# II.2 Energy Models for Sensor Networks

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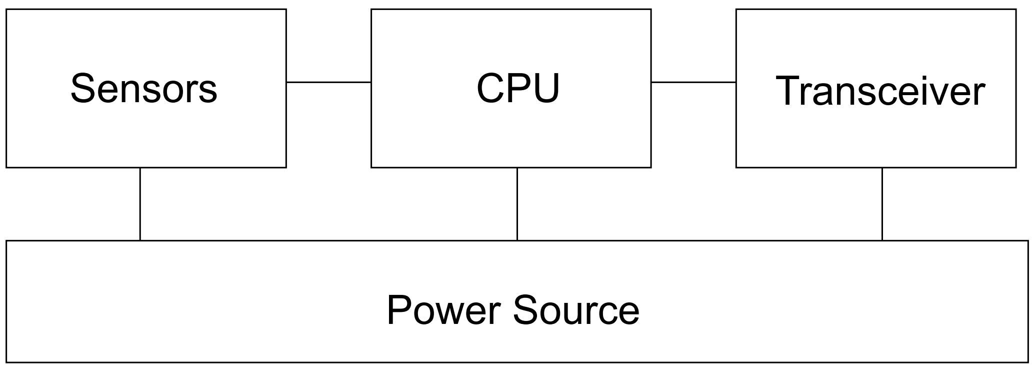
# Basic Architecture



# Sources of Energy Consumption

- Radio
  - Transceiver electronics
- Processing
  - Dynamic Voltage Scaling (DVS) CPU
    - Reduction of frequency allows the processor to run at a lower voltage
    - Supply voltage V
    - Switching Energy consumed $\alpha$ $V^2$
    - 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



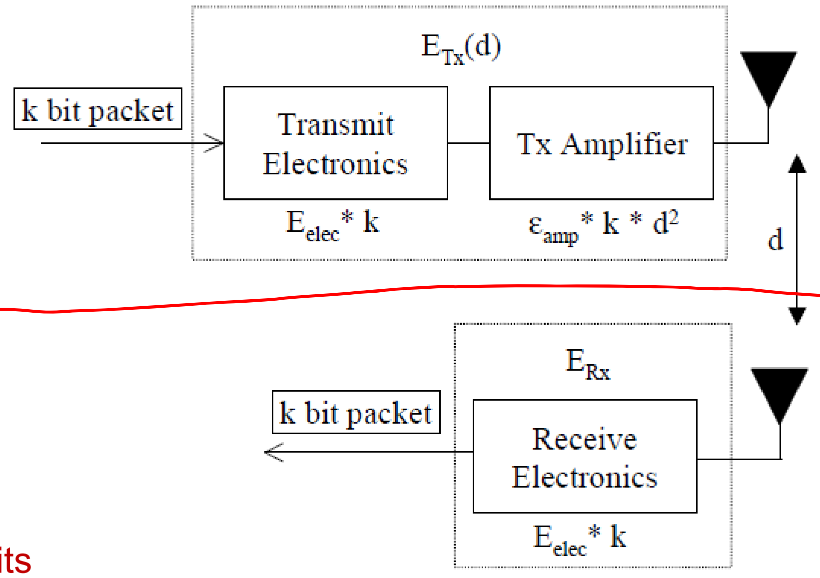
# I. Simple Radio Model

[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 $\varepsilon_{amp}$ = 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

