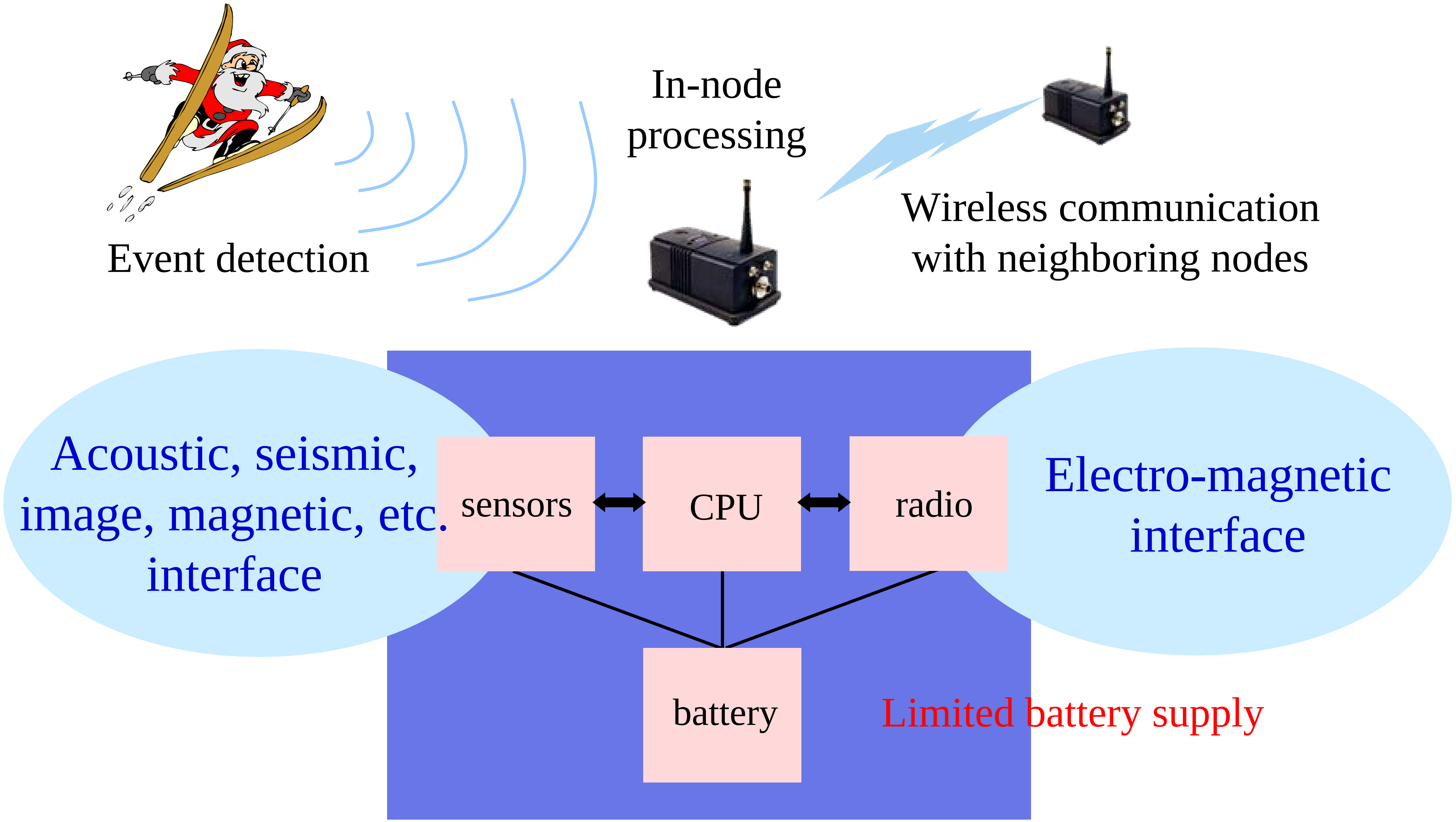
Part II: Sensor Node Platforms & Energy Issues

Mani Srivastava

Sensor Node H/W-S/W Platforms



Energy efficiency is the crucial h/w and s/w design criterion

Overview of this Section

- Survey of sensor node platforms
- Sources of energy consumption
- Energy management techniques

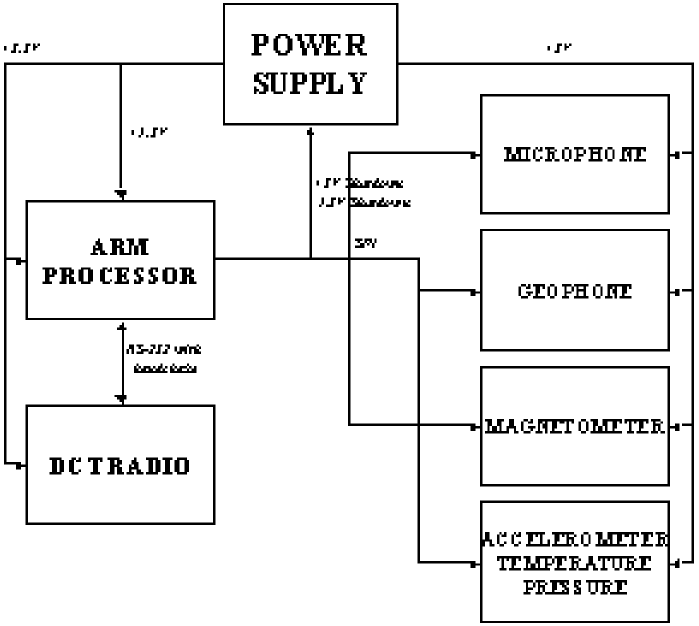
Variety of Real-life Sensor Node Platforms

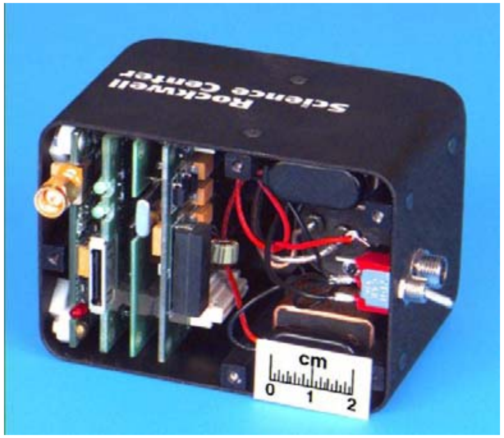
- RSC WINS & Hidra
- Sensoria WINS
- UCLA’s iBadge
- UCLA’s Medusa MK-II
- Berkeley’s Motes
- Berkeley Piconodes
- MIT’s μAMPs
- And many more…

- Different points in (cost, power, functionality, form factor) space

Rockwell WINS & Hidra Nodes

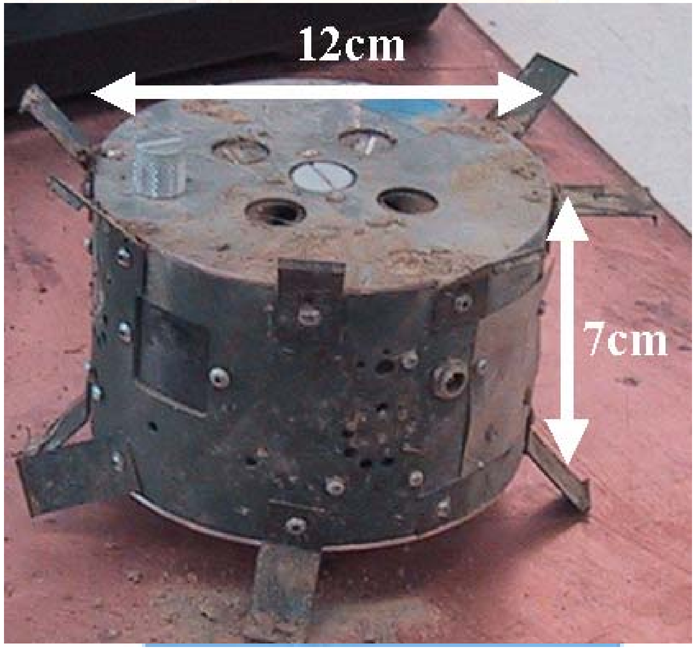
- Consists of 2”x2” boards in a 3.5”x3.5”x3” enclosure
  - StrongARM 1100 processor @ 133 MHz
    - 4MB Flash, 1MB SRAM
  - Various sensors
    - Seismic (geophone)
    - Acoustic
    - magnetometer,
    - accelerometer, temperature, pressure
  - RF communications
    - Connexant’s RDSSS9M Radio @ 100 kbps, 1-100 mW, 40 channels
  - eCos RTOS
- Commercial version: Hidra
  - μC/OS-II
  - TDMA MACwith multihop routing
- http://wins.rsc.rockwell.com/





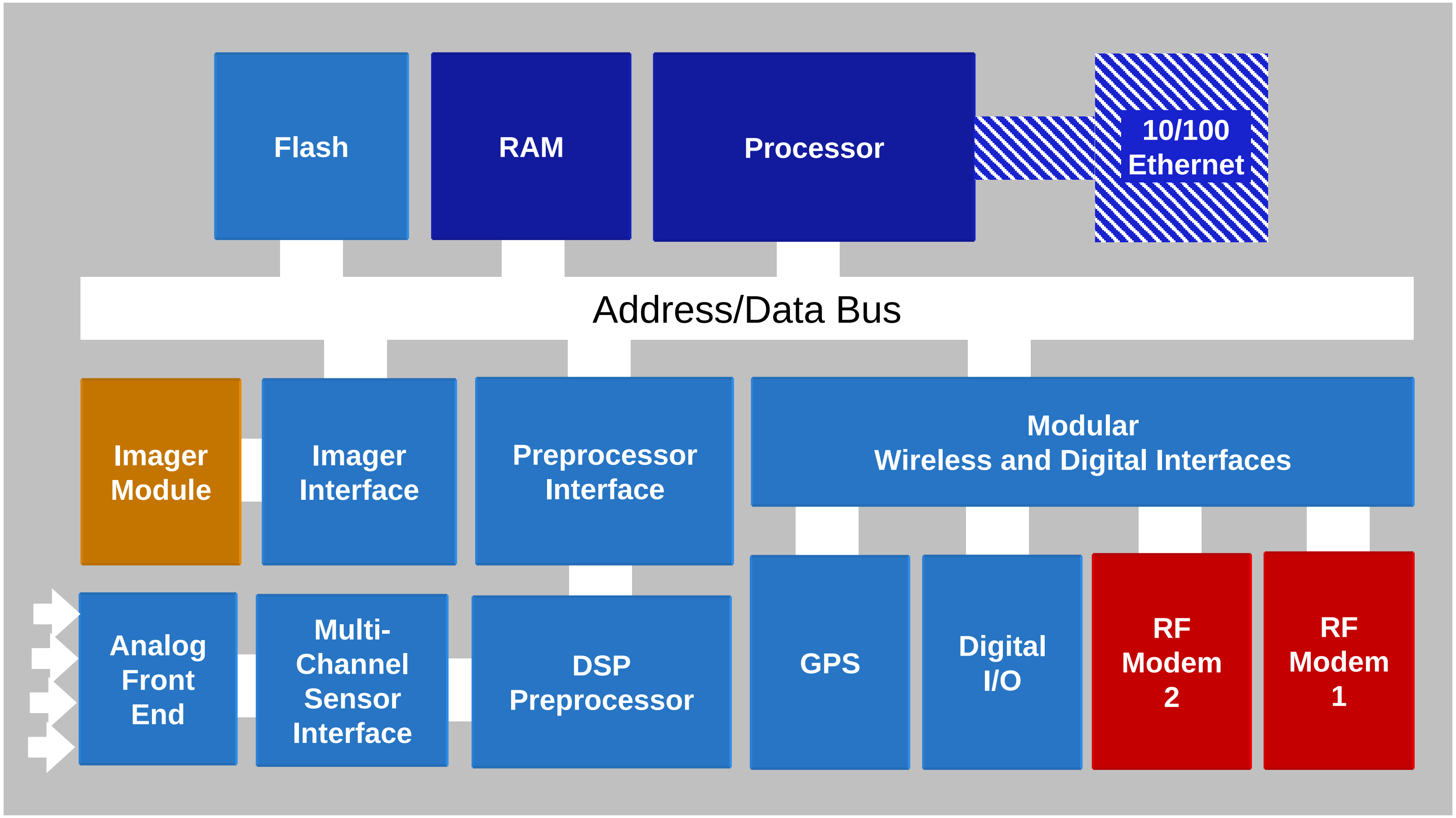
Sensoria WINS NG 2.0, sGate, and WINS Tactical Sensor

- WINS NG 2.0
  - Development platform used in DARPA SensIT
  - SH-4 processor @ 167 MHz
  - DSP with 4-channel 16-bit ADC
  - GPS
  - imaging
  - dual 2.4 GHz FH radios
  - Linux 2.4 + Sensoria APIs
  - Commercial version: sGate
- WINS Tactical Sensor Node
  - geo-location by acoustic ranging and angle
  - time synchronization to 5 μs
  - cooperative distributed event processing



