II.3 Energy Models for Sensor Networks

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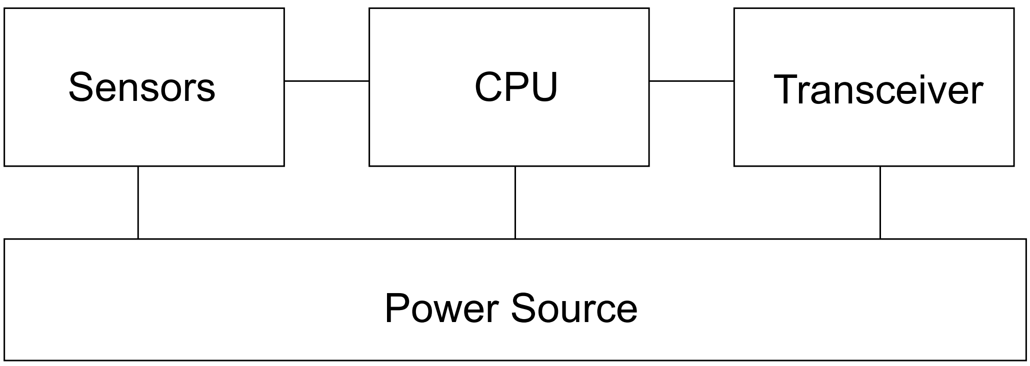
Basic Architecture



Sources of Energy Consumption

- Radio
  - Transceiver electronics
- Processing
  - Dynamic Voltage Scaling (DVS)

    - Reduction of frequency allows the processor to run at a lower voltage
    - Supply voltage V
    - Switching Energy consumed α V^2
    - Leakage Energy
      - due to leakage current (happens even when no work is done)
      - exponential relationship with supply voltage
  - Hence, reducing V reduces energy consumption
  - However, this increases latency
- Switching between active, idle and sleep modes
- Storage

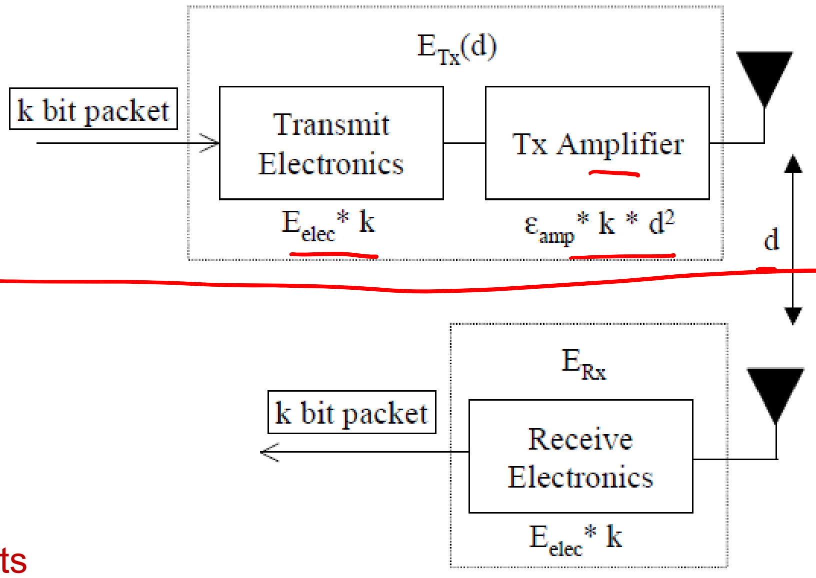
I. Simple Radio Model

[Heinzelman00]

- Different assumptions about the radio characteristics, including energy dissipation in the transmit and receive modes, will change the advantages of different protocols.
- Consider a simple model where the radio dissipates E_{elec} = 50 nJ/bit to run the transmitter or receiver circuitry, and ε_{amp} = 100 pJ/bit/m^2 for the transmit amplifier to achieve an acceptable SNR E_b/N_0.
- *Note*: This model may be overly optimistic.