Transmitter

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

energy loss due to channel txn

Receiver

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

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

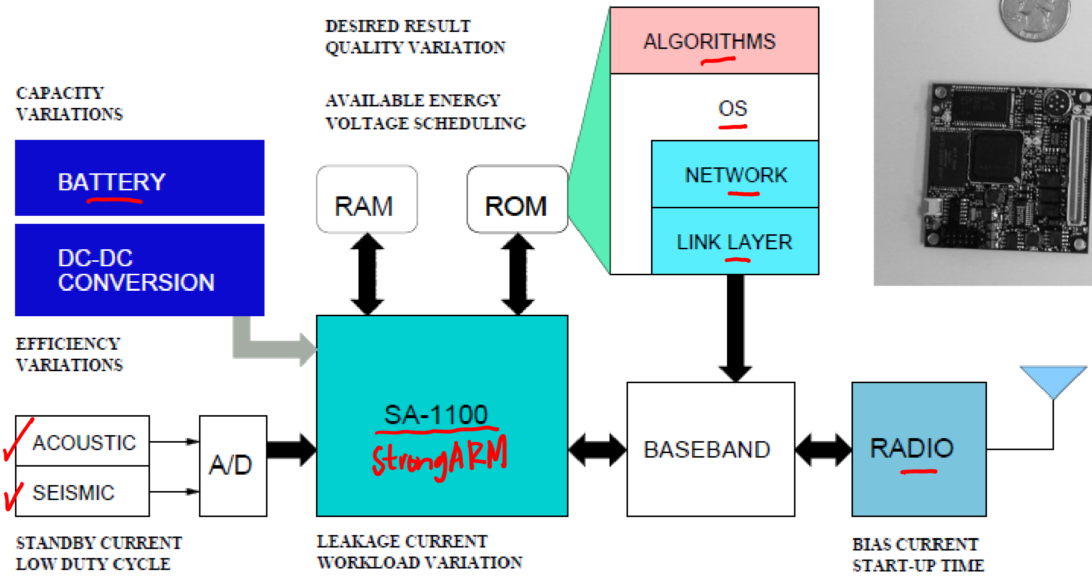


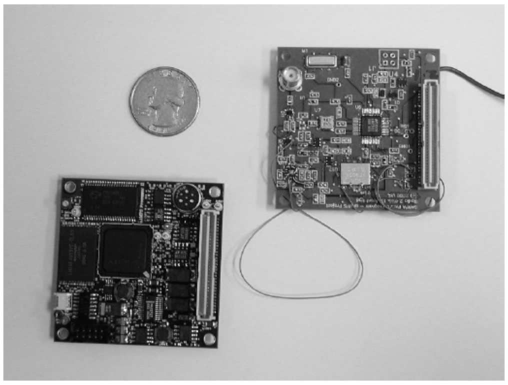
# Points to Note

- 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]





# II.A. 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

II.B.

# More Detailed Radio Model

[Shih01]

Energy per Second

- Average power consumption of the radio

$$P_{radio} \overset{Tx}{=} \left[ N_{tx}[P_{tx}(T_{on-tx} + T_{st}) + P_{out}T_{on-tx}] \right.$$
$$\left. Rx \quad + N_{rx}[P_{rx}(T_{on-rx} + T_{st})] \right]$$

$N_{tx/rx}$ 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)

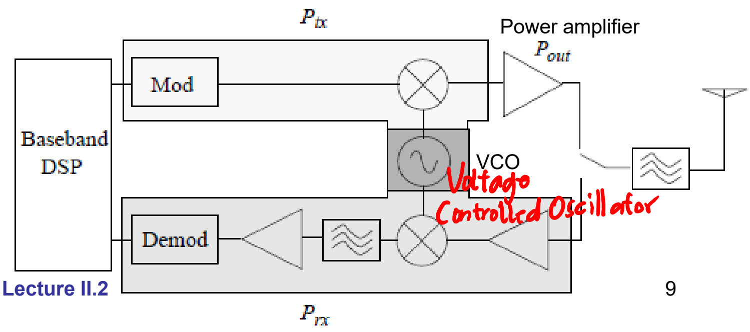
$T_{on-tx/rx}$ is the transmit/receive on-time (actual data transmission/reception time)

$= L/R$, 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. $\approx 180$ 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)
- Start up energy quite high
- Moral: Good only if packet size large enough

energy consumption dominated by start-up transient when packet size is small

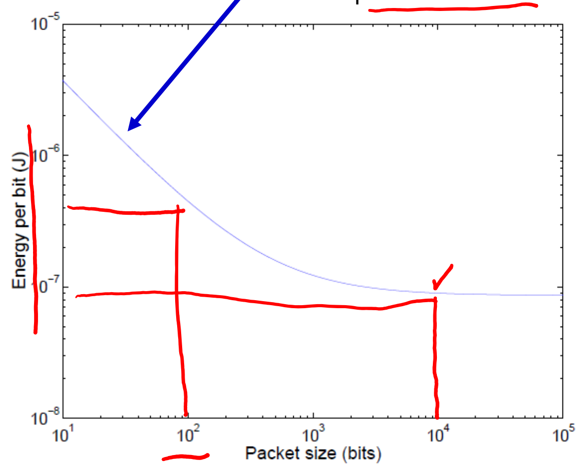



**Figure 5: Effect of startup transient where $R = 1$ Mbps, $T_{st} \approx 450\mu$s, $P_{tx} = 81$ mW, and $P_{out} = 0$ dBm.**

# Energy for Communication

- Other factors
  - Link layer: coding
  - Modulation scheme
  - refer to [Shih01] for details

