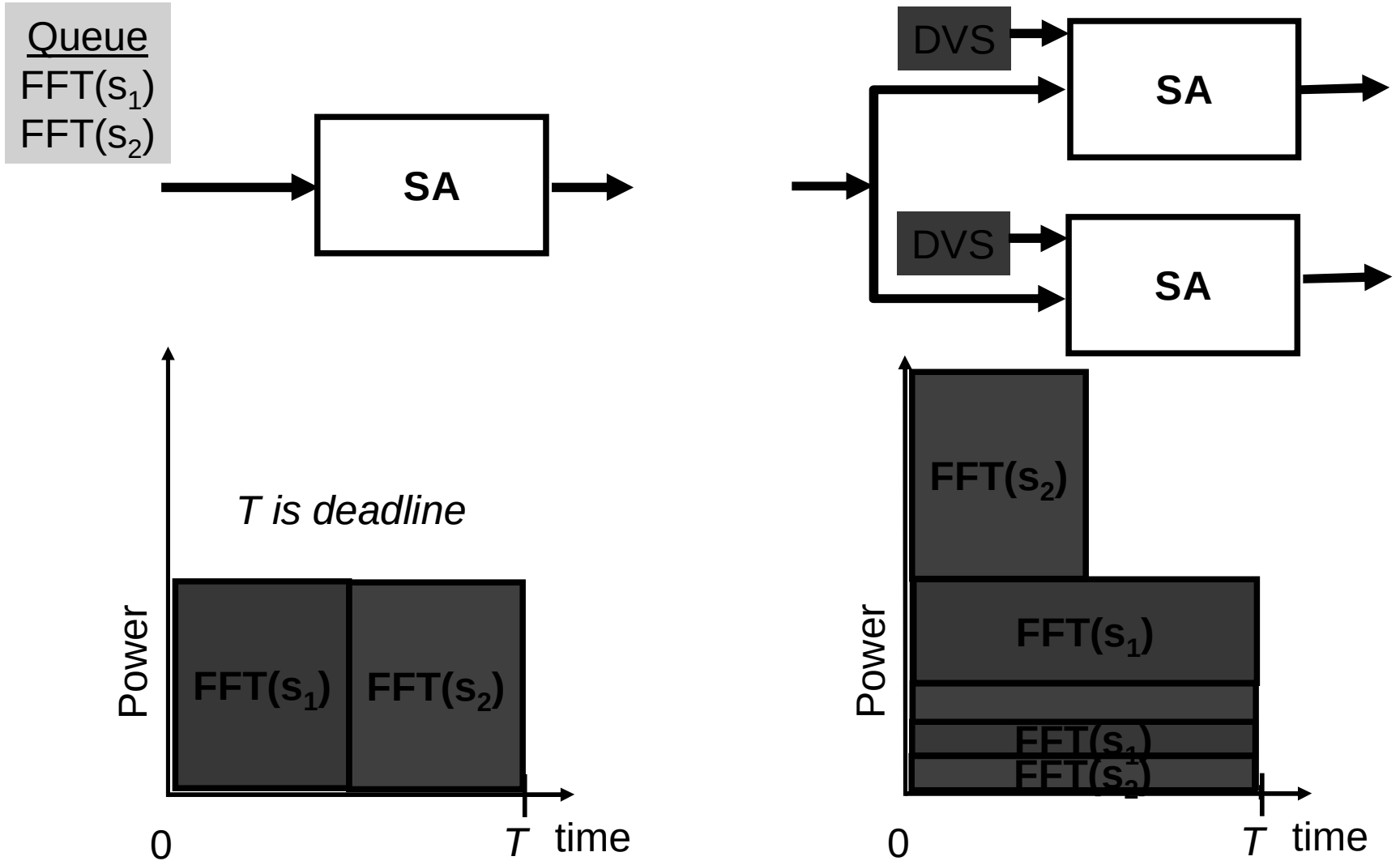
LOB Estimation: Direct Approach



- Direct approach: LOB algorithm performed at the clusterhead and then estimate is sent to user

$$E_{comp}(V_{dd} = 1.44\ \text{V}) = 7 * E_{fft} + E_{bf} + E_{LOB}$$
$$= 6.01\ \text{mJ}$$
$$Latency_{comp} = 19.2\ \text{ms}$$