Transmitter

Receiver



k = no. of bits

$$E_{Tx}(k,d) = E_{Tx-elec}(k) + E_{Tx-amp}(k,d)$$
$$E_{Tx}(k,d) = E_{elec} * k + \epsilon_{amp} * k * d^2$$

energy loss due to channel txn

$$E_{Rx}(k) = E_{Rx-elec}(k)$$
$$E_{Rx}(k) = E_{elec} * k$$

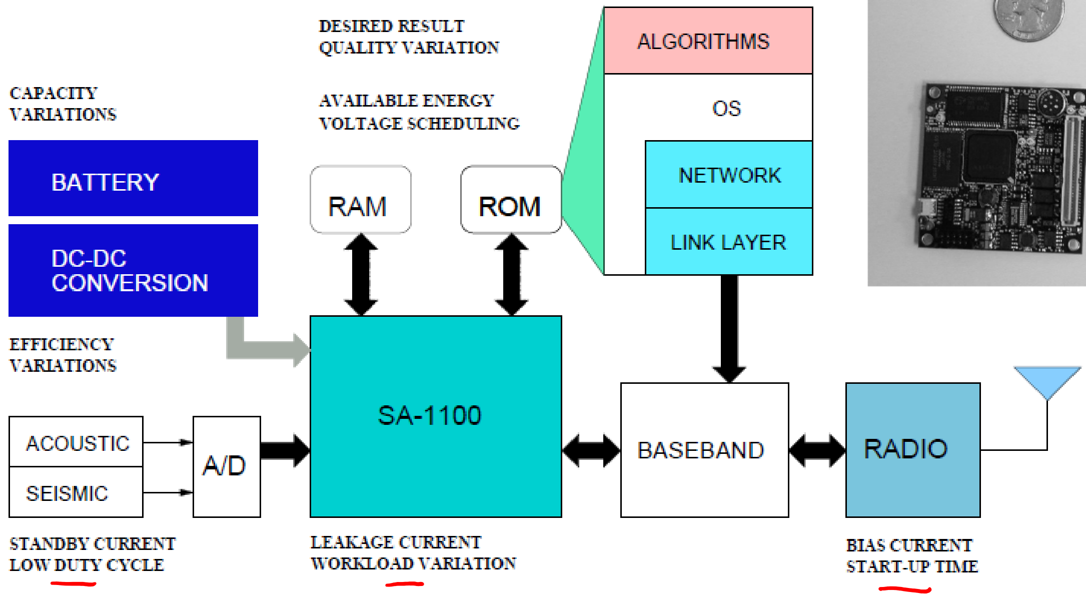
Operation	Energy Dissipated
Transmitter Electronics ($E_{Tx-elec}$) Receiver Electronics ($E_{Rx-elec}$) ($E_{Tx-elec} = E_{Rx-elec} = E_{elec}$)	50 nJ/bit
Transmit Amplifier (ϵ_{amp})	100 pJ/bit/m^2

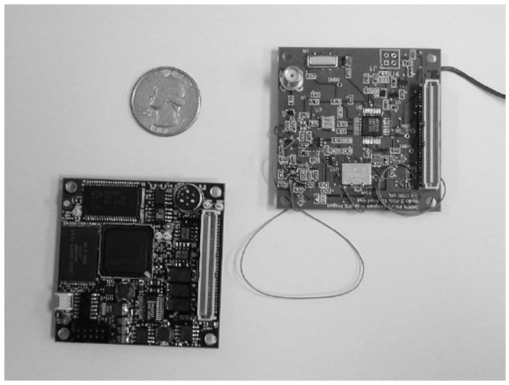
Points to Note

- For these parameter values:
  - receiving a message is not a low cost operation
  - protocols should thus try to minimize not only the transmit distances but also the number of transmit and receive operations for each message

II. µAMPS Wireless Sensor Node

[Shih01]





µAMPS Wireless Sensor Node

- µAMPS (micro-Adaptive Multi-domain Power-aware Sensors)
- Wish to scale the energy consumption of the entire system in order to maximize system lifetime and reduce global energy consumption
  - all layers of the system, including the algorithms, operating system and network protocols can adapt to minimize energy usage
- StrongARM SA 1110 microprocessor
  - clock speed can vary from 59 to 206 MHz, i.e. energy consumption can be varied

More Detailed Radio Model

[Shih01]