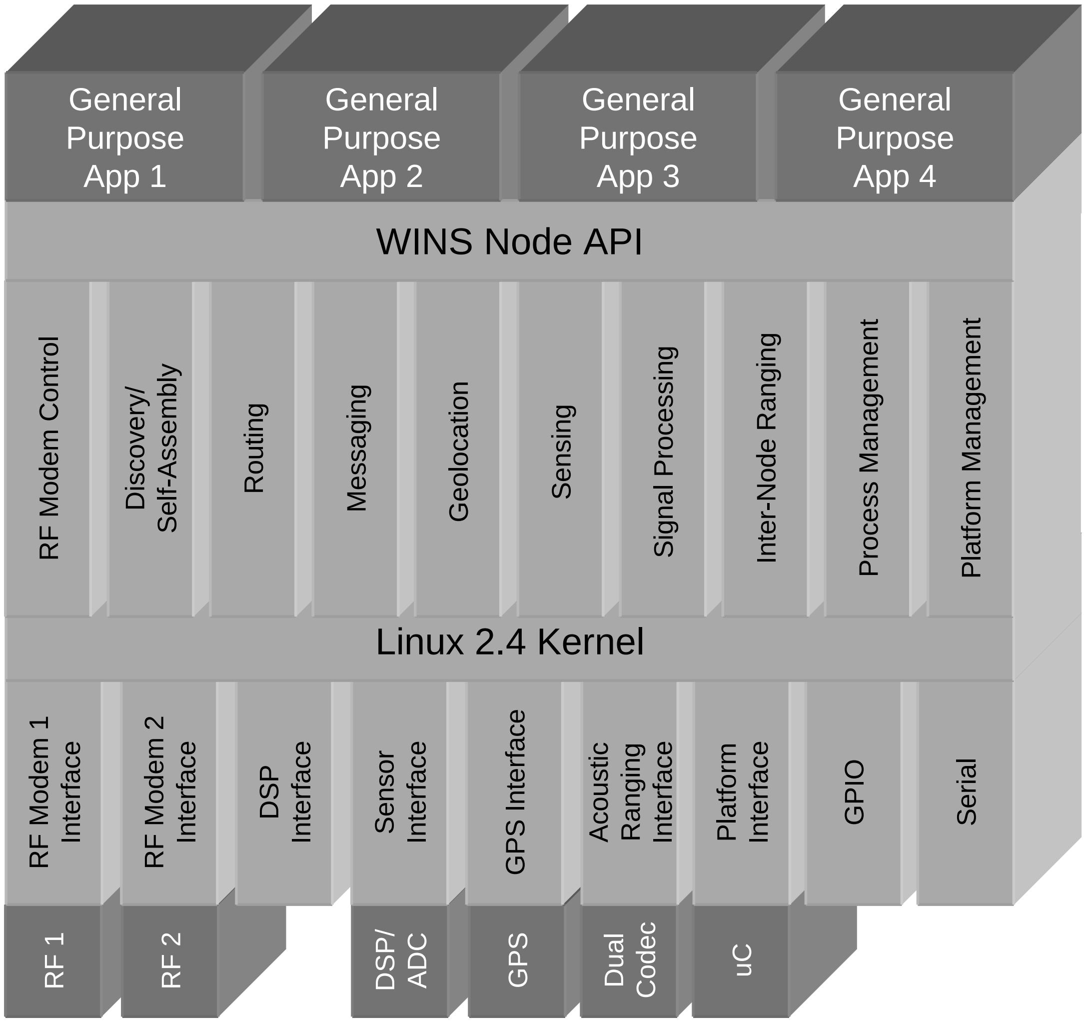
Ref: based on material from Sensoria slides

Sensoria Node Hardware Architecture



Ref: based on material from Sensoria slides

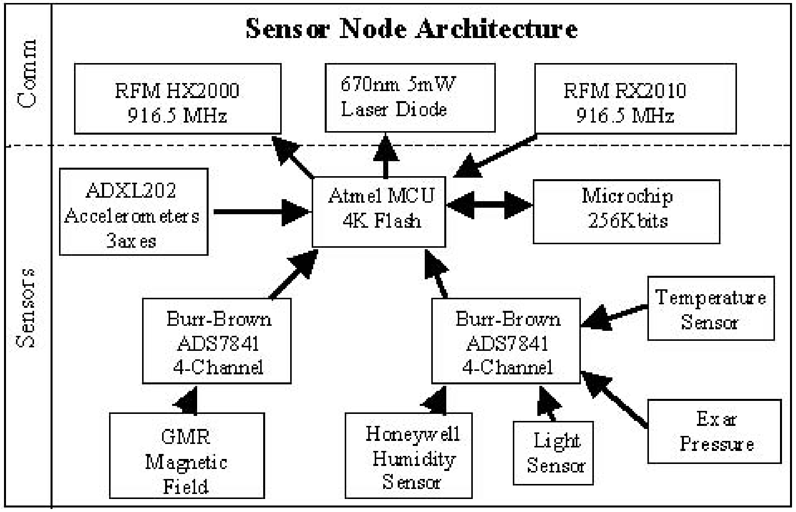
Sensoria Node Software Architecture

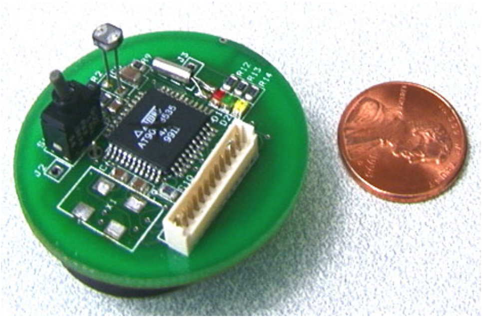


Ref: based on material from Sensoria slides

Berkeley Motes

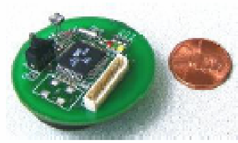
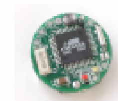
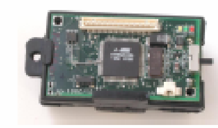
- Devices that incorporate communications, processing, sensors, and batteries into a small package
- Atmel microcontroller with sensors and a communication unit
  - RF transceiver, laser module, or a corner cube reflector
  - temperature, light, humidity, pressure, 3 axis magnetometers, 3 axis accelerometers
- TinyOS





light, temperature,
10 kbps @ 20m

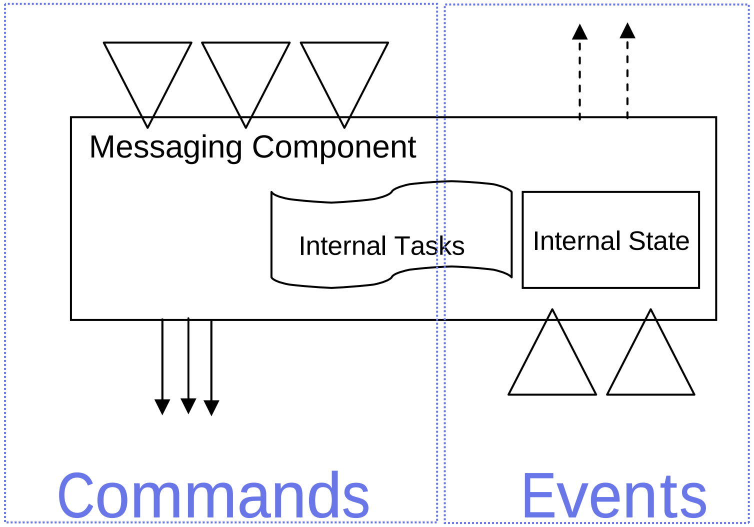
The Mote Family

Mote Type	WeC	rene2	rene2	dot	mica
					
Date	9/99	10/00	6/01	8/01	2/02
Microcontroller					
Type	AT90LS8535		ATMega163		ATMega103
Prog. mem. (KB)	8		16		128
RAM (KB)	0.5		1		4
Nonvolatile storage					
Chip	24LC256				AT45DB041B
Connection type	I2C				SPI
Size (KB)	32				512
Default Power source					
Type	Li	Alk		Li	Alk
Size	CR2450	2xAA		CR2032	2xAA
Capacity (mAh)	575	2850		225	2850
Communication					
Radio	RFM TR1000				
Rate (Kbps)	10	10	10	10	10/40
Modulation type	OOK				OOK/ASK

Ref: from Levis & Culler, ASPLOS 2002

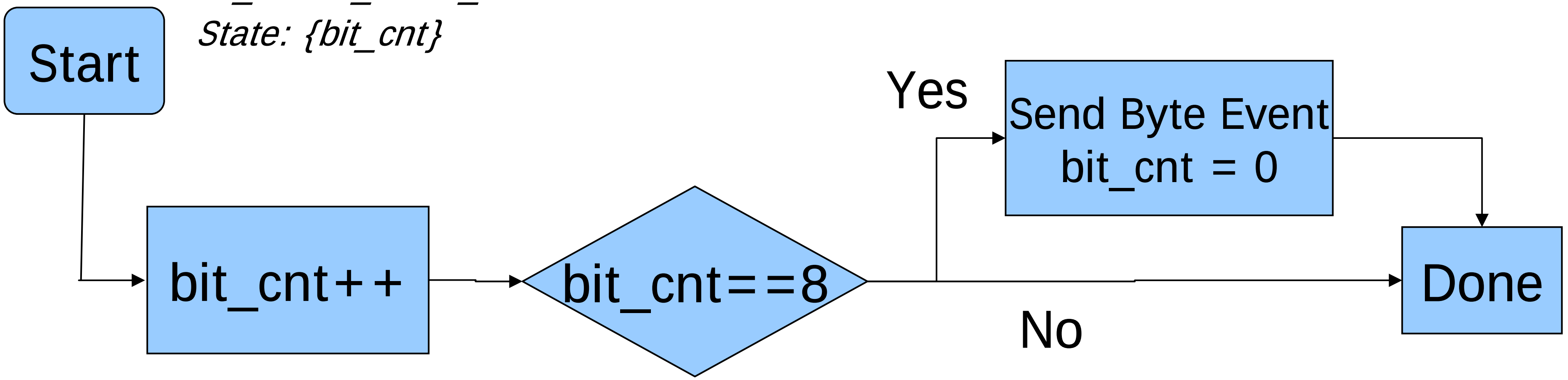
TinyOS

- System composed of concurrent FSM modules
  - Single execution context
- Component model
  - Frame (storage)
  - Commands & event handlers
  - Tasks (computation)
  - Command & Event interface
  - Easy migration across h/w -s/w boundary
- Two level scheduling structure
  - Preemptive scheduling of event handlers
  - Non-preemptive FIFO scheduling of tasks
- Compile time memory allocation
- NestC
- http://webs.cs.berkeley.edu