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

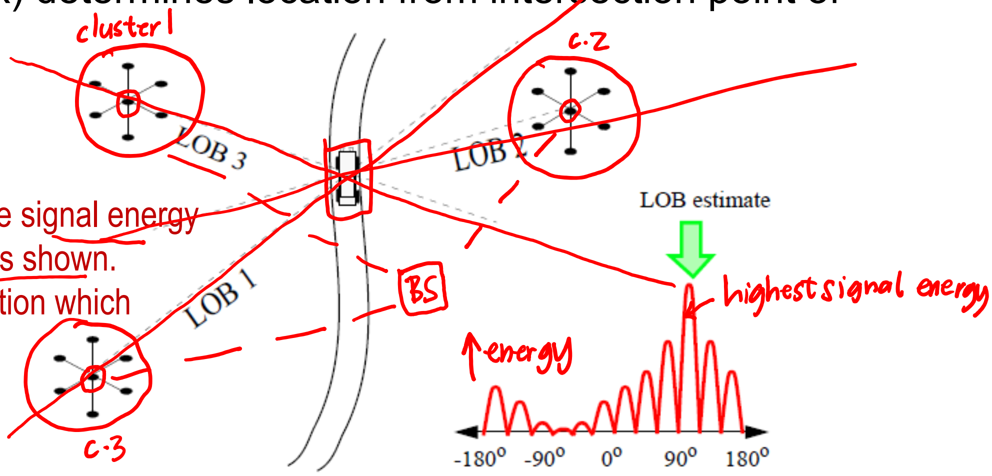


MAMPS (Shih01)