Computation and Energy Partitioning

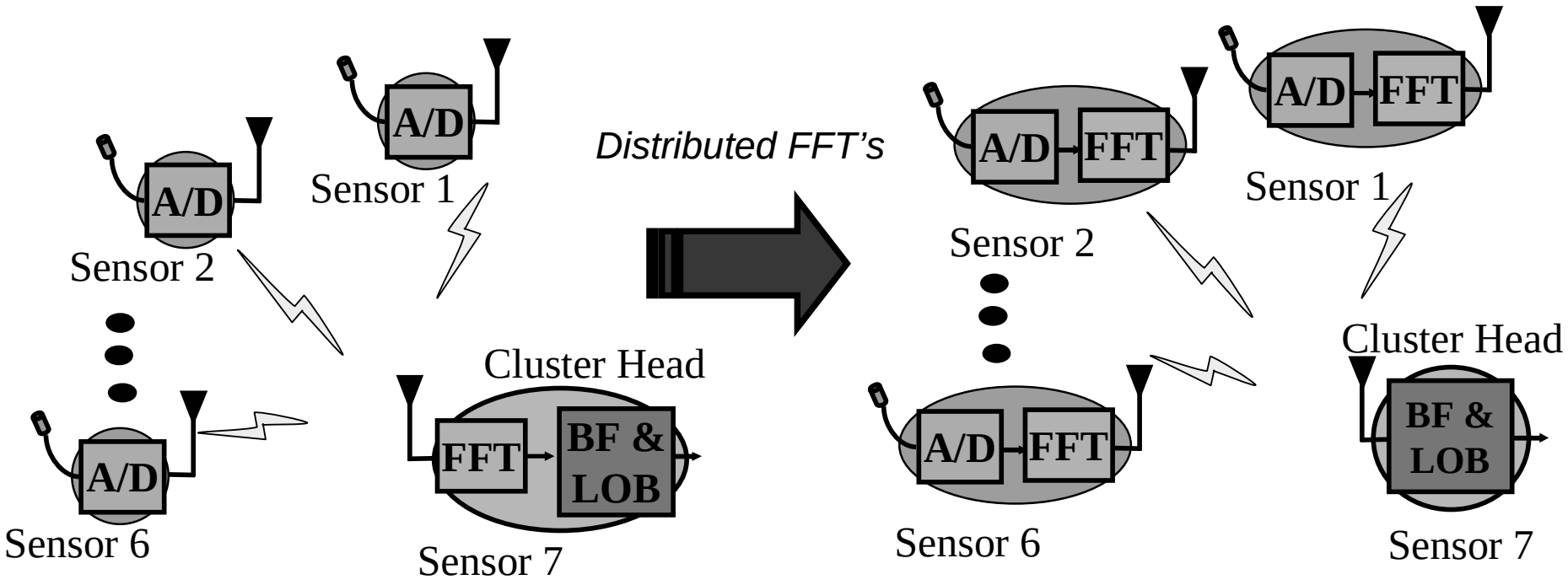


$$E_{fft} = 2\, N_{fft}\, C\, V_{fft}^{2}$$

$$E_{fft} = 2\, N_{fft}\, C\, (V_{fft}/2)^{2}$$

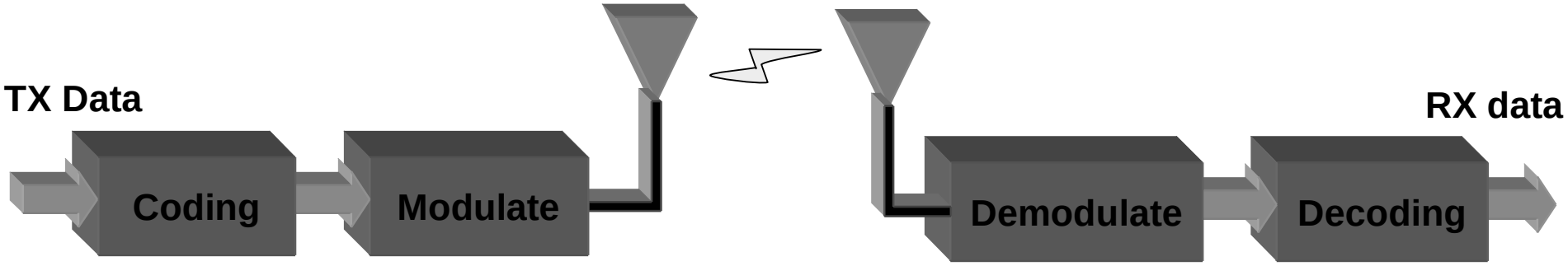
¼ energy dissipated

Energy-Efficient LOB Estimation



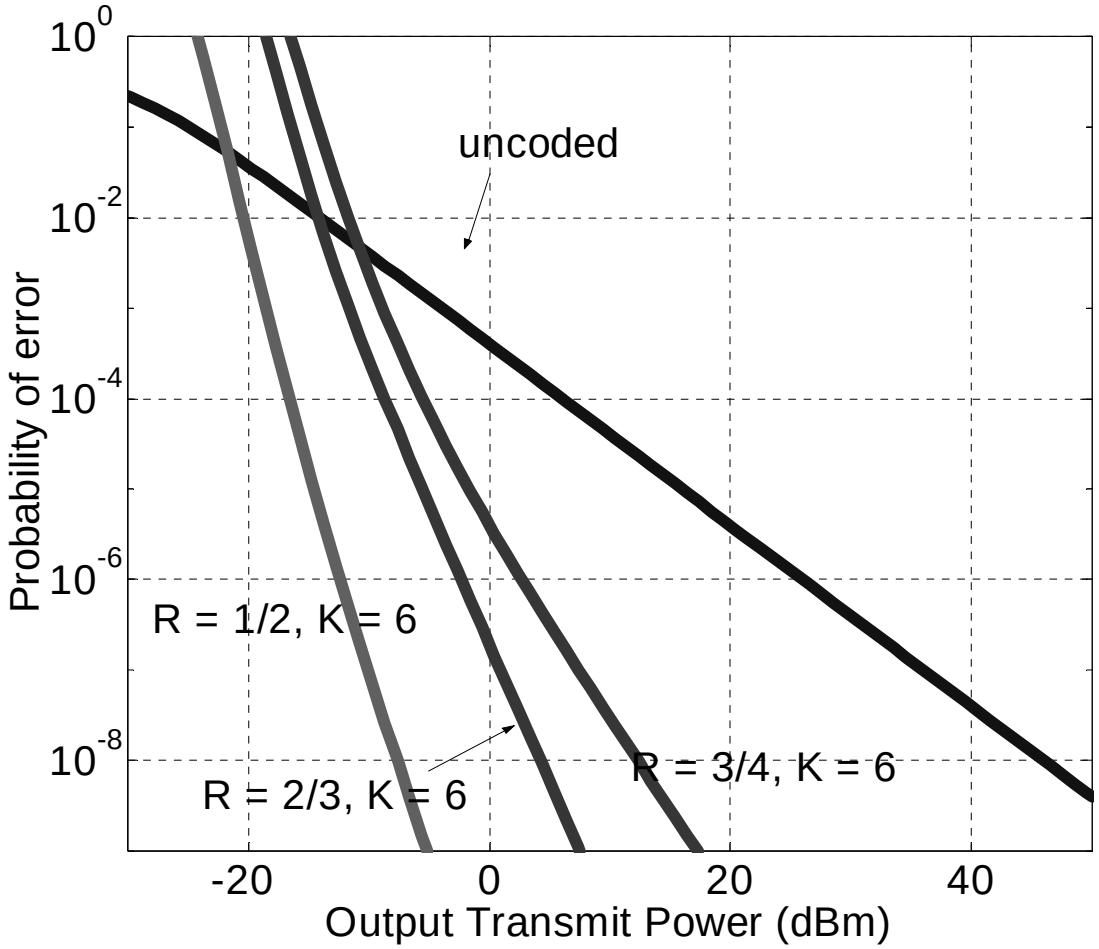
Latency	19.2 ms	18.4 ms
Energy	6.2 mJ	3.4 mJ

Power-Aware Communication



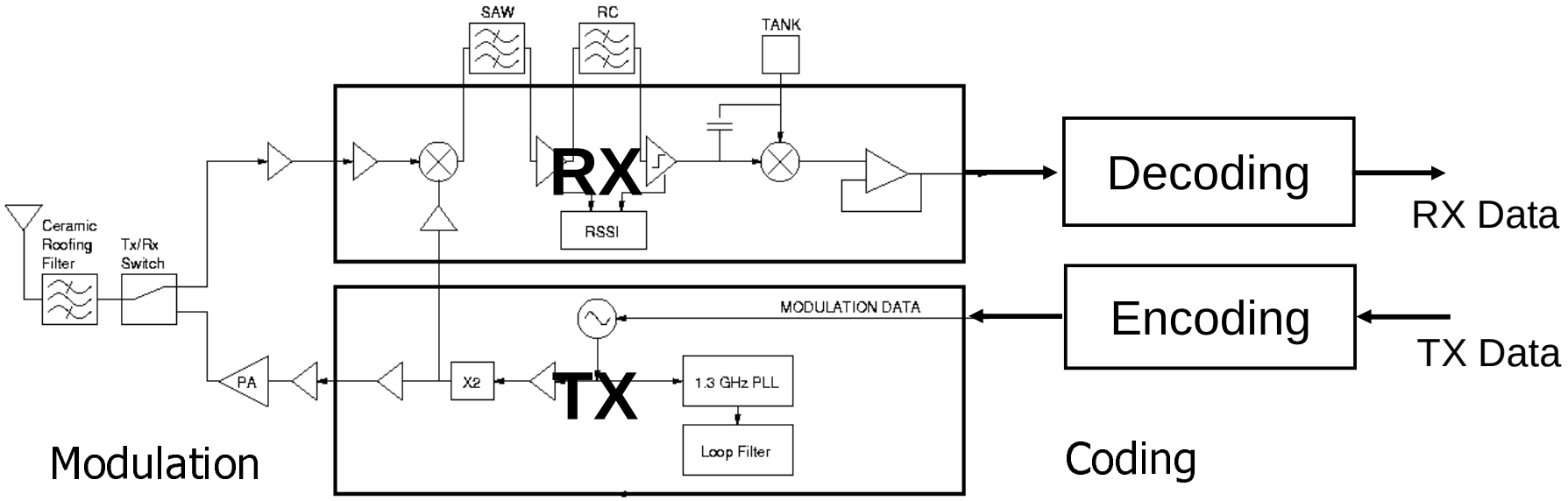
- Assumptions
  - Rayleigh fading with AWGN
  - Probability of error is the desired parameter
- Various techniques to meet requirement
  - Increase transmit power
  - Add forward error correction