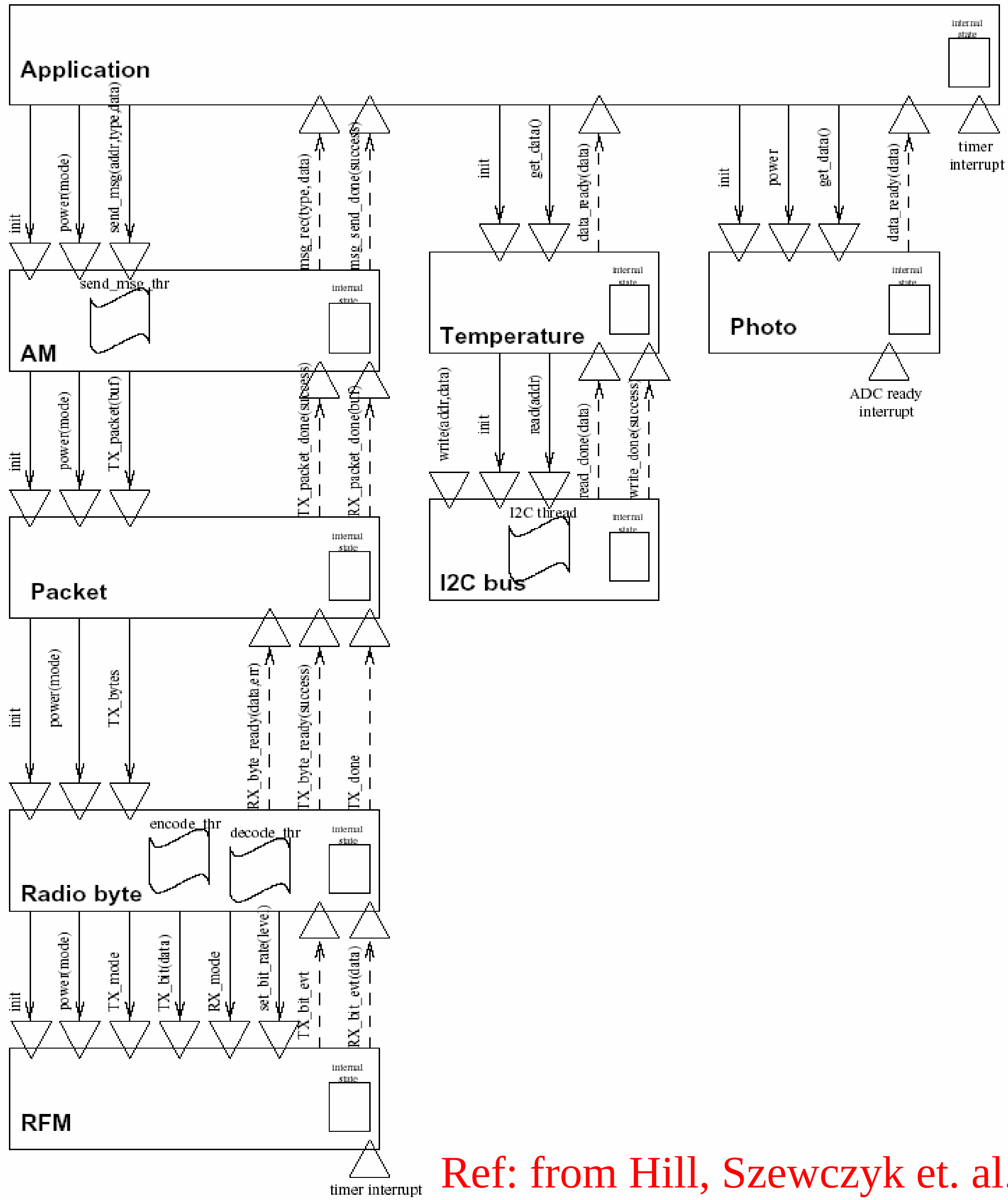
Bit_Arrival_Event_Handler

State: {bit_cnt}



Ref: from Hill, Szewczyk et. al., ASPLOS 2000

Complete TinyOS Application

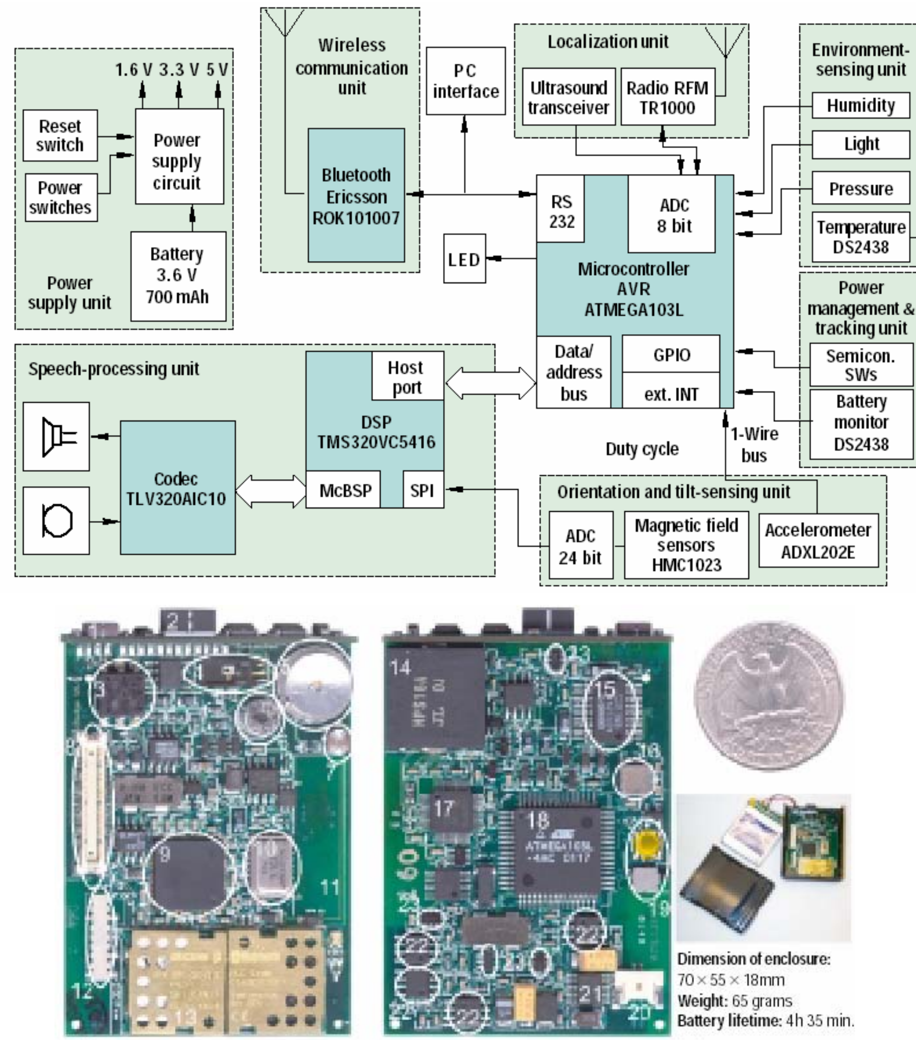


Component Name	Code Size (bytes)	Data Size (bytes)
Multihop router	88	0
AM_dispatch	40	0
AM_temperature	78	32
AM_light	146	8
AM	356	40
Packet	334	40
RADIO_byte	810	8
RFM	310	1
Photo	84	1
Temperature	64	1
UART	196	1
UART_packet	314	40
I2C_bus	198	8
Procesor_init	172	30
TinyOS scheduler	178	16
C runtime	82	0
Total	3450	226

Ref: from Hill, Szewczyk et. al., ASPLOS 2000

UCLA iBadge

- Wearable Sensor Badge
  - acoustic in/out + DSP
  - temperature, pressure, humidity, magnetometer, accelerometer
  - ultrasound localization
  - orientation via magnetometer and accelerometer
  - bluetooth radio
- Sylph Middleware



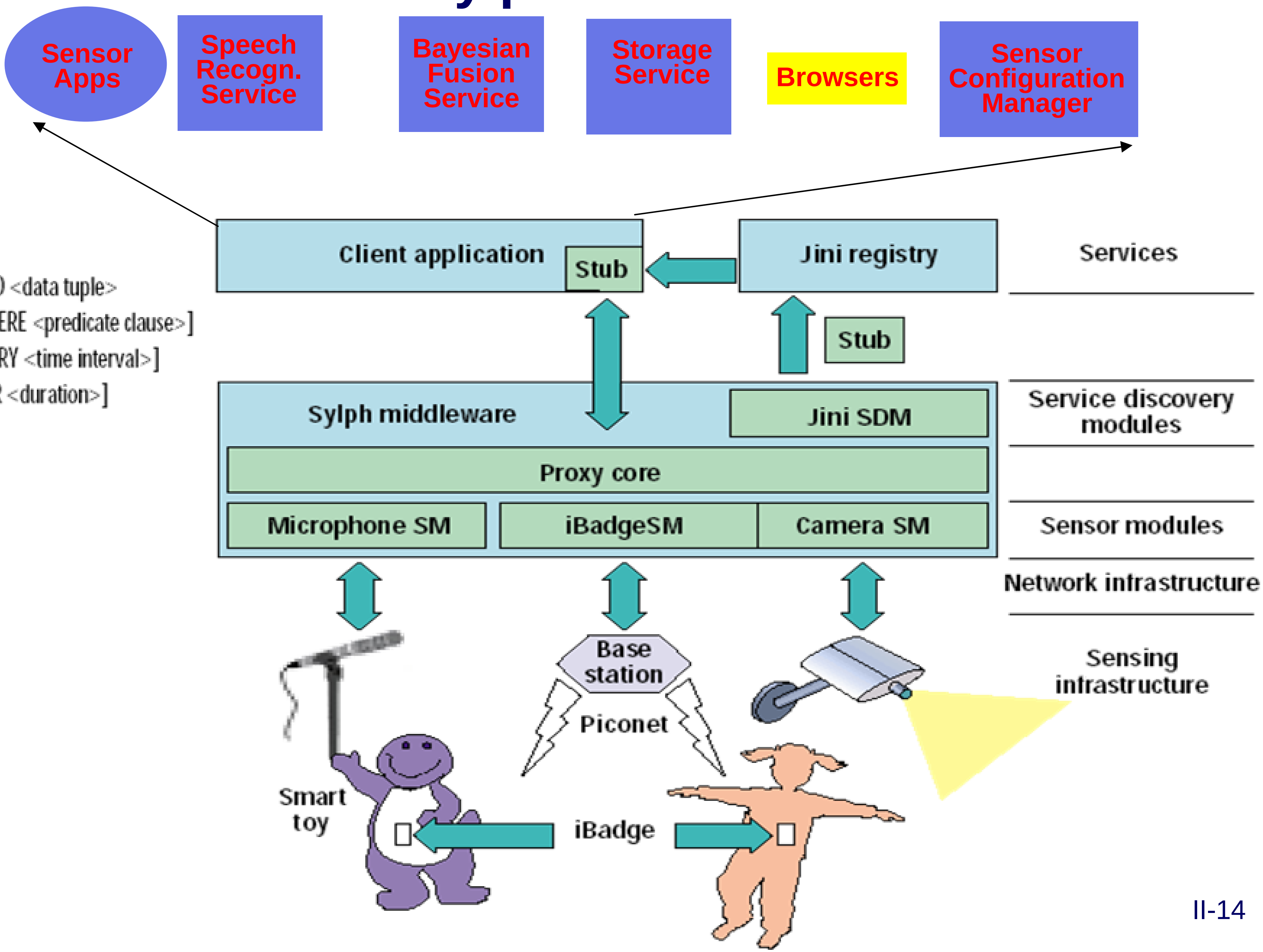
(a) Top Bottom (b)

47 × 68 × 7 mm (1.85 ×2.78 × 0.28")

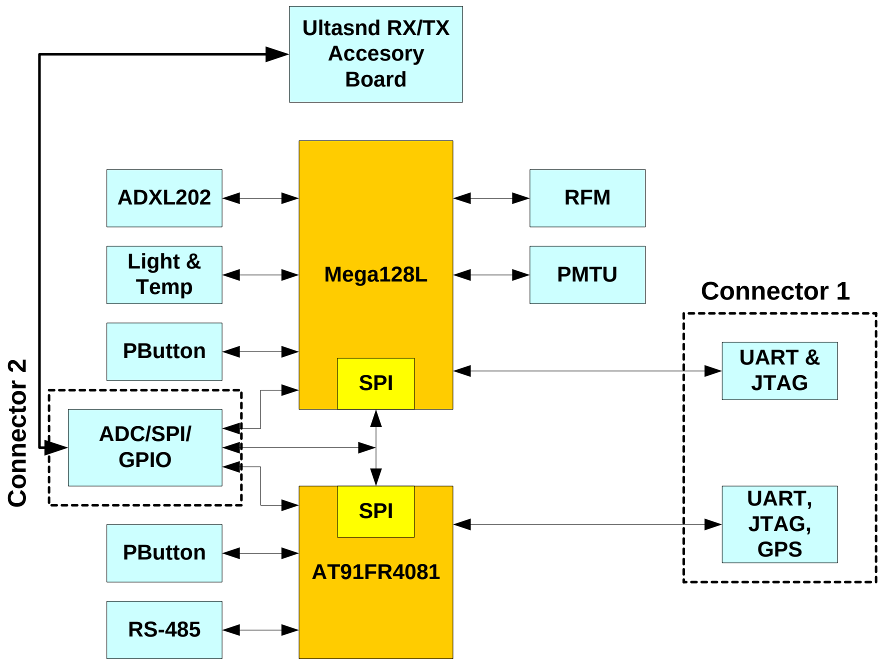
1. Accelerometer forx, y-axis
2. Magnetic field sensor
3. Pressure sensor
4. Humidity sensor
5. Ultrasound tranceiver
6. Microphone
7. Light sensor
8. Connector (SW download)
9. DSP
10. RFM radio (for localization)
11. PCB antenna for RFM radio
12. Blue tooth antenna
13. Blue tooth module
14. Loudspeaker
15. ADC magnetic field sensor
16. Accelerometer for x-axis
17. Codec chip
18. Microcontroller
19. Switches (Power, Reset)
20. Battery connector
21. Power supply
22. Battery monitors
23. Switches to functional units

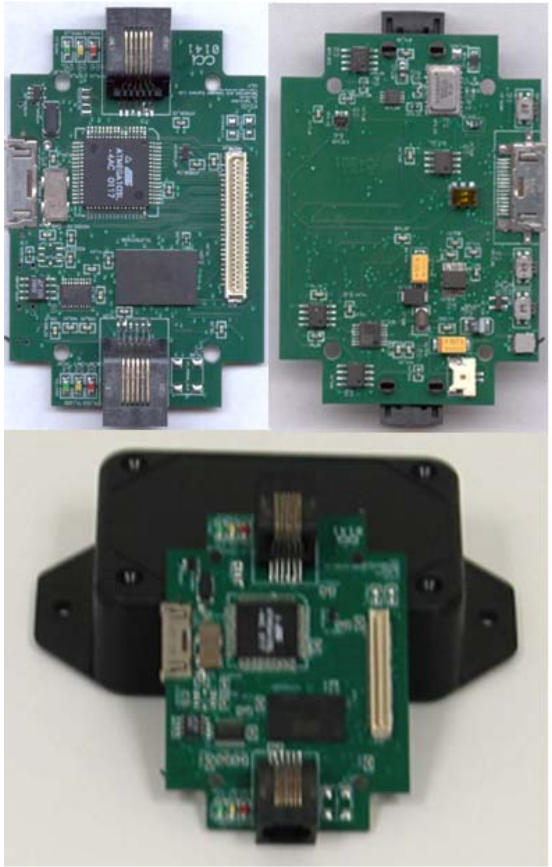
Sylph Middleware

READ <data tuple>
[WHERE <predicate clause>]
[EVERY <time interval>]
[FOR <duration>]