Energy per Second

- Average power consumption of the radio

$$P_{radio} = N_{tx}[P_{tx}(T_{on-tx} + T_{st}) + P_{out}T_{on-tx}] \quad \text{Txr}$$
$$+ N_{rx}[P_{rx}(T_{on-rx} + T_{st})] \quad \text{Rx}$$

$N_{tx/rx}$ is the average number of times per second that the transmitter/receiver is used

$P_{tx/rx}$ is the power consumption of the transmitter/receiver

P_{out} is the output transmit power (power amplifier)

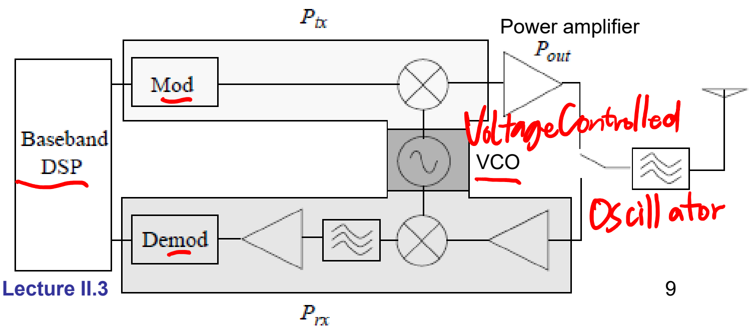
$T_{on-tx/rx}$ is the transmit/receive on-time (actual data transmission/reception time)

$= L/R$, where L is the packet size in bits and R is the data rate in bits per second

T_{st} is the startup time of the transceiver

The power amplifier is on only when communications occur.

P_{rx} is 2 to 3 times higher than P_{tx} as the receiver circuitry is more complex, e.g. ≈ 180 mW



Start Up Energy

- Common energy saving strategy: shut off radio when not in use
- Is this always good?
- No!
- Start up time: for phase-locked loop (PLL) of transceiver to be locked to desired carrier frequency using voltage controlled oscillator (VCO) e.g. 2GHz
- Start up energy quite high
- Moral: Good only if packet size large enough

log scale

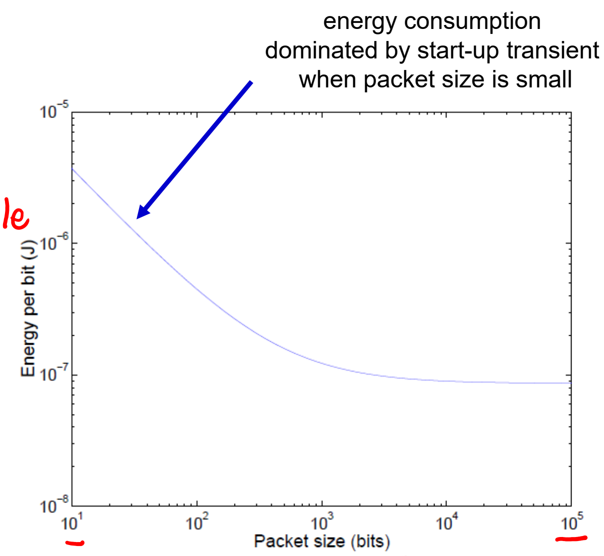


Figure 5: Effect of startup transient where $R = 1$ Mbps, $T_{st} \approx 450\mu$s, $P_{tx} = 81$ mW, and $P_{out} = 0$ dBm.

1mW

Energy for Communication

- Other factors
  – Link layer: coding
  – Modulation scheme Binary, M-nary modulation
  – refer to [Shih01] for details

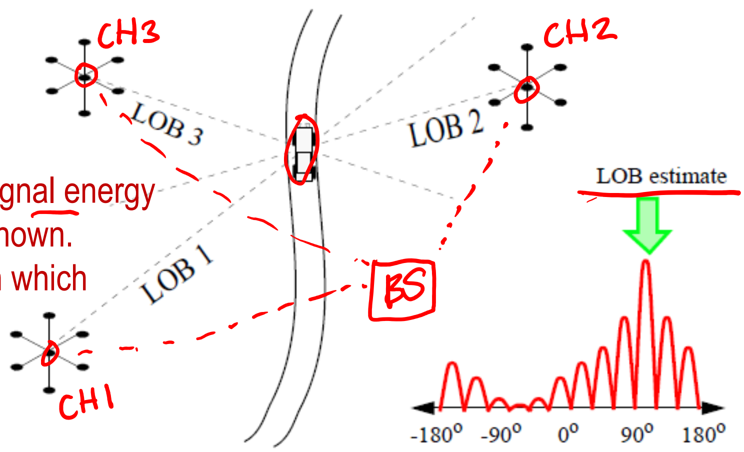
16-QAM

- Effects of MAC, routing and transport protocols will be studied in greater detail in subsequent lectures