Effect of Coding



Communication View: Coding Always Good

Energy Cost of Communication



$$E_{radio} = E_{rx} + E_{tx}$$

$$E_{radio} = [P_{rx}(T_{on} + T_{startup})] + [P_{tx}(T_{on} + T_{startup}) + P_{out}(T_{on})]$$

$$E_{FEC} = E_{FEC}^{(e)} + E_{FEC}^{(d)}$$

Fixed Parameters

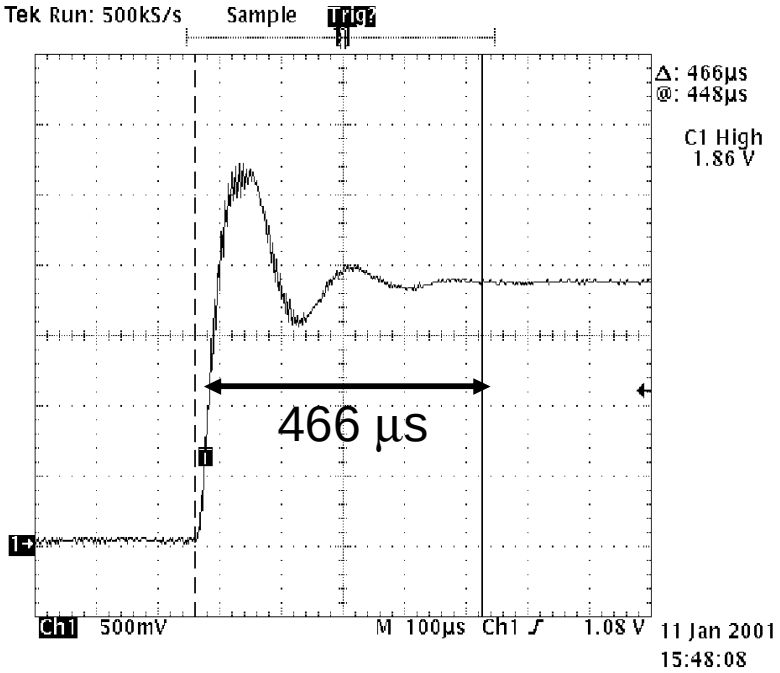
P_{tx}	*81* mW
P_{rx}	*180* mW
$T_{startup}$	*466 µs*