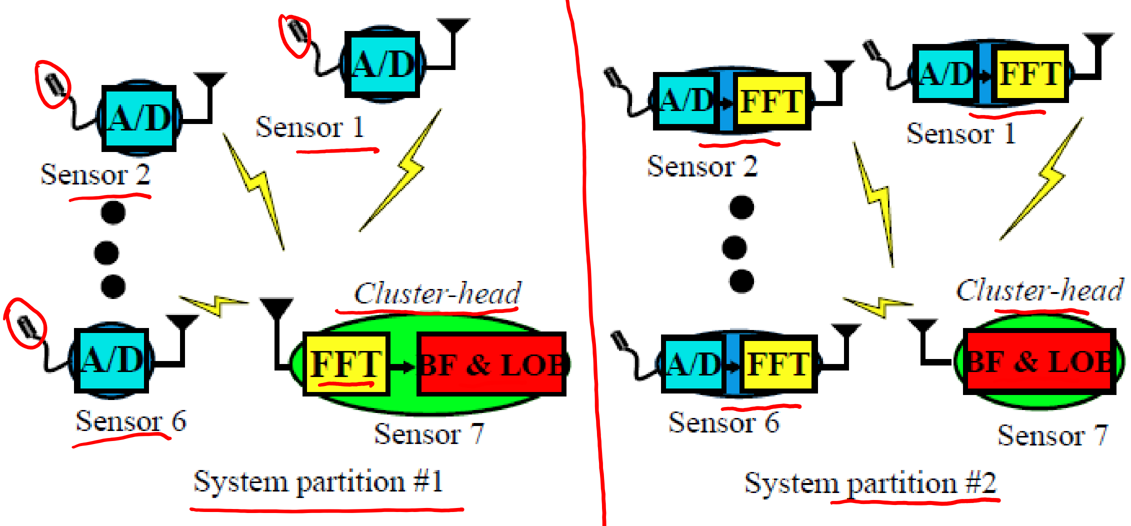
# II C Vehicle Tracking Application

- 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

II.D

# 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



# Node Operating Modes

- System power model like ACPI

Advanced Configuration & Power Interface

**Table 1: Useful sleep states for the sensor node.**

MAMPS

| 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

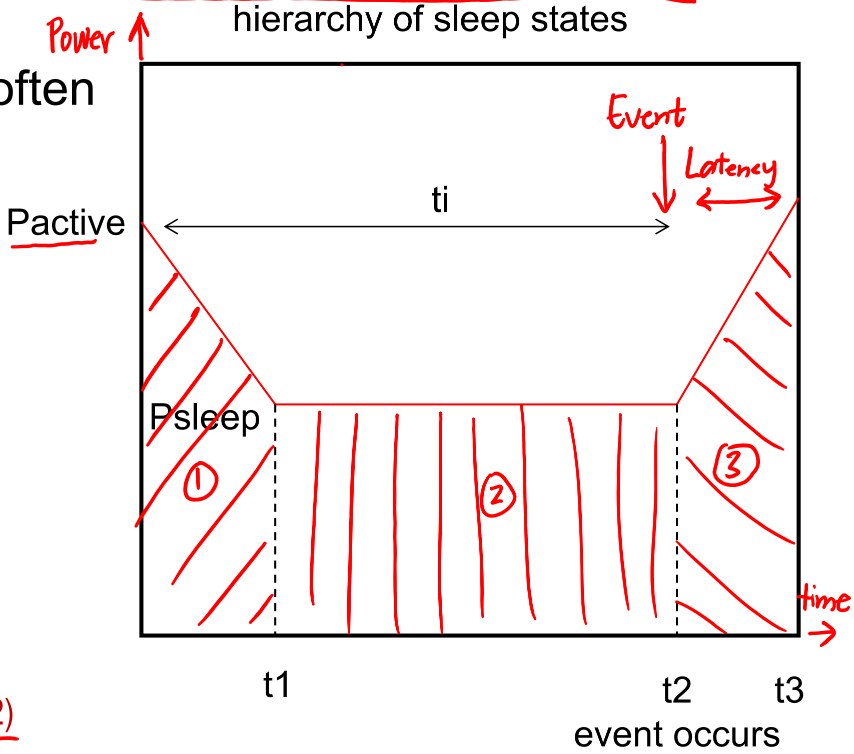
$t_i$ = time between end of processing of previous event and arrival of next event

- 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 > ① Eact->sleep + ② Esleep + ③ Esleep->active

If awake all the time

- 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

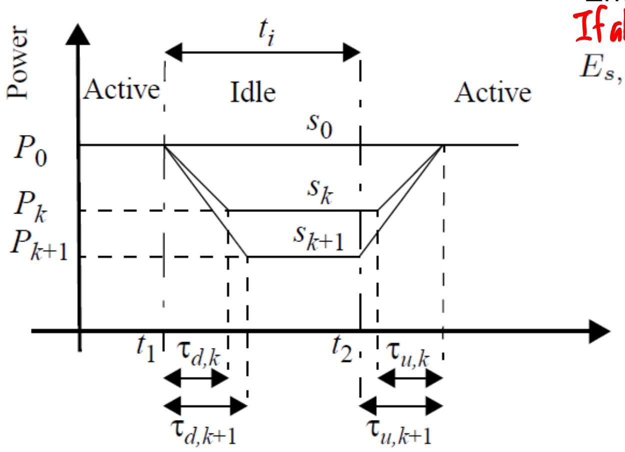



**Figure 11: State transition latency and power.**

Worthwhile going to mode k

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

Energy saving $E_s$ due to transitioning: If sleep

If always on

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

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

What is $t_i$? set $= 0$

Transition is only justified when

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

value of $t_i$ when expression is zero

Transition time threshold

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

# State Transitions

- Implications $t_i > T_{th,k}$ ?
  - the longer the delay overhead of the transition $s_0 \rightarrow s_k$, the longer the transition time threshold bad, since harder to satisfy condition (and vice versa)
  - the greater the difference between $P_0$ and $P_k$, the shorter the threshold good, since easier to satisfy condition (and vice versa)

**Table 2: Sleep state power, latency and thresholds.**

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

Note: may miss events in deep sleep



# State Transitions – Energy Consumption

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

Adapts to event arrival statistics

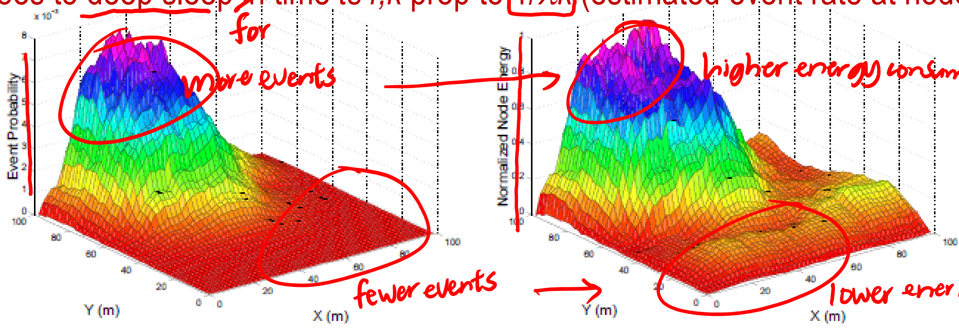
Node $k$ goes to deep sleep in time $t_{s4,k}$ prop to $\boxed{1/\lambda_k}$ (estimated event rate at node $k$)

e.g. $0.75 \times 1/0.2$ if $\lambda_k = 5$ events/s

note: different meaning of k

for more events → higher energy consumption

fewer events → lower energy consumption




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.