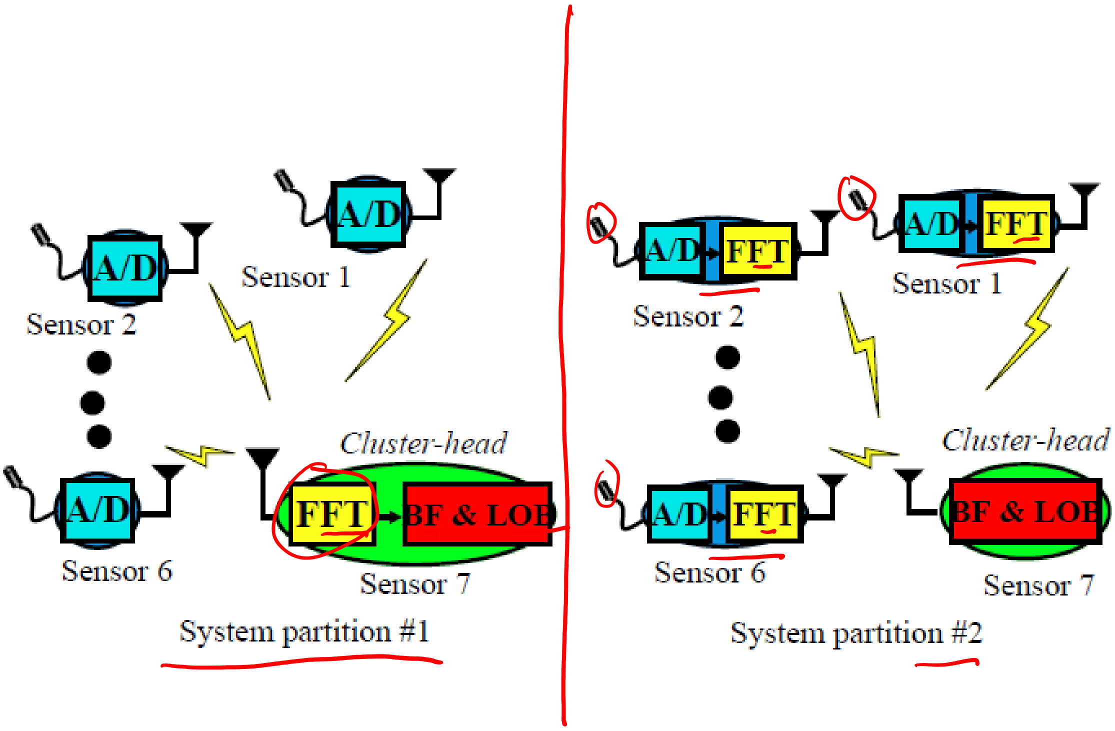
μAMPS Vehicle Tracking Application

- Objective: find the location of the vehicle using acoustic sensing
- Assume clustered sensor nodes
- Entities: node, clusterhead, base station
- Each node sends data to clusterhead which computes the LOB (line of bearing) through signal processing (Fast Fourier Transform)
- Basestation (sink) determines location from intersection point of multiple LOB

The basestation is not shown.
In the figure on the bottom, the signal energy for twelve different directions is shown.
The LOB estimate is the direction which has the most signal energy.



Computation Partitioning



Beamforming (BF): sum outputs of filtered sensor outputs

Computation Partitioning

Note: Reducing processor frequency allows it to run at a lower voltage.