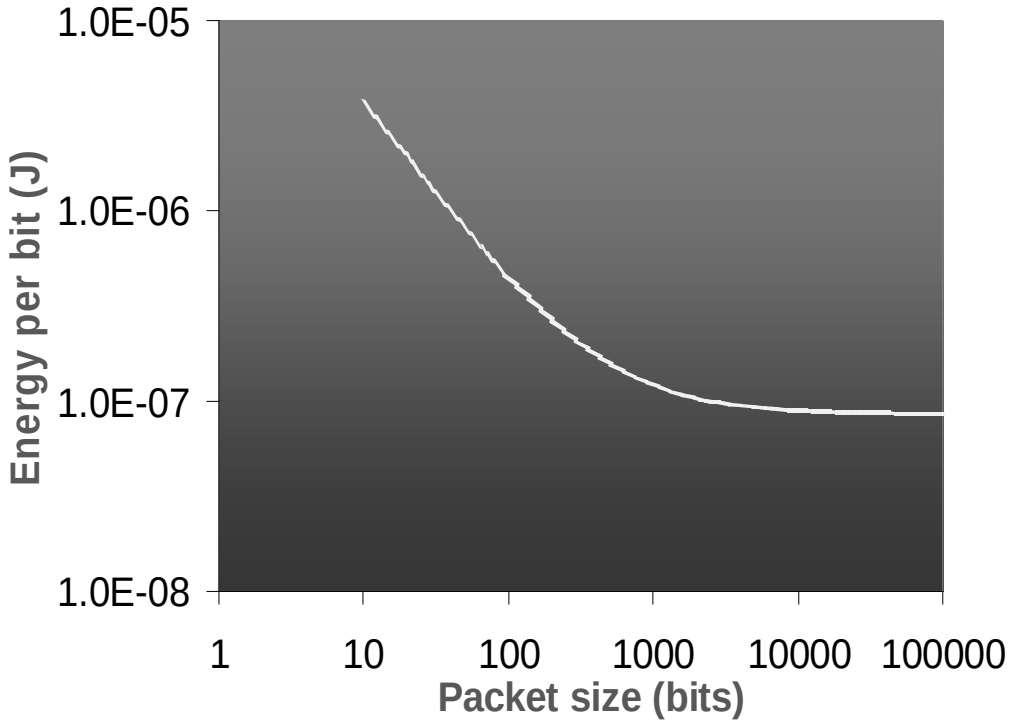
Tunable Parameters

P_{out}
T_{on}
E_{FEC}

Wasted Energy: Startup Time

Startup time screen capture



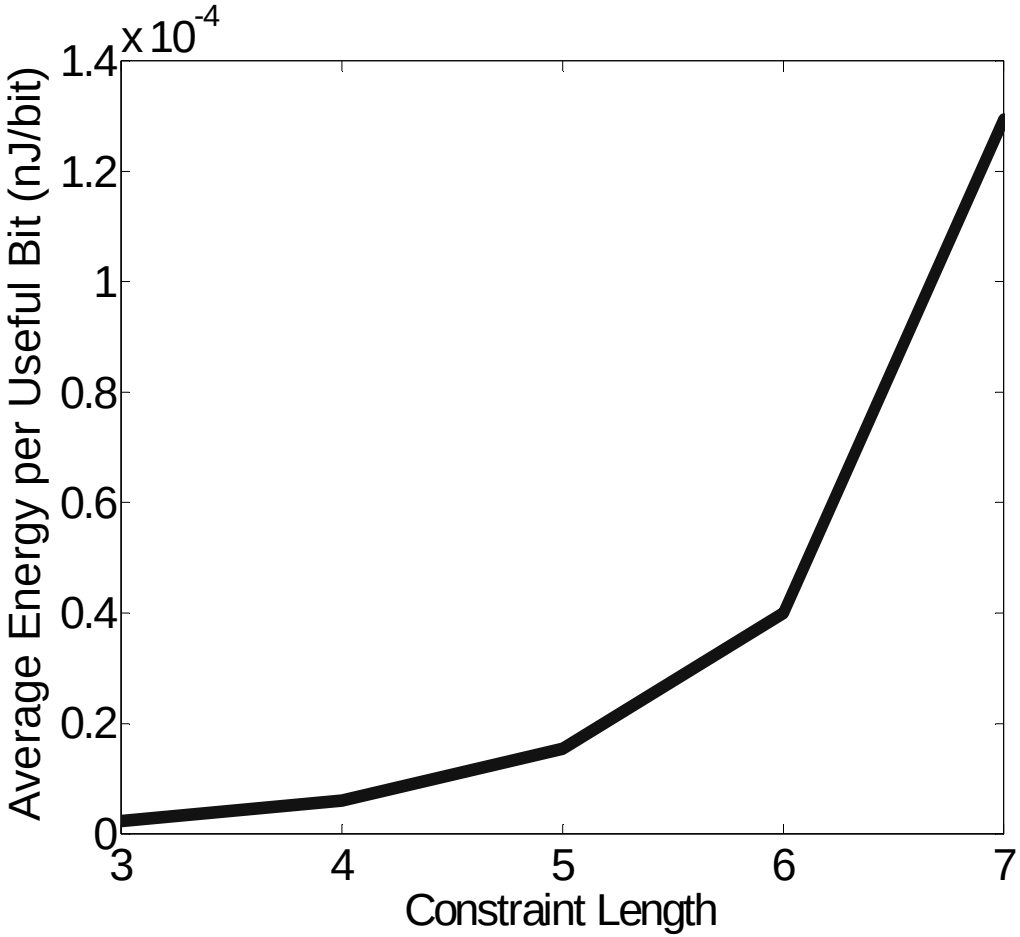


- Fixed cost of communication (startup time)
  - High energy per bit for small packet

Coding Energy: StrongARM

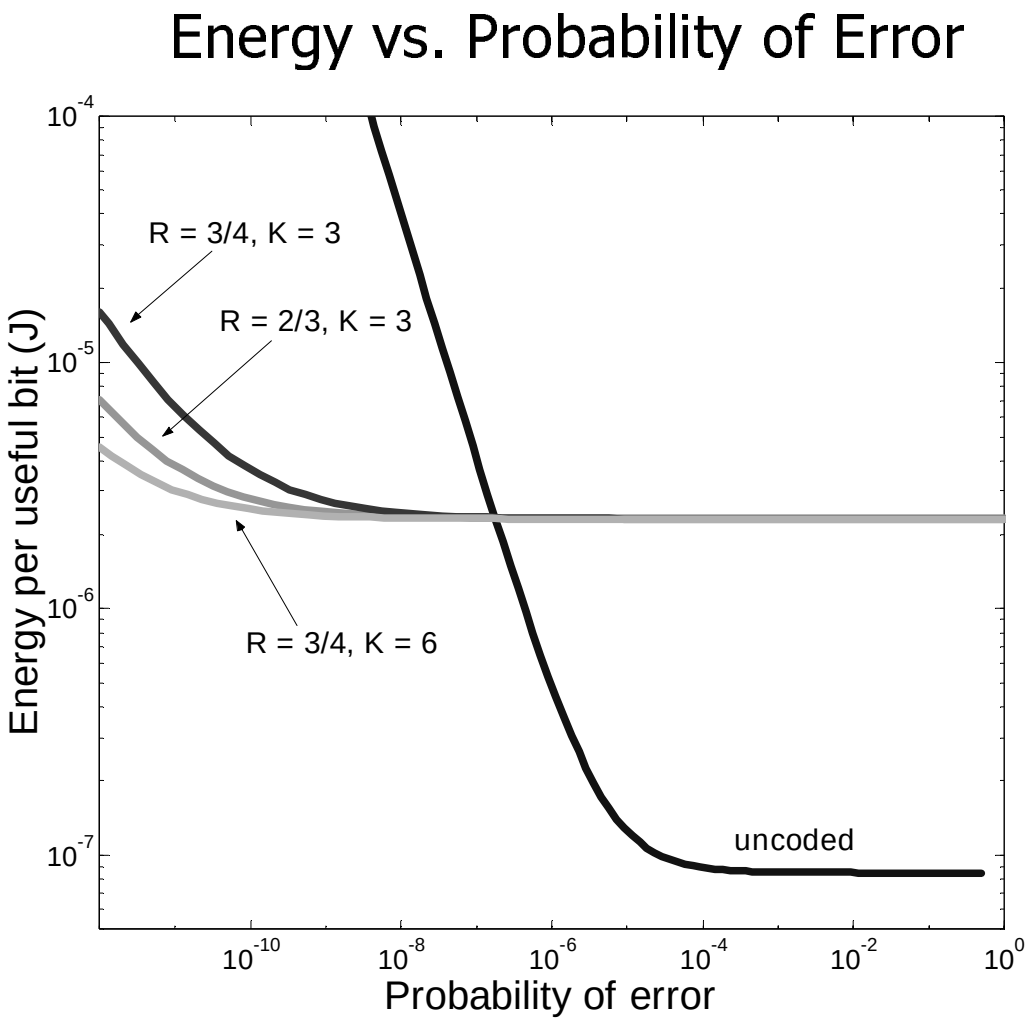
- Encoding energy negligible
- Decoder energy increases with constraint length
  - States proportional to 2^{K-1}