UCLA Medusa MK-II Localizer Nodes

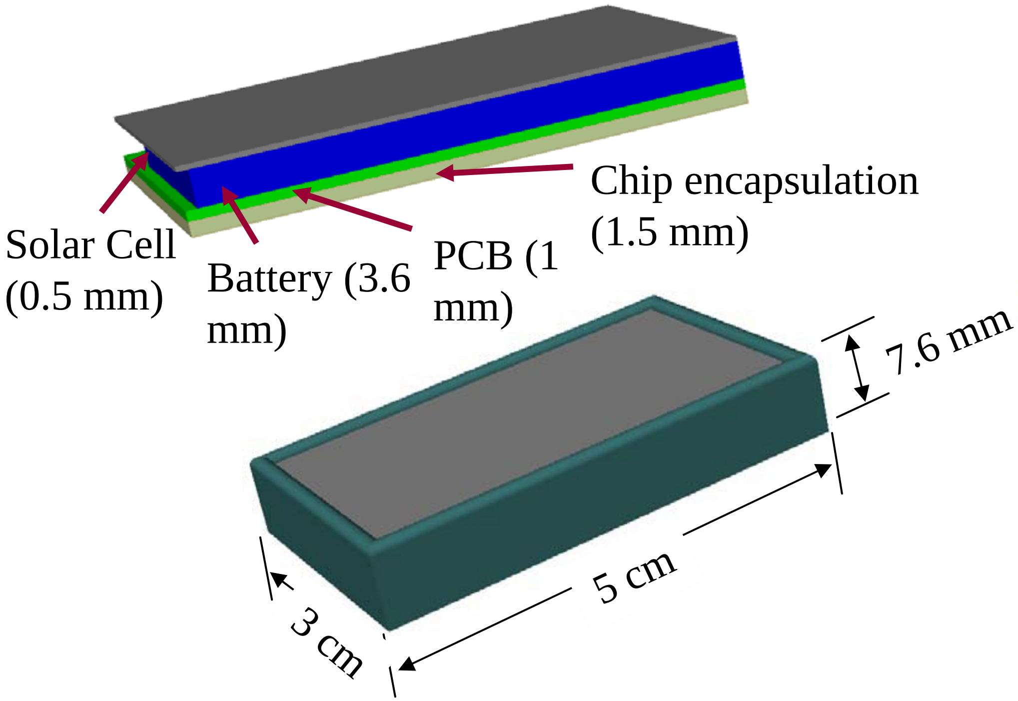


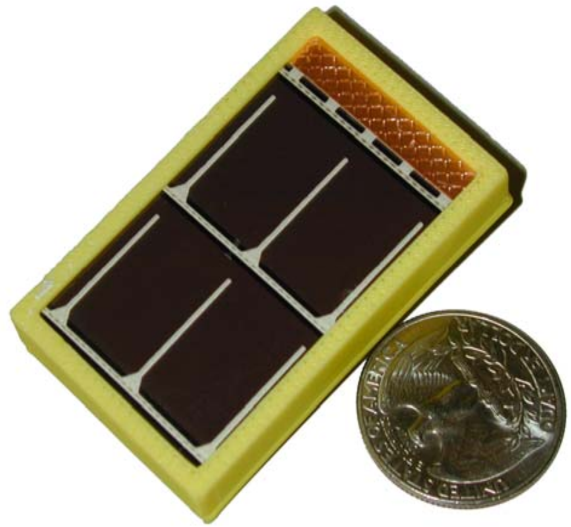


- 40MHz ARM THUMB
  - 1MB FLASH, 136KB RAM
  - 0.9MIPS/MHz 480MIPS/W (ATMega 242MIPS/W)
- RS-485 bus
  - Out of band data collection, formation of arrays
- 3 current monitors (Radio, Thumb, rest of the system)
- 540mAh Rechargeable Li-Ion battery

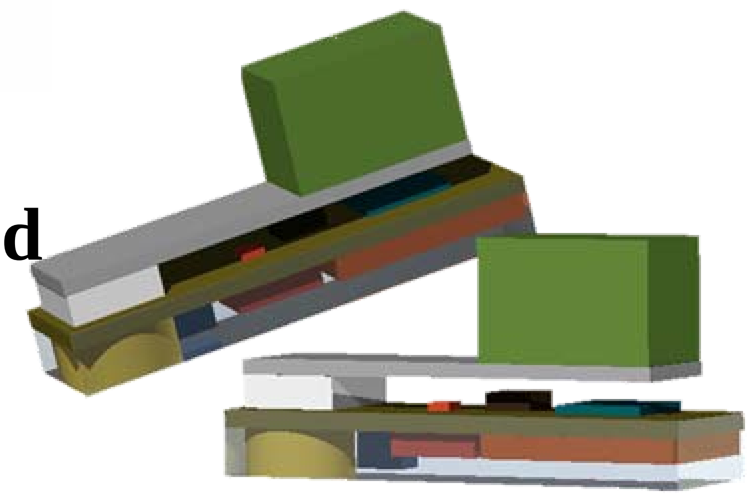
Component	Active(mA)	Sleep(uA)
ATMega128L	5.5	1
RFM	2.9	5
AT91FR4081	25	10
RS-485	3	1
RS-232	3	10
	39.4	**27**

BWRC's *PicoNode* TripWire Sensor Node





Version 1: Light Powered

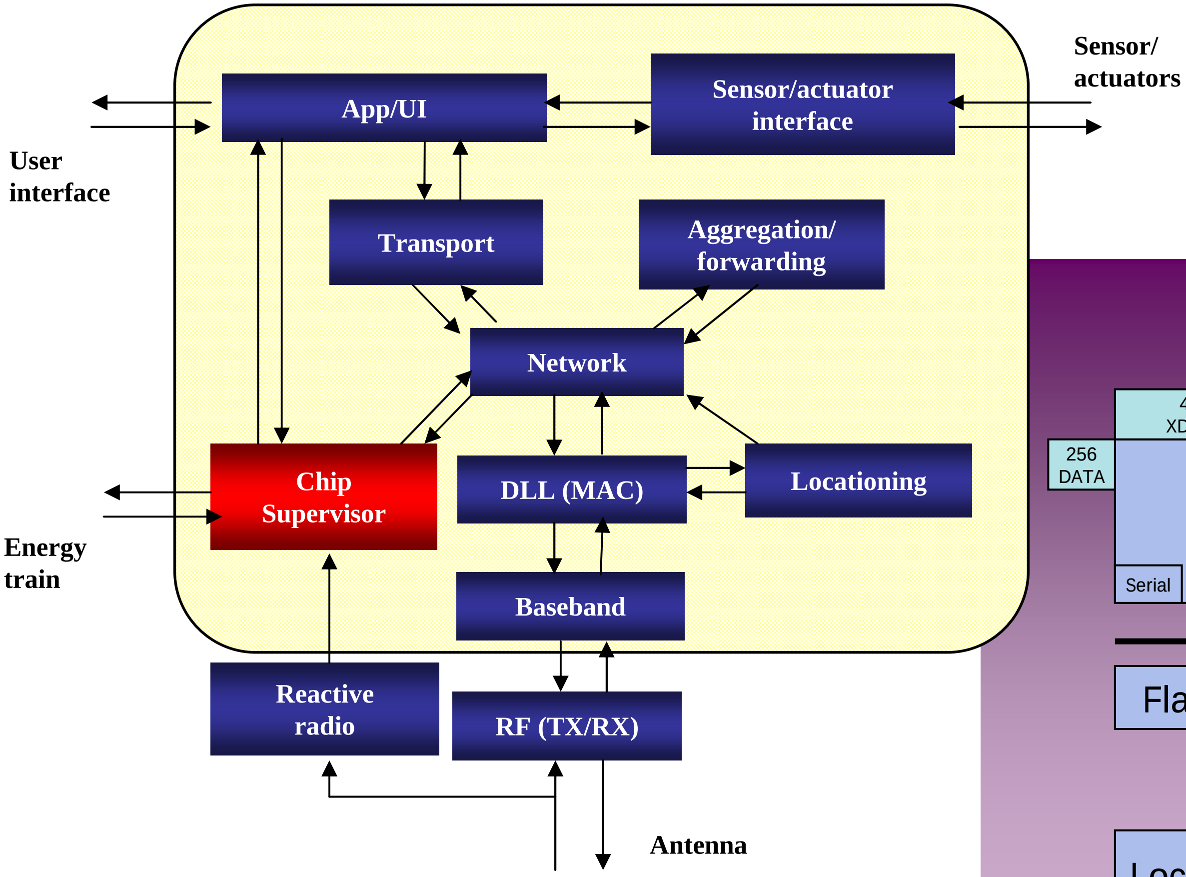


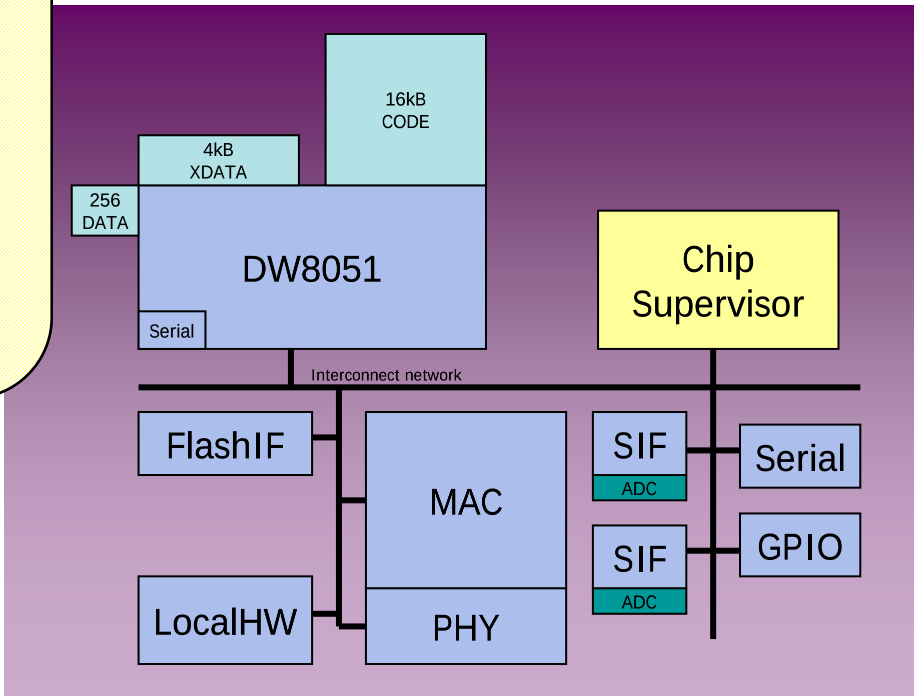
Size determined by power dissipation (1 mW avg)

Version 2: Vibration Powered

Ref: from Jan Rabaey, PAC/C Slides

BWRC PicoNode (contd.)



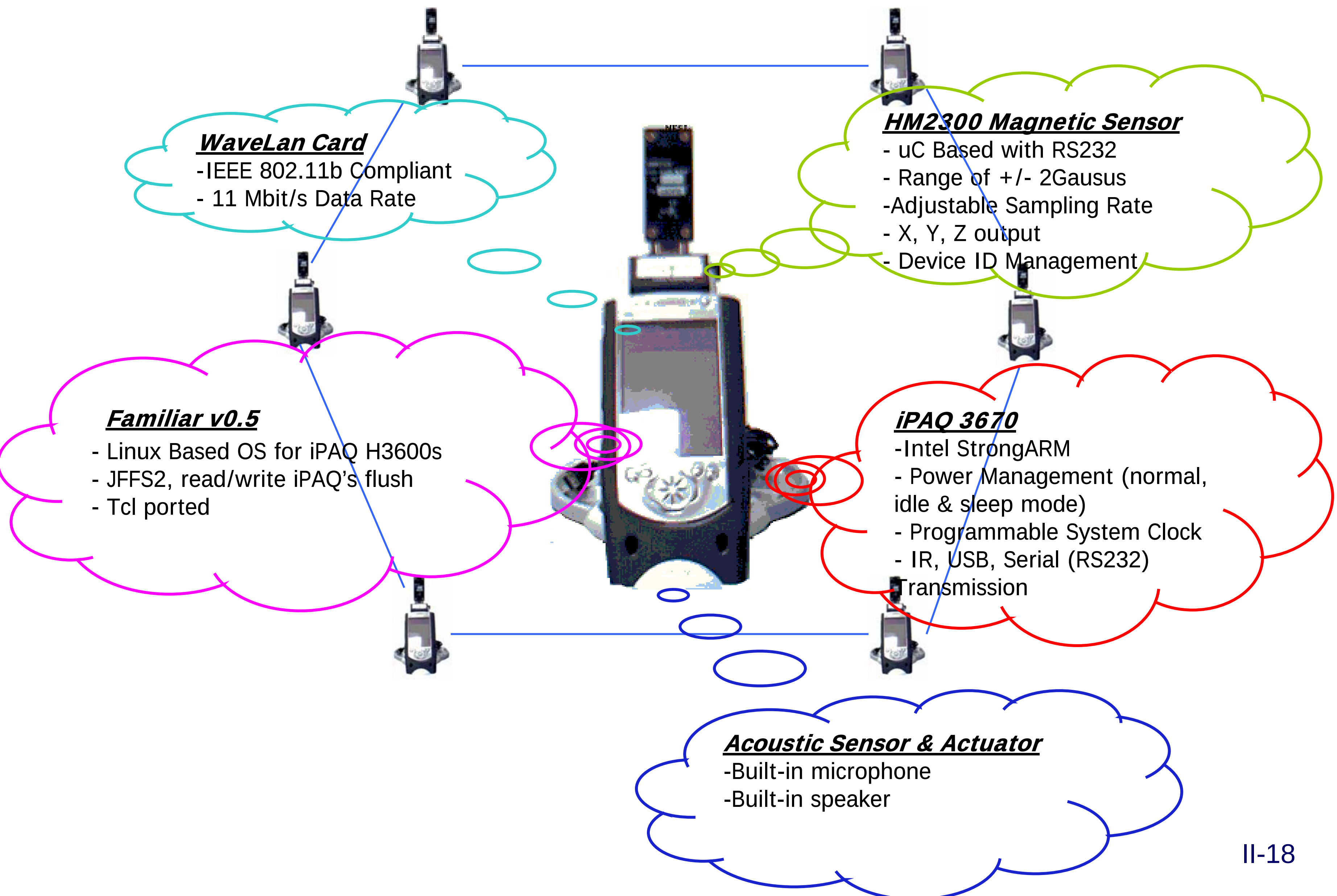


- Reactive inter- and intra-chip signaling
- Modules in power-down (low-leakage) mode by default
- Events at interface cause wake-up
- Hw Modules selected to meet flexibility needs while optimizing energy efficiency (e.g. 8051 microcontroller)