Latency limit: 20 ms

- All computation is done on the clusterhead
- FFT & BF at cluster head: f=206 MHz at 1.44 V
- Energy = 6.2mJ
- Latency = 19.2ms

System Partition 1

- 1024 pt FFT at each sensor at 0.85 V and 74 MHz
- BF at cluster head at 1.17 V and 162 MHz
- Energy = 3.4mJ
- Latency = 18.4ms

System Partition 2

Node-Level Power Mode Scheduling

- A power mode scheduling algorithm manages the active and sleep modes of the underlying device in order to increase node lifetime
  - wasted energy due to leakage can be reduced since if a device is completely turned off, no leakage energy is dissipated

Wireless Sensor node

Node Operating Modes

- System power model like ACPI

Advanced Configuration & Power Interface

Table 1: Useful sleep states for the sensor node.

State	SA-1110	Sensor, A/D	Radio
Active (s_0)	active	sense	tx/rx
Ready (s_1)	idle	sense	rx
Monitor (s_2)	sleep	sense	rx
Observe (s_3)	sleep	sense	off
Deep Sleep (s_4)	sleep	off	off

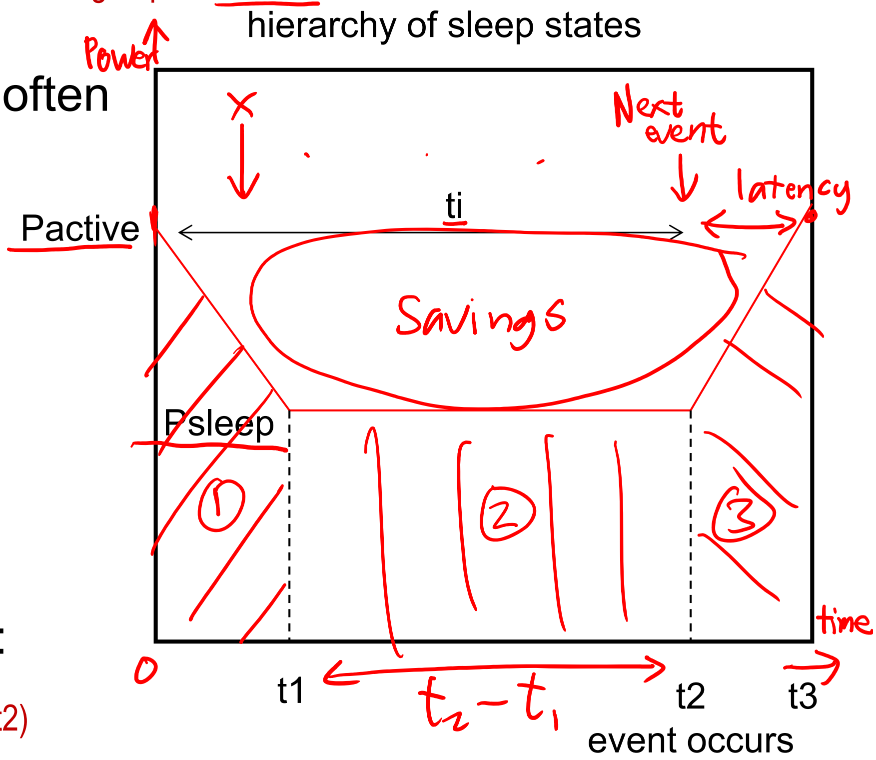
↓ 1. Increasing latency to sleep/wake
2. Decreasing power consumption

State Transitions

t_i = time between end of processing of previous event and arrival of next event

- Should not switch between states very often
  - 1 Eact->sleep = (Pactive +Psleep)*t1/2
  - 2 Esleep = Psleep*(t2-t1)
  - 3 Esleep->act = (Pactive+Psleep)*(t3-t2)/2
- Therefore, sleep if
- Pactive*ti > Eact->sleep + Esleep + Esleep->active
- One other drawback: latency!

Latency is (t3-t2)



State Transitions

t_i = time between end of processing of previous event and arrival of next event

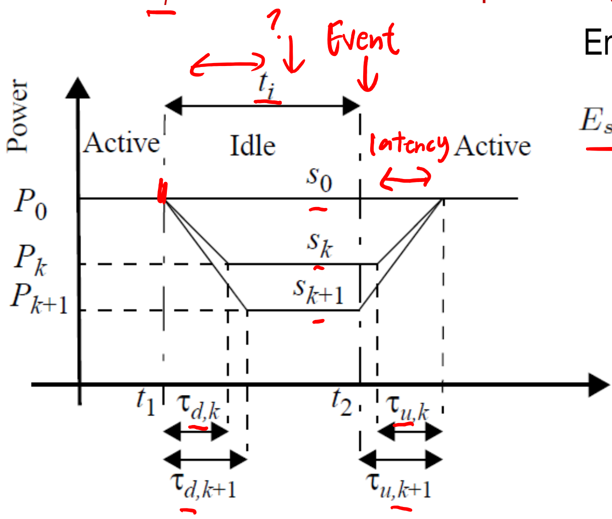


Figure 11: State transition latency and power.