R = ½, K = 3	2200 nJ/bit
R = ½, K = 6	40000 nJ/bit

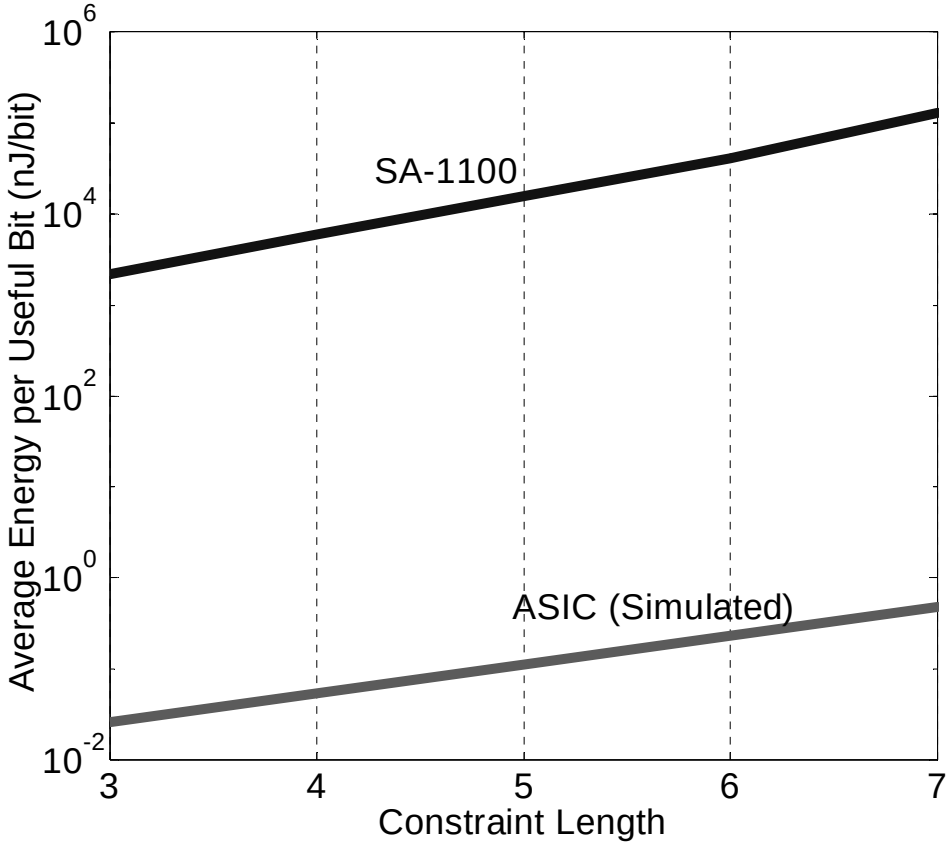


Coding Depends on BER

- Computation energy dominates at high BER
- Transceiver and power amplifier dominates at low BER
  - "Strongest" ECC most energy-efficient



Computation Cost: StrongARM vs. ASIC

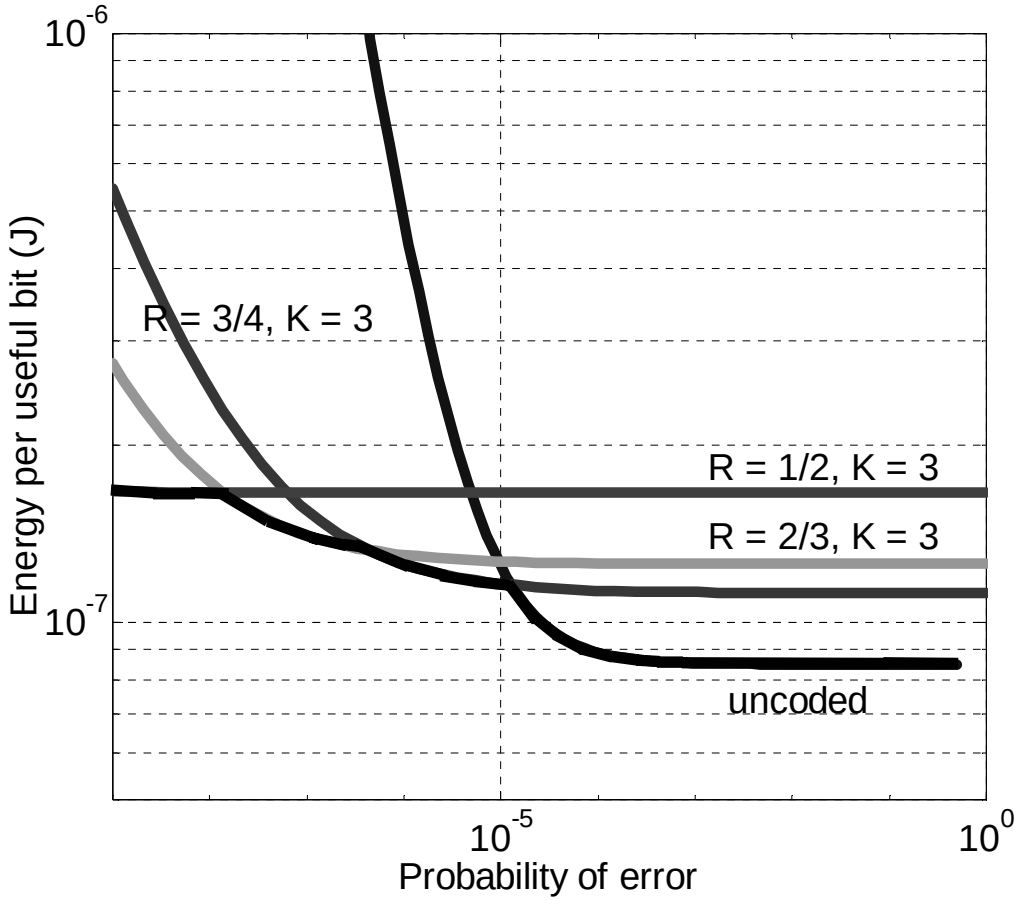


	R = ½ K = 3	R = ½ K = 6
ASIC (nJ/bit)	0.026	**0.225**
SA-1100 (nJ/bit)	2200	**40000**

- Viterbi decoder on StrongARM is inefficient
- Decoding energy is 5 orders less

Tradeoff Still Exists with ASIC

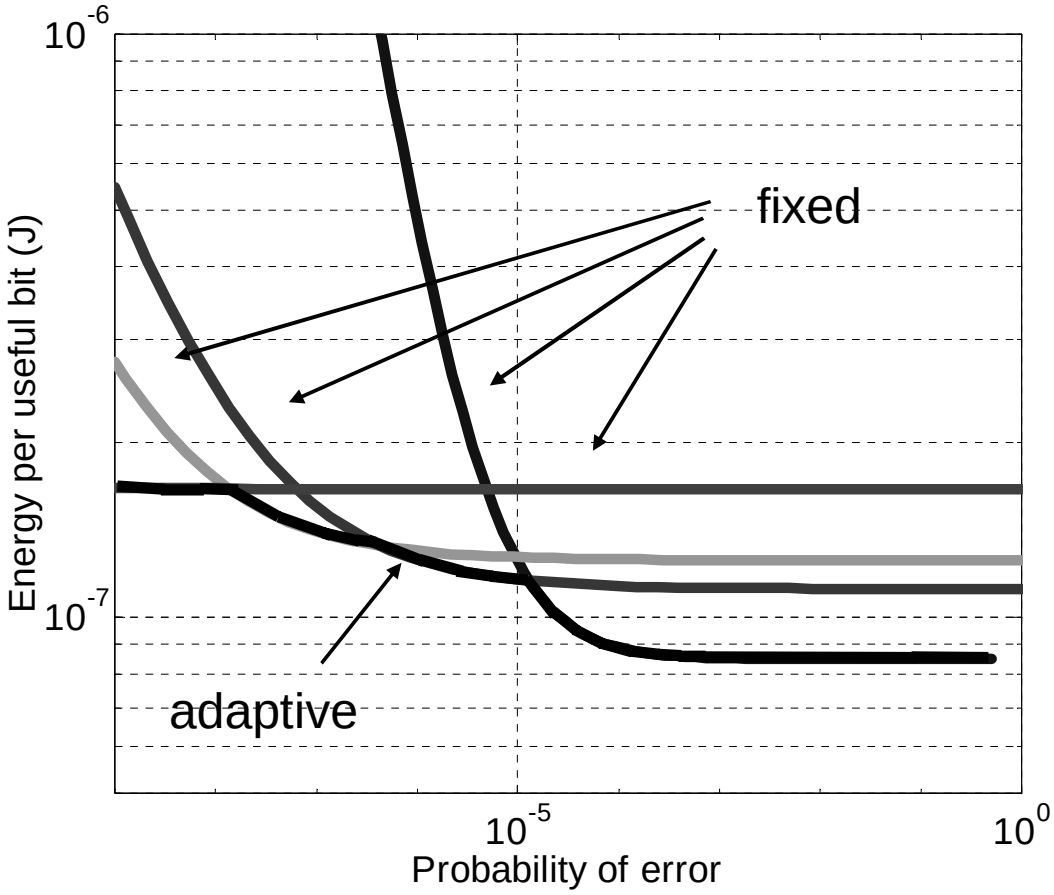
- Computation is cheaper, but coding does not always win
  - Transceiver energy dominant at high BER
- Reduce transceiver energy
  - Use higher rate code