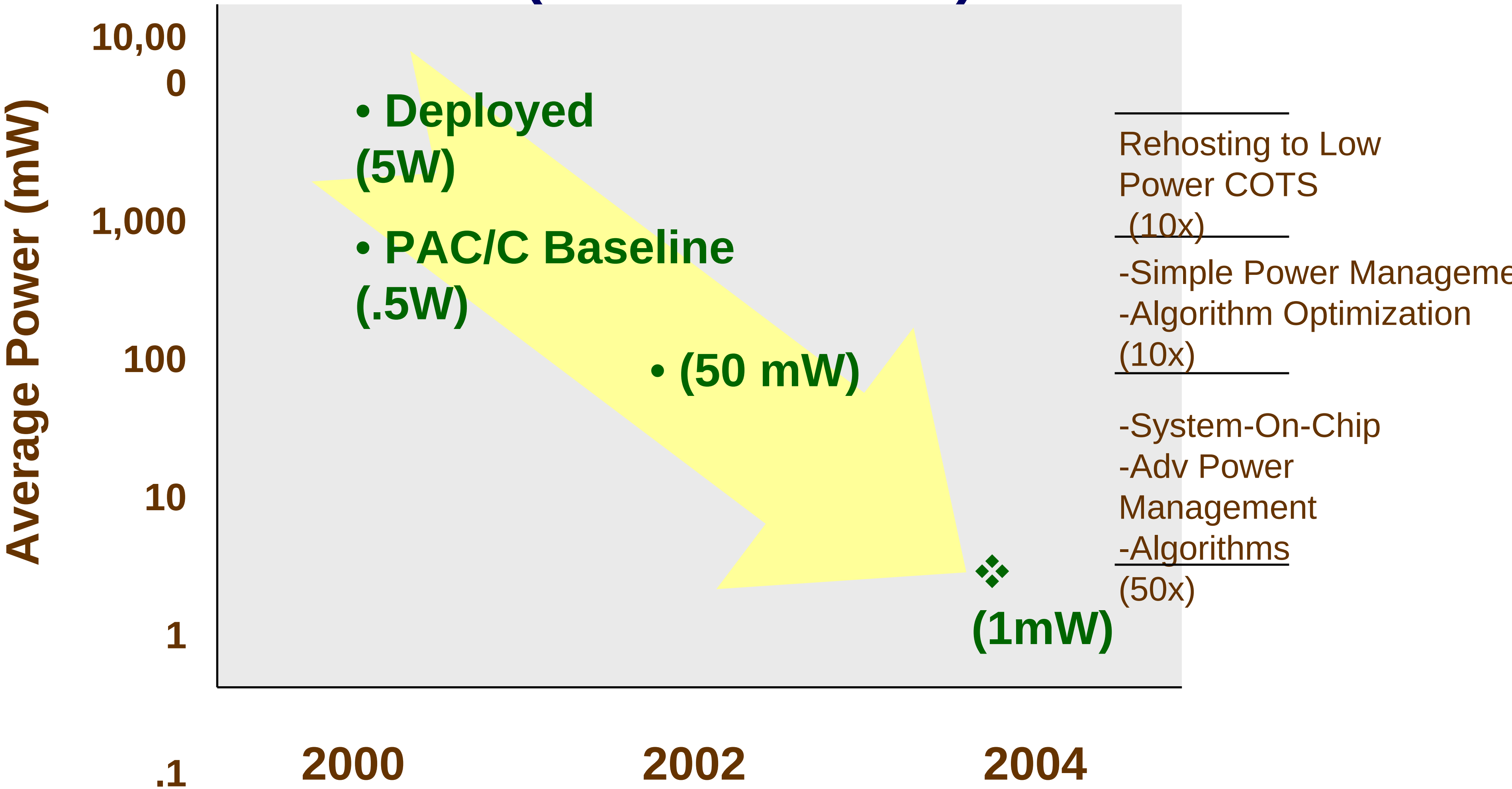
1 mW on
< 10 μW sleep
Size: 6 mm^2

Ref: from Jan Rabaey, PAC/C Slides

Quick-and-dirty iPaq-based Sensor Node!

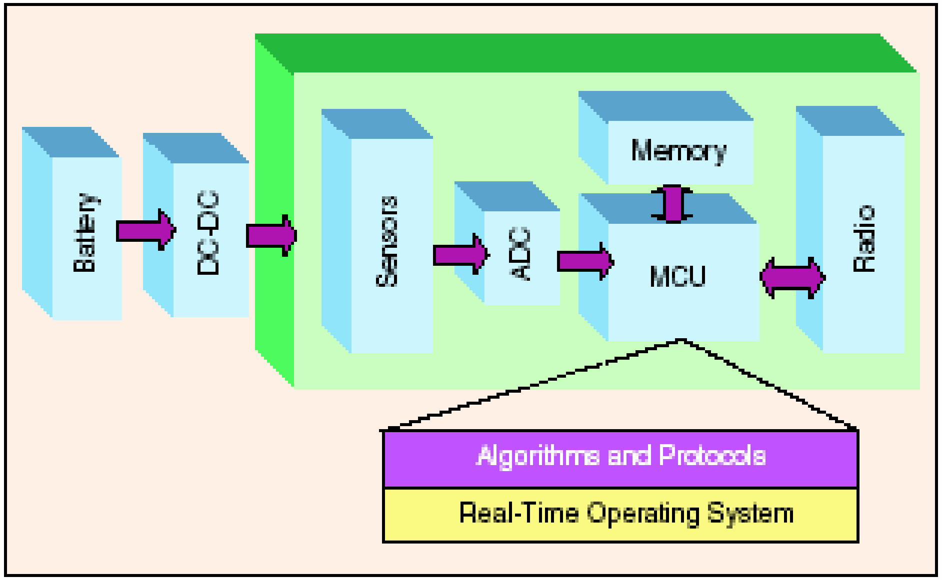


Sensor Node Energy Roadmap (DARPA PAC/C)



- Low-power design
- Energy-aware design

Where does the energy go?



- Processing
  - excluding low-level processing for radio, sensors, actuators
- Radio
- Sensors
- Actuators
- Power supply

Processing

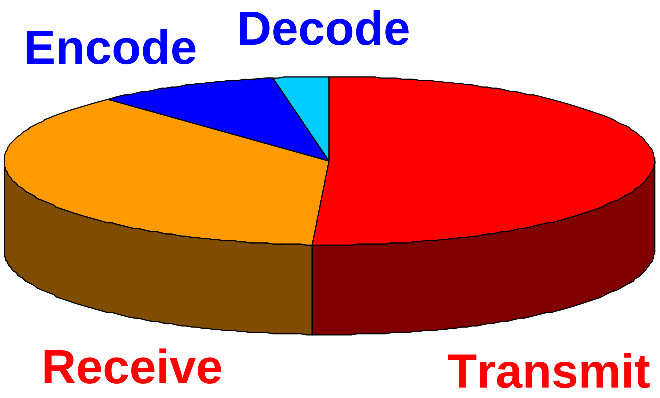
- Common sensor node processors:
  - Atmel AVR, Intel 8051, StrongARM, XScale, ARM Thumb, SH Risc
- Power consumption all over the map, e.g.
  - 16.5 mW for ATMega128L @ 4MHz
  - 75 mW for ARM Thumb @ 40 MHz
- But, don't confuse low-power and energy-efficiency!
  - Example
    - 242 MIPS/W for ATMega128L @ 4MHz (4nJ/Instruction)
    - 480 MIPS/W for ARM Thumb @ 40 MHz (2.1 nJ/Instruction)
  - Other examples:
    - 0.2 nJ/Instruction for Cygnal C8051F300 @ 32KHz, 3.3V
    - 0.35 nJ/Instruction for IBM 405LP @ 152 MHz, 1.0V
    - 0.5 nJ/Instruction for Cygnal C8051F300 @ 25MHz, 3.3V
    - 0.8 nJ/Instruction for TMS320VC5510 @ 200 MHz, 1.5V
    - 1.1 nJ/Instruction for Xscale PXA250 @ 400 MHz, 1.3V
    - 1.3 nJ/Instruction for IBM 405LP @ 380 MHz, 1.8V
    - 1.9 nJ/Instruction for Xscale PXA250 @ 130 MHz, .85V (leakage!)
  - And, the above don't even factor in operand size differences!
- However, need power management to actually exploit energy efficiency
  - Idle and sleep modes, variable voltage and frequency

Radio

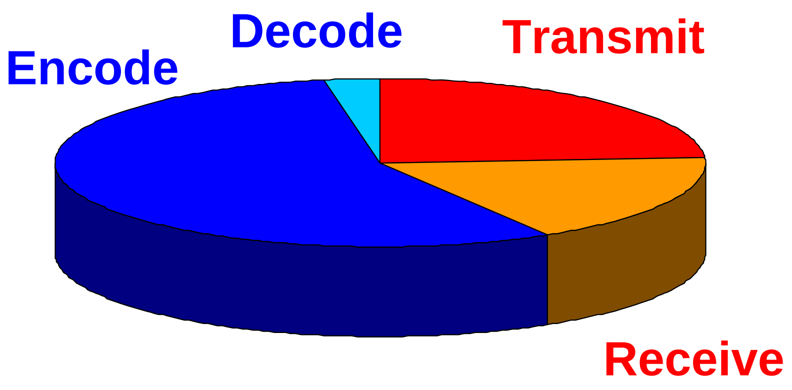
- Energy per bit in radios is a strong function of desired communication performance and choice of modulation
  - Range and BER for given channel condition (noise, multipath and Doppler fading)
- Watch out: different people count energy differently
  - E.g.
    - Mote’s RFM radio is only a transceiver, and a lot of low-level processing takes place in the main CPU
    - While, typical 802.11b radios do everything up to MAC and link level encryption in the “radio”
- Transmit, receive, idle, and sleep modes
- Variable modulation, coding
- Currently around 150 nJ/bit for short ranges
- More later…

Computation & Communication

Energy breakdown for voice



Energy breakdown for MPEG



Radio: Lucent WaveLAN at 2 Mbps

Processor: StrongARM SA-1100 at 150 MIPS

- Radios benefit less from technology improvements than processors
- The relative impact of the communication subsystem on the system energy consumption will grow

Sensing

- Several energy consumption sources
  - transducer
  - front-end processing and signal conditioning
    - analog, digital
  - ADC conversion
- Diversity of sensors: no general conclusions can be drawn
  - Low-power modalities
    - Temperature, light, accelerometer
  - Medium-power modalities
    - Acoustic, magnetic
  - High-power modalities
    - Image, video, beamforming

Actuation

- Emerging sensor platforms
  - Mounted on mobile robots
  - Antennas or sensors that can be actuated
- Energy trade-offs not yet studied
- Some thoughts:
  - Actuation often done with fuel, which has much higher energy density than batteries
    - E.g. anecdotal evidence that in some UAVs the flight time is longer than the up time of the wireless camera mounted on it
  - Actuation done during boot-up or once in a while may have significant payoffs
    - E.g. mechanically repositioning the antenna once may be better than paying higher communication energy cost for all subsequent packets
    - E.g. moving a few nodes may result in a more uniform distribution of node, and thus longer system lifetime

Power Analysis of RSC's WINS Nodes

Table 1. Power Analysis of Rockwell's Wins Nodes.

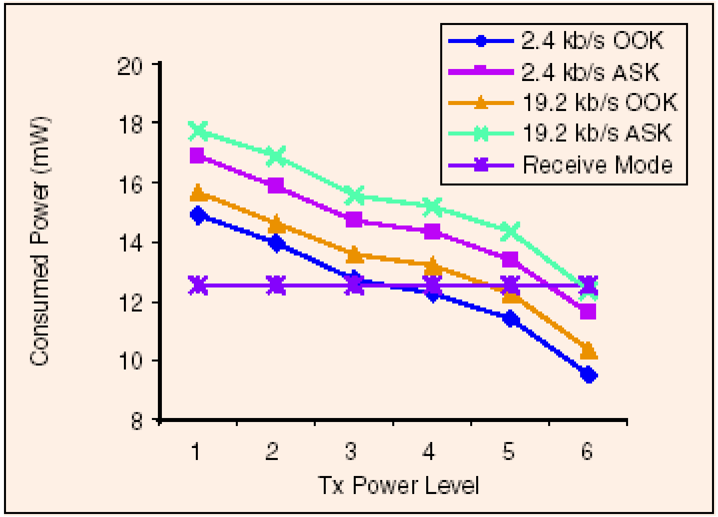
MCU Mode	Sensor Mode	Radio Mode	Power (mW)
Active	On	Tx (Power: 36.3 mW)	1080.5
		Tx (Power: 19.1 mW)	986.0
		Tx (Power: 13.8 mW)	942.6
		Tx (Power: 3.47 mW)	815.5
		Tx (Power: 2.51 mW)	807.5
		Tx (Power: 0.96 mW)	787.5
		Tx (Power: 0.30 mW)	773.9
		Tx (Power: 0.12 mW)	771.1
Active	On	Rx	751.6
Active	On	Idle	727.5
Active	On	Sleep	416.3
Active	On	Removed	383.3
Sleep	On	Removed	64.0
Active	Removed	Removed	360.0

- <u>Summary</u>
- Processor
  - Active = 360 mW
    - doing repeated transmit/receive
  - Sleep = 41 mW
  - Off = 0.9 mW
- Sensor = 23 mW
- Processor : Tx = 1 : 2
- Processor : Rx = 1 : 1
- Total Tx : Rx = 4 : 3 at maximum range
  - comparable at lower Tx

Power Analysis of Mote-Like Node

Table 2. Power Analysis of Medusa II Nodes.