Energy saving E_s due to transitioning:

Always on

$$E_{s,k} = P_0 t_i - \left[\frac{P_0 + P_k}{2}\right](\tau_{d,k} + \tau_{u,k}) - P_k(t_i - \tau_{d,k})$$

$$= (P_0 - P_k)t_i - \left[\frac{P_0 - P_k}{2}\right]\tau_{d,k} - \left[\frac{P_0 + P_k}{2}\right]\tau_{u,k}$$

? =0

Transition is only justified when

$$E_{s,k} > 0$$

Transition time threshold

$$T_{th,k} = \frac{1}{2}\left[\tau_{d,k} + \left(\frac{P_0 + P_k}{P_0 - P_k}\right)\tau_{u,k}\right]$$

Nett energy saving if $t_i > T_{th,k}$

State Transitions

- Implications
  - the longer the delay overhead of the transition $s_0 \rightarrow s_k$, the longer the transition time threshold
  - the greater the difference between P_0 and P_k, the shorter the threshold

Table 2: Sleep state power, latency and thresholds.

State	P_k (mW)	τ_k (ms)	$T_{th,k}$ (ms)
Active s_0	1040	-	-
Ready s_1	400	5	8
Monitor s_2	270	15	20
observe – Look s_3	200	20	25
Sleep s_4	10	50	50

Note: may miss events in deep sleep

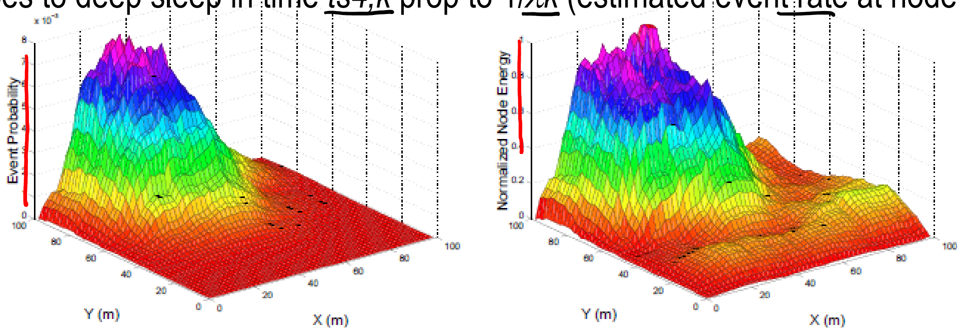
State Transitions – Energy Consumption

μAMPS

- Performance of adaptive probabilistic sleep state transition scheme in event processing task

Adapts to event arrival statistics

Node k goes to deep sleep in time $t_{s4,k}$ prop to $1/\lambda k$ (estimated event rate at node k)



1,000 nodes
Distributed uniformly
100mX100m area

(a) (b)

Figure 12: (a) Spatial distribution of events (b) Spatial energy consumption of nodes. High event probability→High energy consumption

Summary

- We have not discussed energy consumption arising from physical layer communications operations such as coding and modulation
  - refer to [Shih01] for details
- We will consider energy consumption at MAC, routing and transport layers in subsequent lectures

References

- [Heinzelman00] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan. Energy-Efficient Communication Protocol for Wireless Microsensor Networks. In *The 33rd Hawaiian International Conference on Systems Sciences (HICSS)*, Maui, HA, January 2000.
- [Shih01] Eugene Shih, Seong-Hwan Cho, Nathan Ickes, Rex Min, Amit Sinha, Alice Wang, and Anantha Chandrakasan. "Physical Layer Driven Protocol and Algorithm Design for Energy-Efficient Wireless Sensor Networks", *Proceedings of the Seventh Annual ACM Conference on Mobile Computing and Networking*, Rome, Italy, July 2001.