Coding **Not** Always Good

Total Communication Energy Savings

- Scenario:
  - Receiving node has 5 BER requirements
    - 10^{-3} to 10^{-7}
  - Send 100 packets per BER requirement
  - Adaptive strategy vs. non-adaptive strategies



Total Communication Energy Savings

Strategy	Energy (J)
No coding	4.5
R = ½, K = 3	0.83
R = ¾, K = 3	0.61
Variable	0.55

Table 1: Total energy consumed to transmit 500 packets while maintaining user requirements (10^{-3} to 10^{-7})

Adaptive Strategy vs. Fixed Scheme	Percentage Energy Saved by Adaptive Strategy (%)
R = ½, K = 3	51
R = ¾, K = 3	11

Table 2: Energy savings of adaptive strategy over 3 different fixed strategies in scenario described

Conclusion

- Nodes energy-constrained in wireless sensor networks
- Power-aware design is critical to achieve long lifetimes required in such networks
  - Must pervade all system layers
- Enabling power-awareness:
  - Need hardware that can be adapted
  - Energy characterization absolutely necessary
  - Apply DVS, physical layer adaptation, etc.

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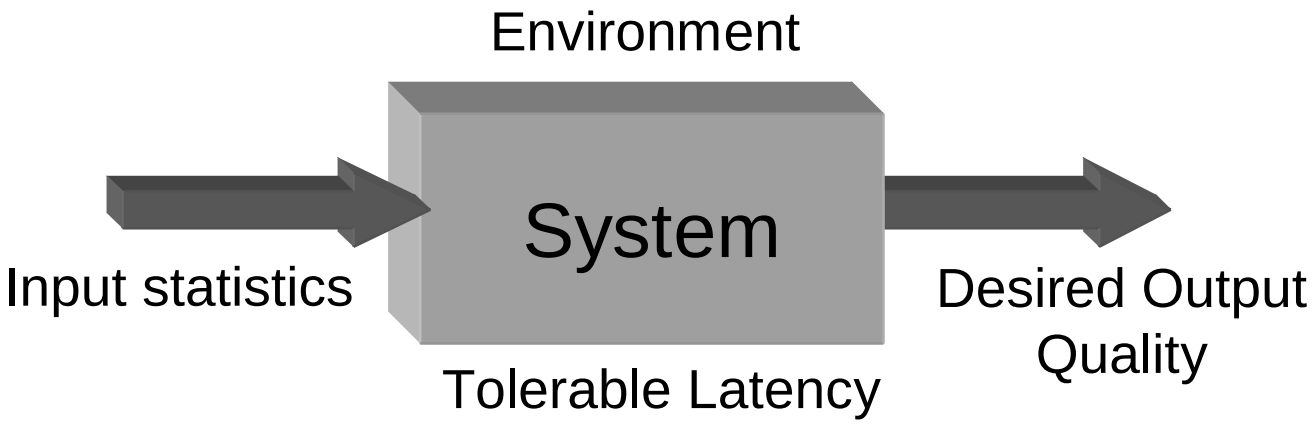
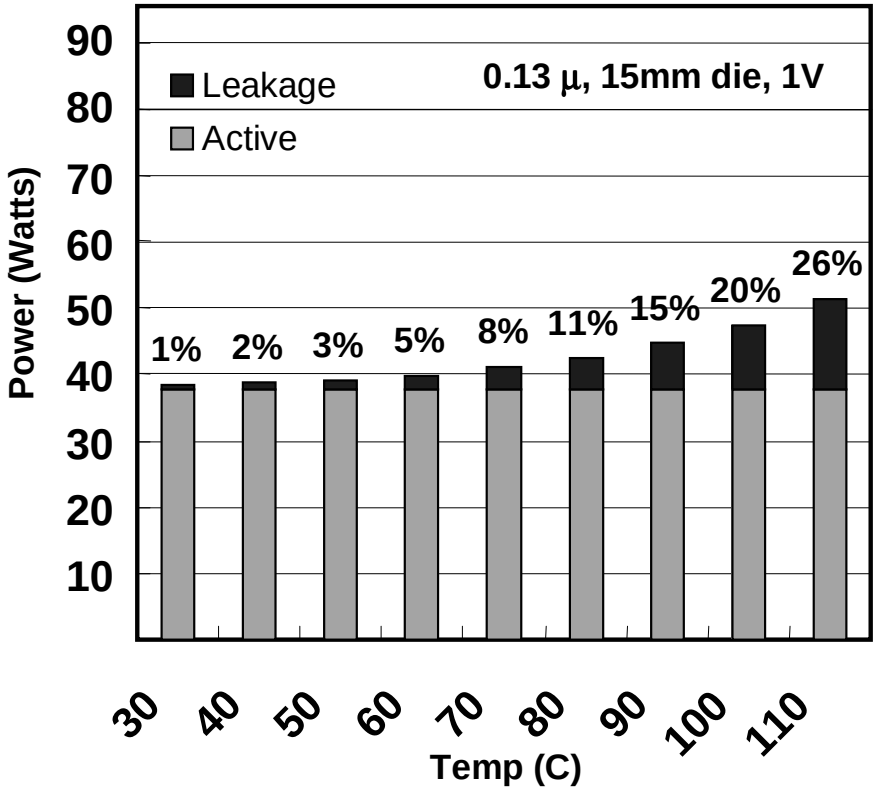
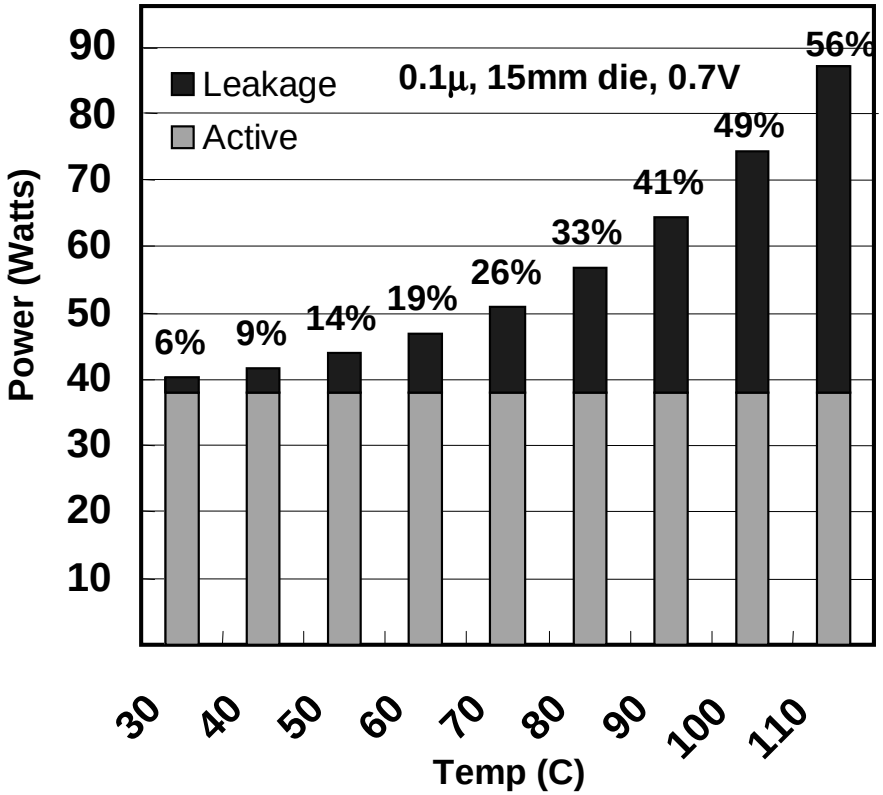
Power-Awareness