MCU Mode	Sensor Mode	Radio Mode	Mod. Scheme	Data Rate	Power (mW)
Active	On	Tx(Power: 0.7368 mW)	OOK	2.4 kb/s	24.58
		Tx(Power: 0.0979 mW)	OOK	2.4 kb/s	19.24
		Tx(Power: 0.7368 mW)	OOK	19.2 kb/s	25.37
		Tx(Power: 0.0979 mW)	OOK	19.2 kb/s	20.05
		Tx(Power: 0.7368 mW)	ASK	2.4 kb/s	26.55
		Tx(Power: 0.0979 mW)	ASK	2.4 kb/s	21.26
		Tx(Power: 0.7368 mW)	ASK	19.2 kb/s	27.46
		Tx(Power: 0.0979 mW)	ASK	19.2 kb/s	22.06
Active	On	Rx	Any	Any	22.20
Active	On	Idle	Any	Any	22.06
Active	On	Off	Any	Any	9.72
Idle	On	Off	Any	Any	5.92
Sleep	Off	Off	Any	Any	0.02



Some Observations

- Using low-power components and trading-off unnecessary performance for power savings can have orders of magnitude impact
- Node power consumption is strongly dependent on the operating mode
  - E.g. WINS consumes only 1/6-th the power when MCU is asleep as opposed to active
- At short ranges, the Rx power consumption > T power consumption
  - multihop relaying not necessarily desirable
- Idle radio consumes almost as much power as radio in Rx mode
  - Radio needs to be completely shut off to save power as in sensor networks idle time dominates
    - MAC protocols that do not “listen” a lot
- Processor power fairly significant (30-50%) share of overall power
- In WINS node, radio consumes 33 mW in “sleep” vs. “removed”
  - Argues for module level power shutdown
- Sensor transducer power negligible
  - Use sensors to provide wakeup signal for processor and radio
  - Not true for active sensors though…

Energy Management Problem

- Actuation energy is the highest
  - Strategy: ultra-low-power “sentinel” nodes
    - Wake-up or command movement of mobile nodes
- Communication energy is the next important issue
  - Strategy: energy-aware data communication
    - Adapt the instantaneous performance to meet the timing and error rate constraints, while minimizing energy/bit
- Processor and sensor energy usually less important

MICA mote Berkeley

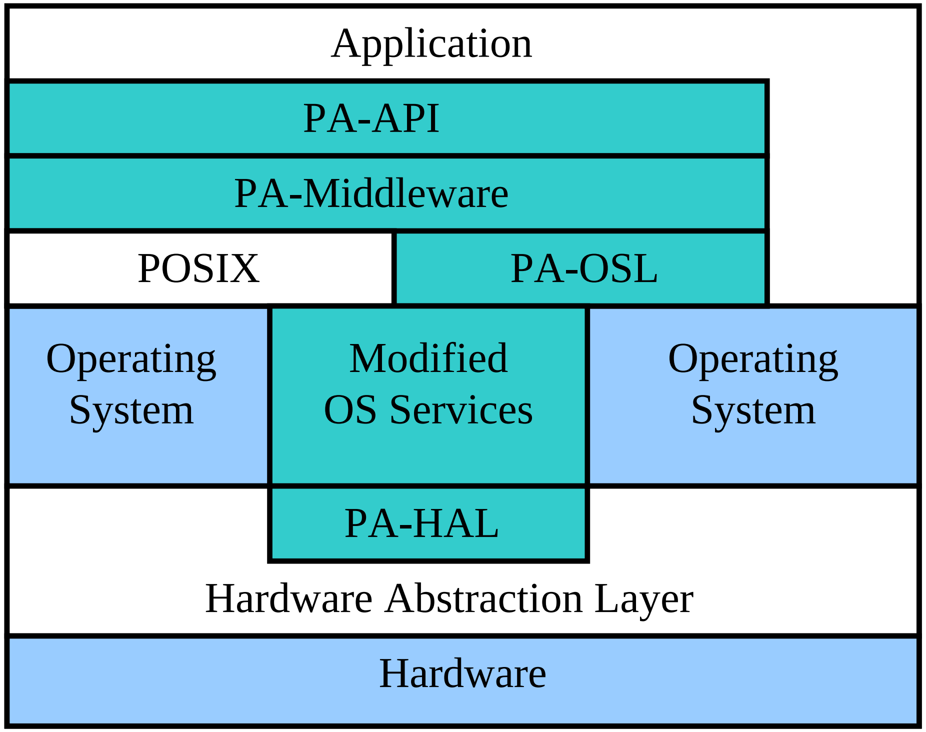
Transmit	**720 nJ/bit**	Processor	**4 nJ/op**
Receive	**110 nJ/bit**	**~ 200 ops/bit**	

WINS node RSC

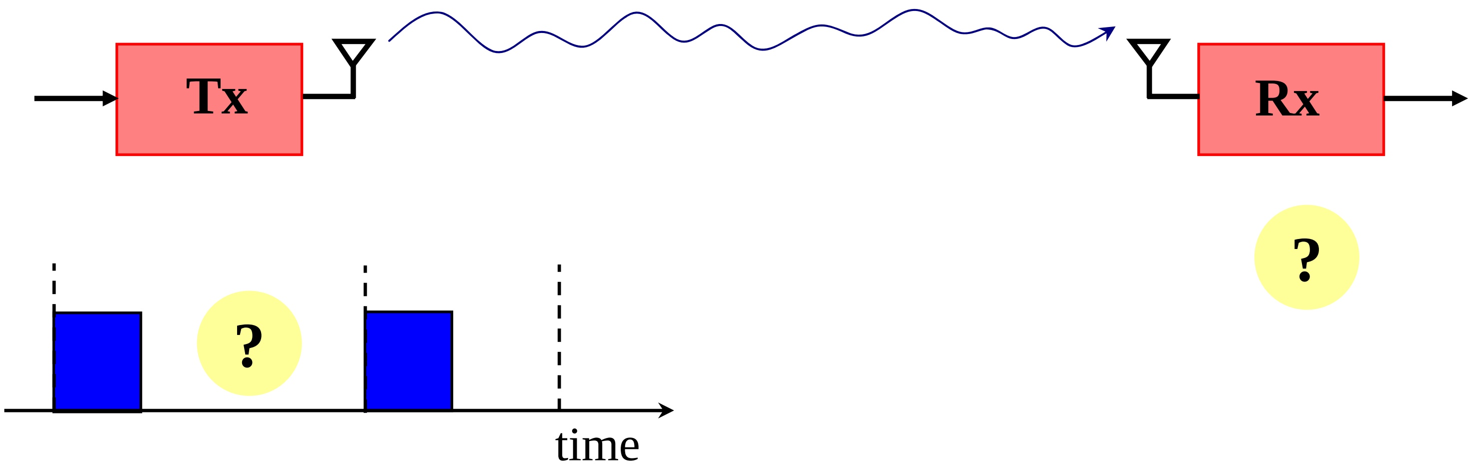
Transmit	**6600 nJ/bit**	Processor	**1.6 nJ/op**
Receive	**3300 nJ/bit**	**~ 6000 ops/bit**	

Processor Energy Management

- Knobs
  - Shutdown
  - Dynamic scaling of frequency and supply voltage
  - More recent: dynamic scaling of frequency, supply voltage, and threshold voltage
- All of the above knobs incorporated into sensor node OS schedulers
  - e.g. PA-eCos by UCLA & UCI has Rate-monotonic Scheduler with shutdown and DVS
- Gains of 2x-4x typically, in CPU power with typical workloads
- Predictive approaches
  - Predict computtion load and set voltage/frequency accordingly
  - Exploit the resiliency of sensor nets to packet and event losses
  - Now, losses due to computation noise

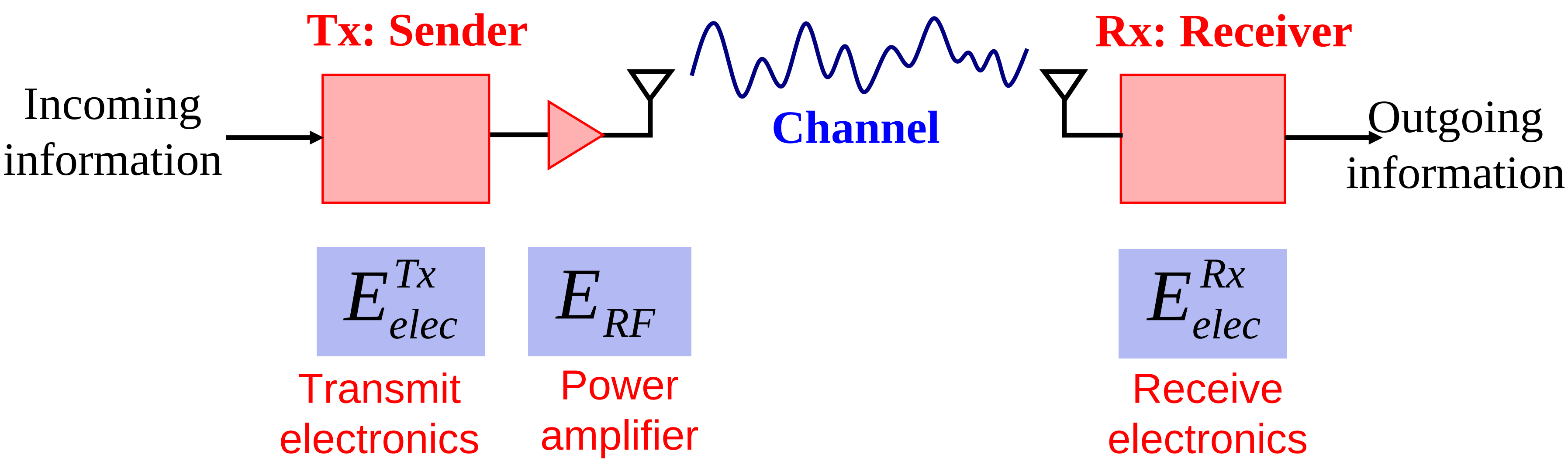


Radio Energy Management



- During operation, the required performance is often less than the peak performance the radio is designed for
- How do we take advantage of this observation, in both the sender and the receiver?

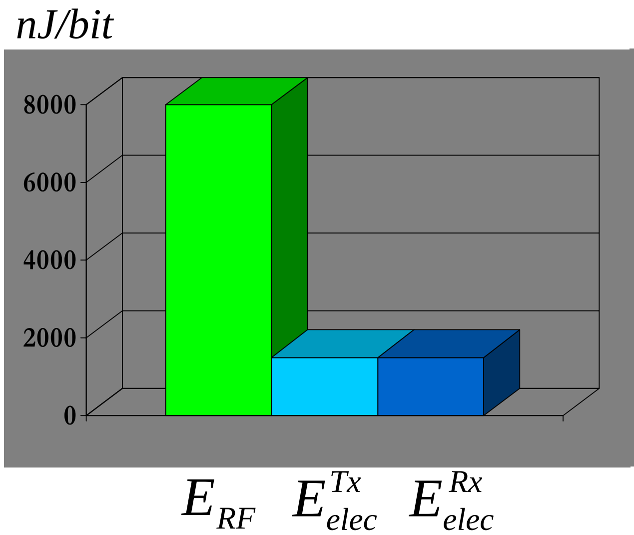
Energy in Radio: the Deeper Story….



- Wireless communication subsystem consists of three components with substantially different characteristics
- Their relative importance depends on the **transmission range** of the radio

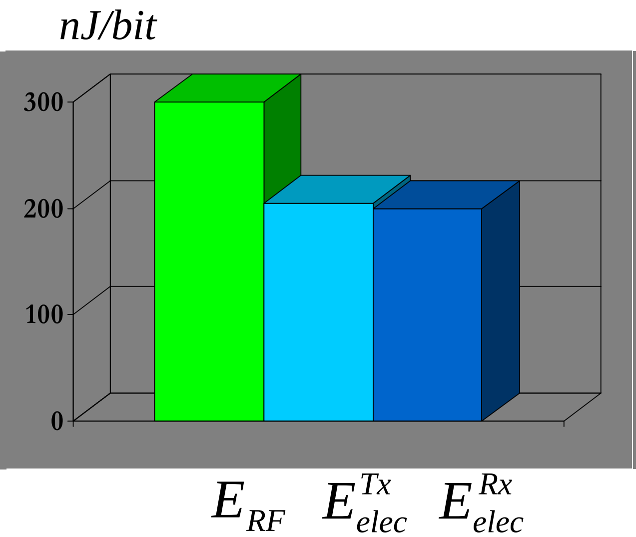
Examples

GSM



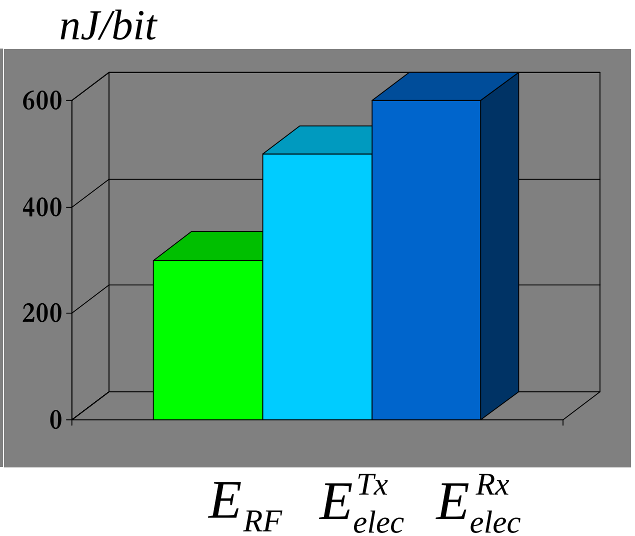
~ 1 km

Nokia C021 Wireless LAN



~ 50 m

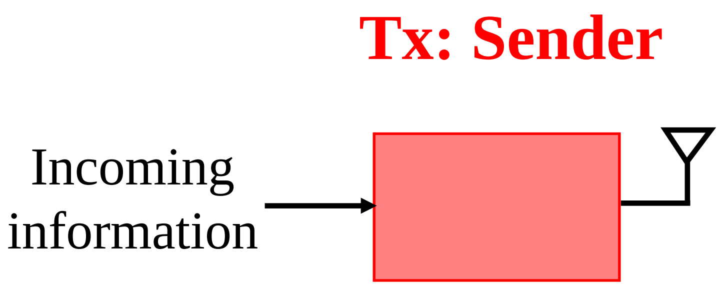
Medusa Sensor Node (UCLA)