- Operating scenarios are diverse and dynamic
  - Changes in environment, signal statistics, etc.
  - Focus on adaptation to achieve desired output quality
- Power-aware system design explicitly adapts energy dissipation to changing scenario

Switching vs. Leakage: Trends



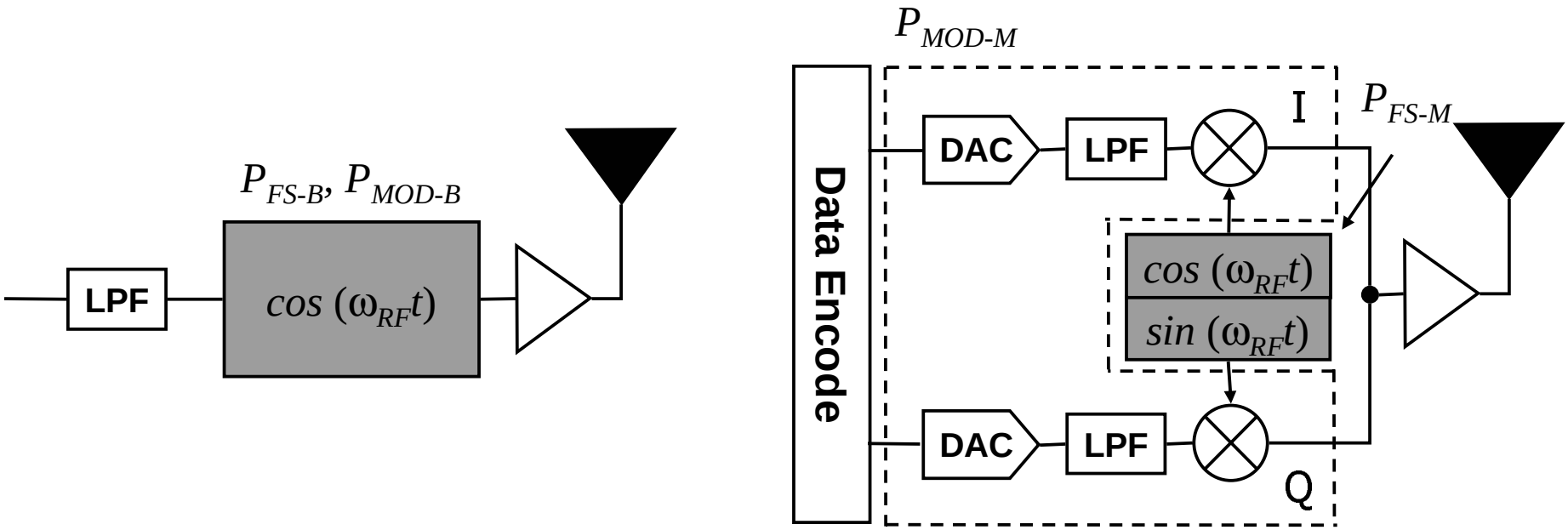


Courtesy Vivek De (Intel)

- Leakage dominance worsens as feature sizes decrease
- Need leakage control techniques
  - Dynamic voltage scaling and power management

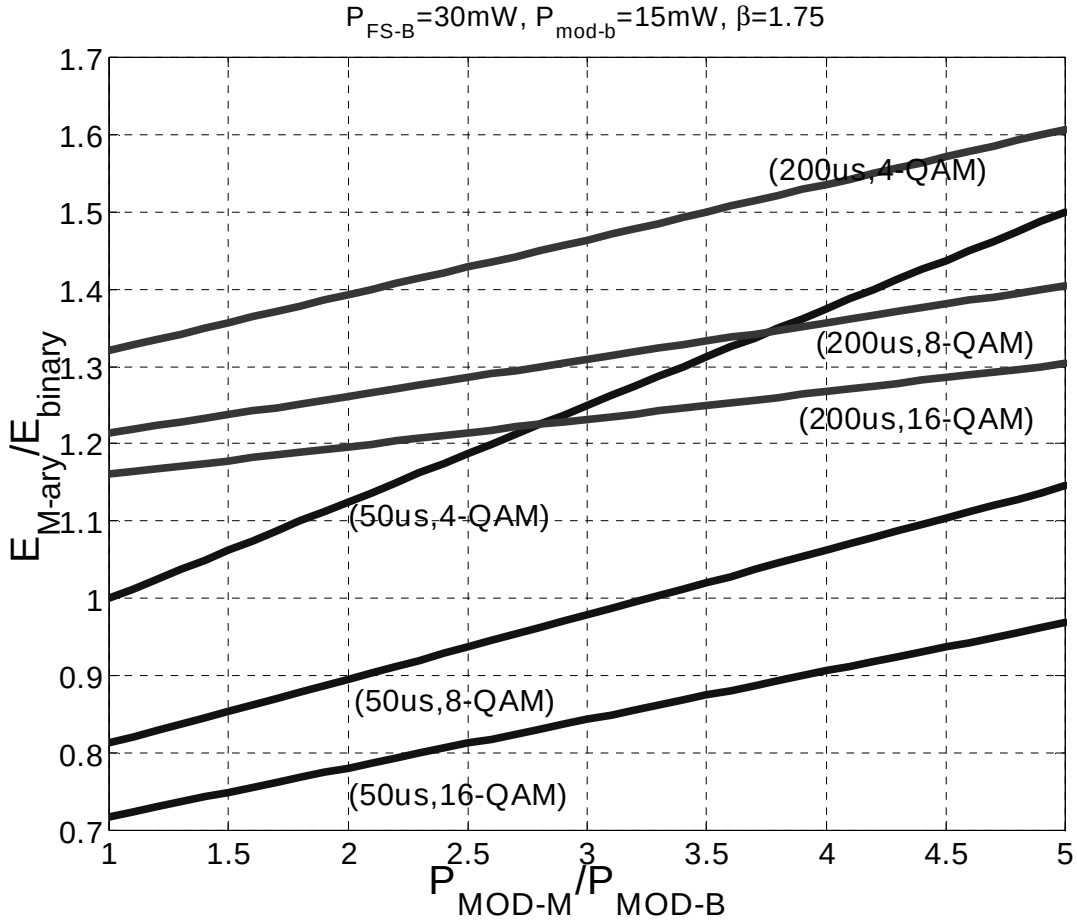
Energy-Efficient Modulation Schemes

$$E_{radio} = [P_{rx}(T_{on} + T_{startup})] + [P_{tx}(T_{on} + T_{startup}) + P_{out}(T_{on\text{-}tx})]$$