~ 10 m

- The RF energy increases with transmission range
- The electronics energy for transmit and receive are typically comparable

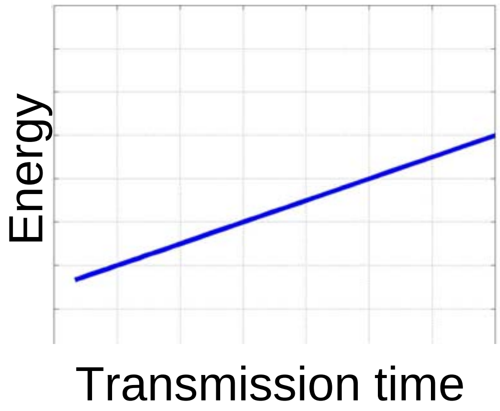
Energy Consumption of the Sender



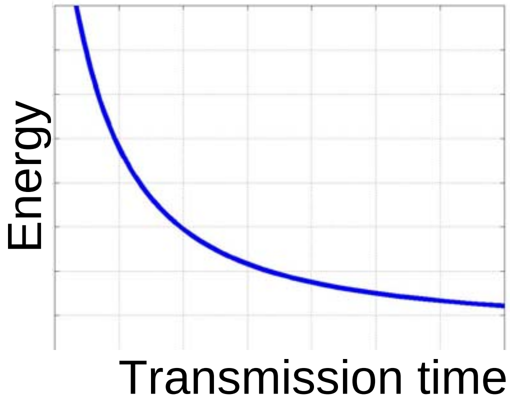
- Parameter of interest:
  - energy consumption per bit

$$E_{bit} = \frac{P}{T_{bit}}$$

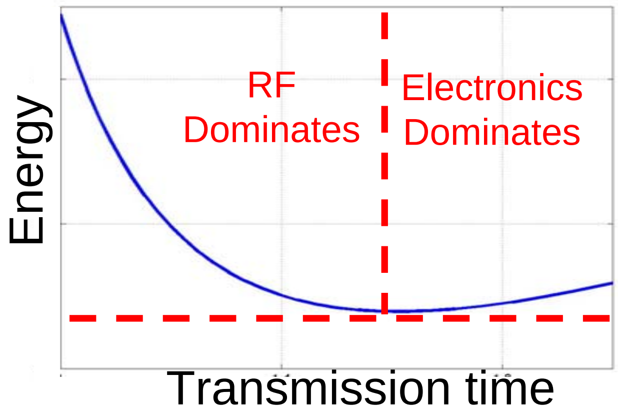
$$P_{elec}^{Tx}$$



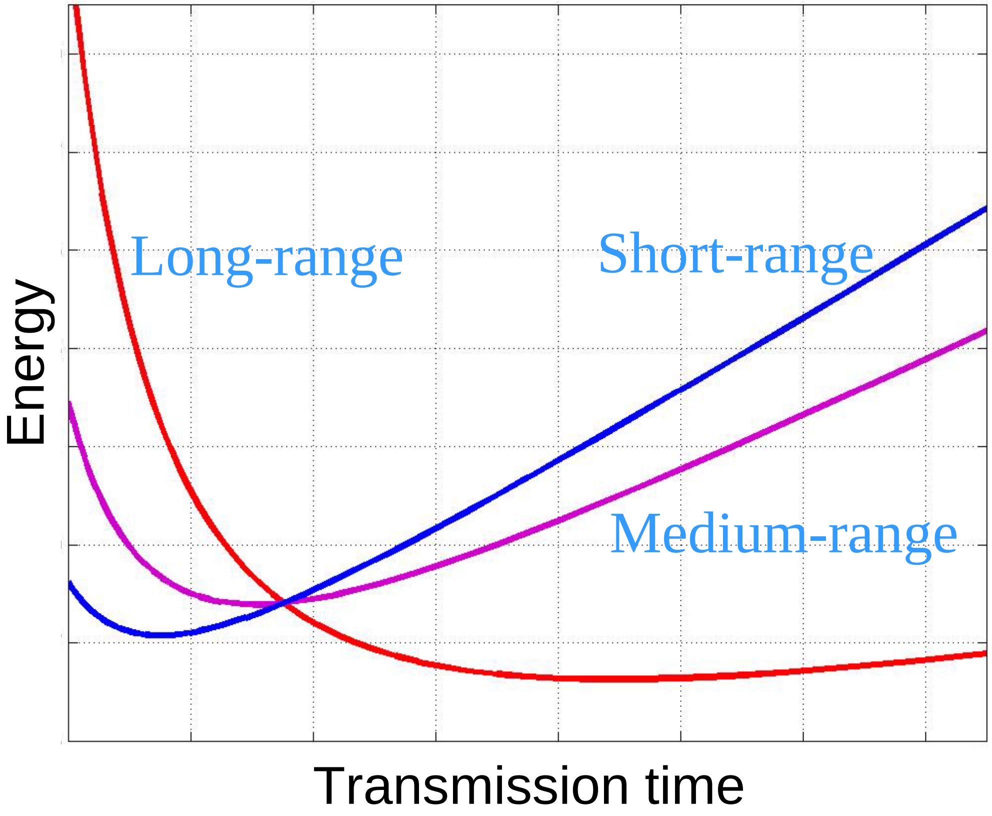
$$P_{RF}$$



$$P_{Total}$$



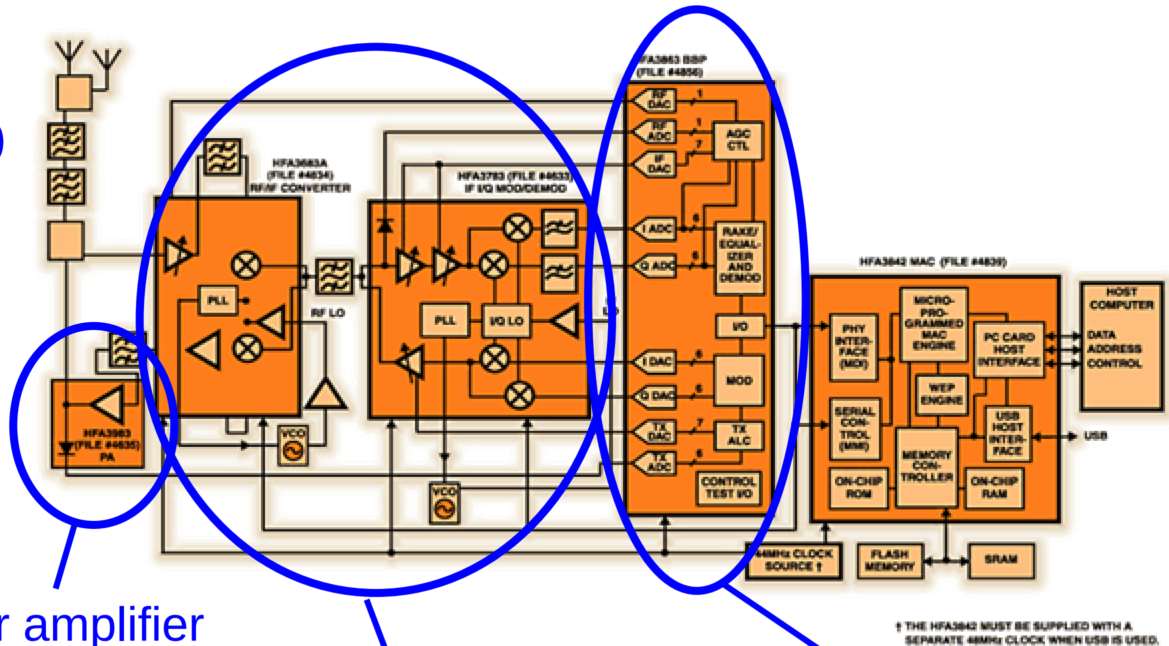
Effect of Transmission Range



Power Breakdowns and Trends

Radiated power
63 mW (18 dBm)

Intersil PRISM II
(Nokia C021 wireless LAN)



Power amplifier
600 mW
(~11% efficiency)

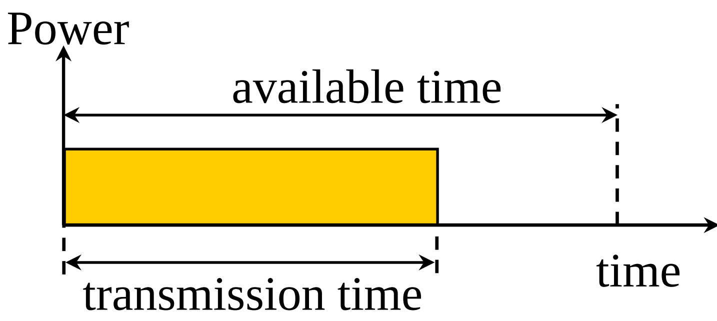
Analog electronics
240 mW

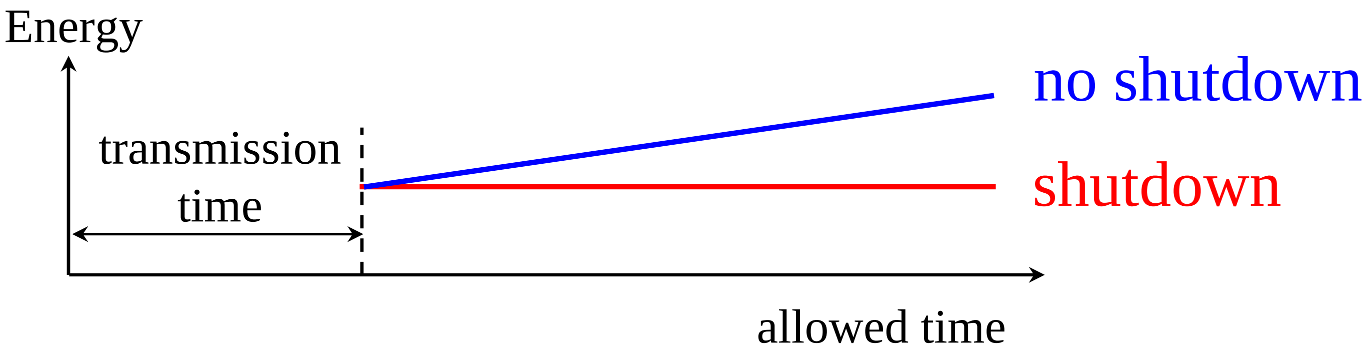
Digital electronics
170 mW

- Trends:
  - Move functionality from the analog to the digital electronics
  - Digital electronics benefit most from technology improvements
- Borderline between ‘long’ and ‘short’-range moves towards shorter transmit distances

Radio Energy Management #1: Shutdown

- **Principle**
  - Operate at a fixed speed and power level
  - Shut down the radio after the transmission
  - No superfluous energy consumption
- **Gotcha**
  - When and how to wake up?
  - More later …

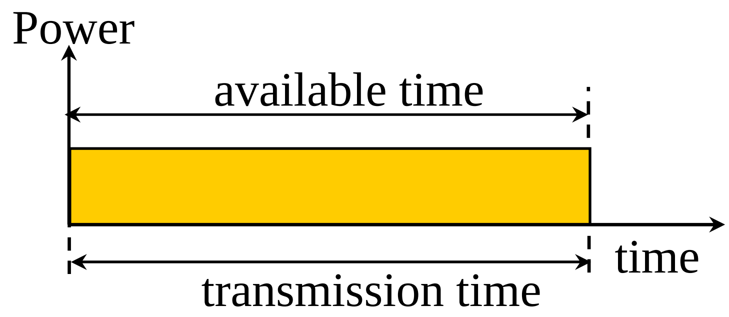




Radio Energy Management #2: Scaling along the Performance-Energy Curve

Principle

- Vary radio 'control knobs' such as modulation and error coding
- Trade off energy versus transmission time