- Reduce energy consumption of radio by reducing T_{on}
  - M-ary modulation
- Must evaluate cost of electronics:
  - $P_{MOD\text{-}M}$ vs. $P_{MOD\text{-}B}$: M-ary modulation has higher power than binary
  - $P_{FS\text{-}M}$ vs. $P_{FS\text{-}B}$: Synthesizing for M-ary modulation has higher power

Binary vs. M-ary modulation



- Compare energy for M-ary modulation and binary modulation
  - Take into account power of synthesizers and amplifiers
  - Assume fixed overhead for synthesizer power and variable overhead for modulation

Latency-Awareness

Fixed Power Supply

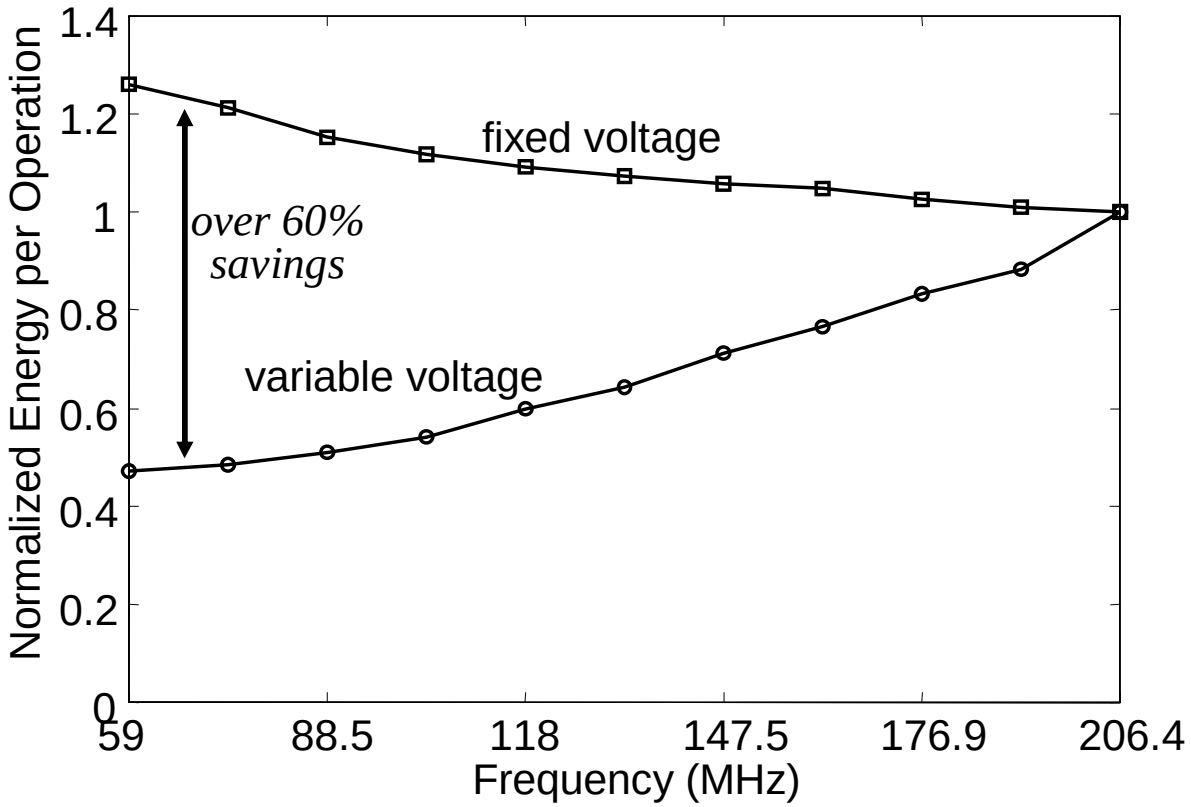
ACTIVE	IDLE

Variable Power Supply

ACTIVE

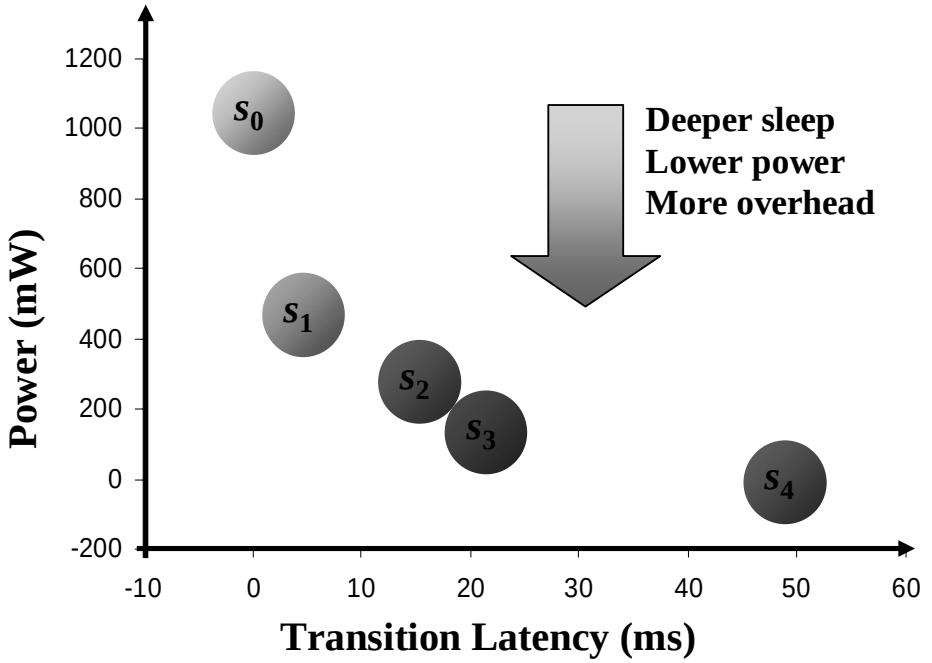
$E_{FIXED} = \frac{1}{2} C V_{DD}^2$

$E_{VARIABLE} = \frac{1}{2} C (V_{DD}/2)^2 = E_{FIXED} / 4$



Shutdown Modes

	ARM	Memory	Sensor	Radio
S_0	active	active	on	tx, rx
S_1	idle	sleep	on	rx
S_2	sleep	sleep	on	rx
S_3	sleep	sleep	on	off
S_4	sleep	sleep	off	off



- Node can operate in various sleep-states
- Moving state to state has an associated penalty