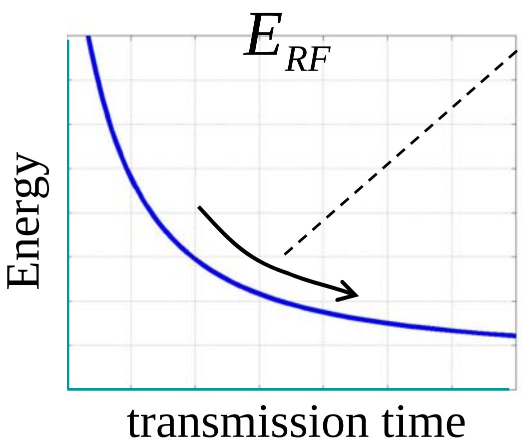


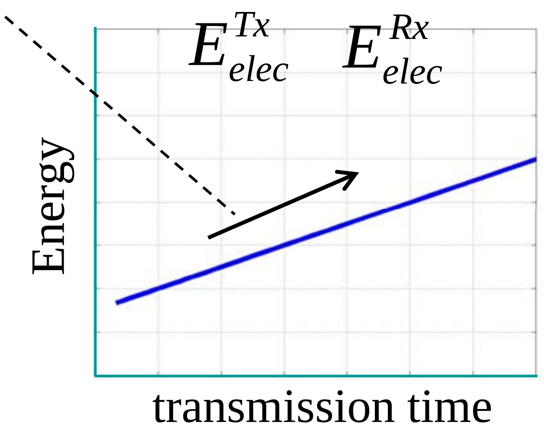
Modulation scaling

fewer bits per symbol

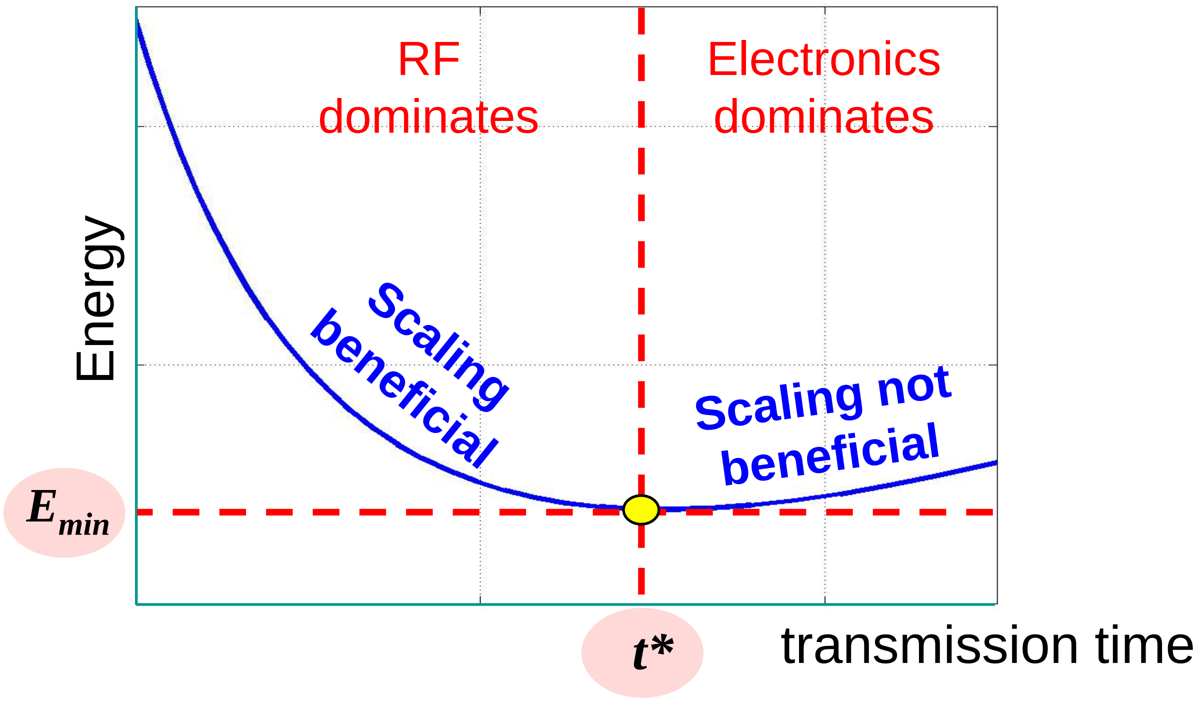
Code scaling

more heavily coded



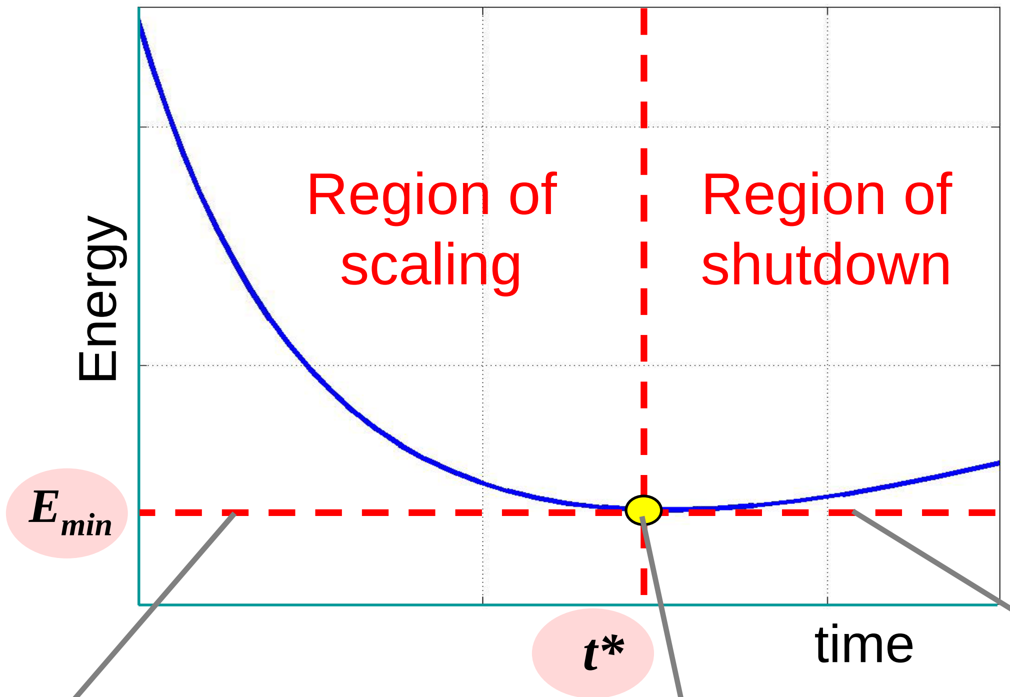


When to Scale?

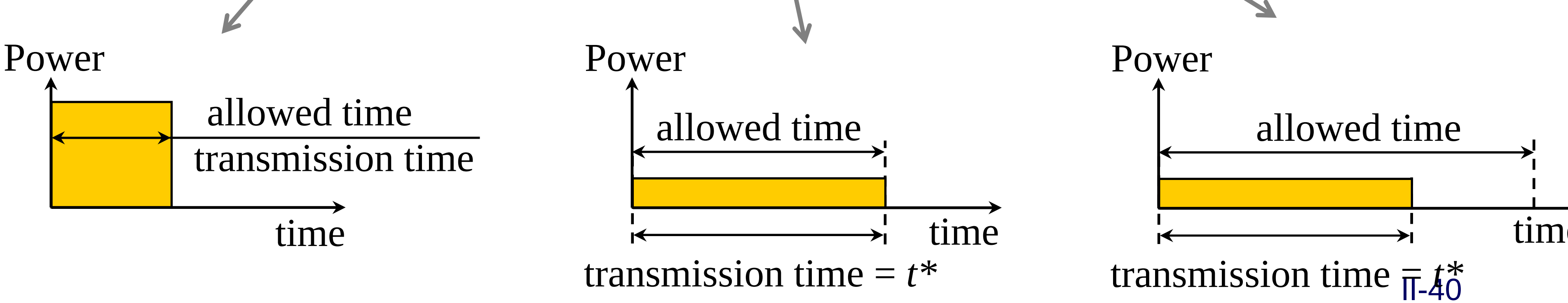


- Scaling results in a convex curve with an energy minimum E_{min}
- It only makes sense to slow down to transmission time $\boldsymbol{t^*}$ corresponding to this energy minimum

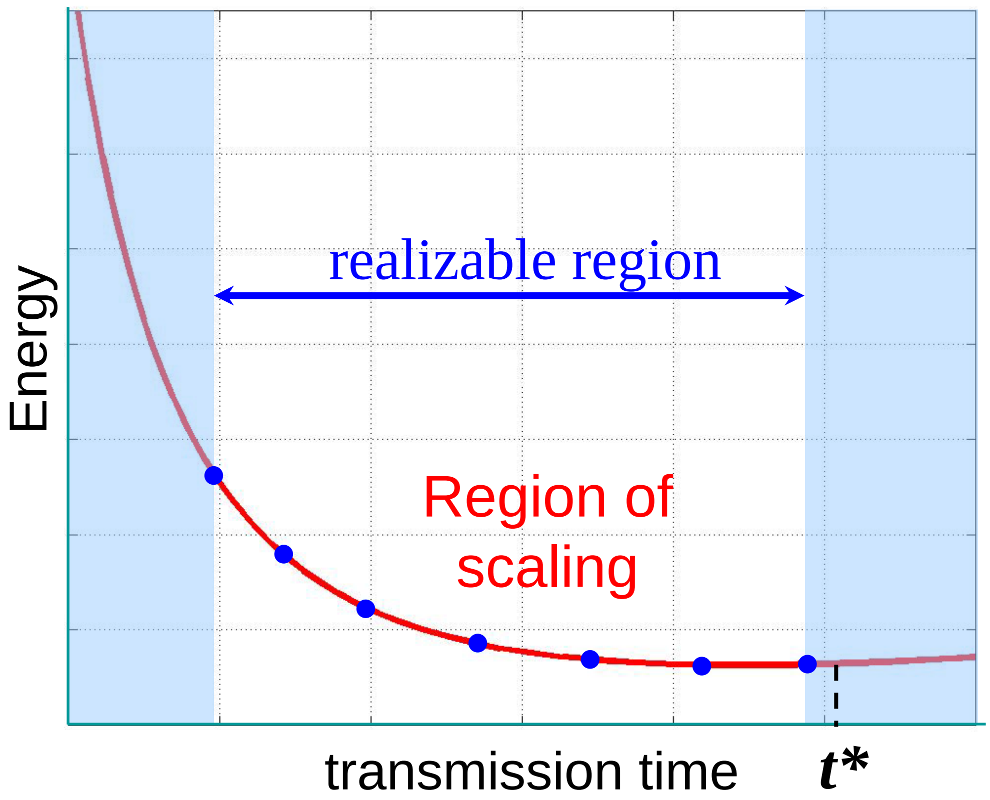
Scaling vs. Shutdown



- Use scaling while it reduces the energy
- If more time is allowed, scale down to the minimum energy point and subsequently use shutdown

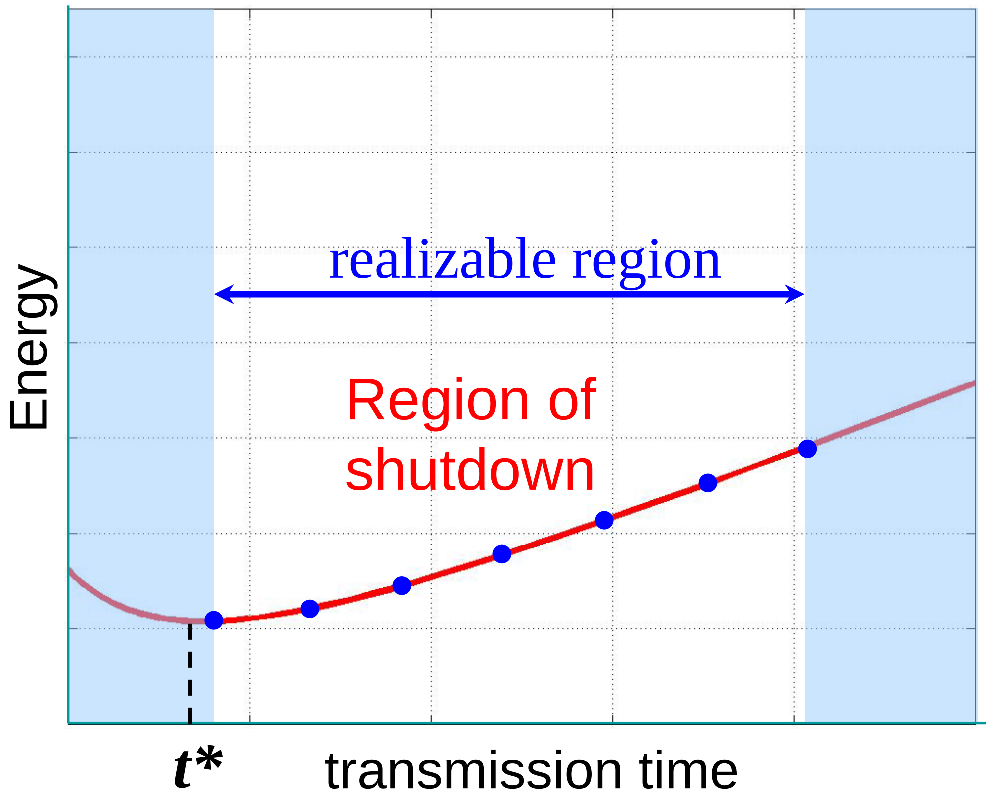


Long-range System



- The shape of the curve depends on the relative importance of RF and electronics
- This is a function of the transmission range
- Long-range systems have an operational region where they benefit from scaling

Short-range Systems

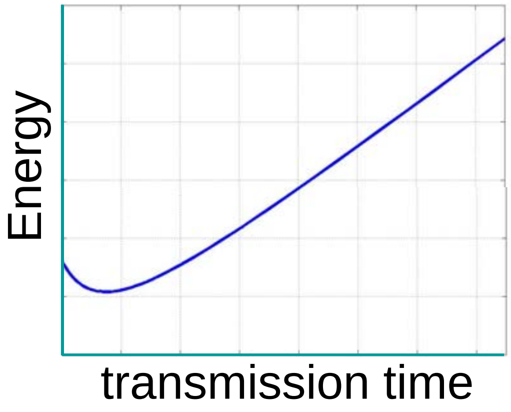


- Short-range systems have an operational region where scaling in not beneficial
- Best strategy is to transmit as fast as possible and shut down

Sensor Node Radio Power Management Summary

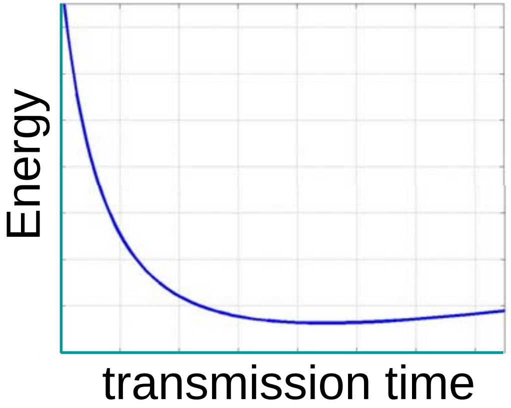
Short-range links

- Shutdown based
- Turn off sender and receiver
- Topology management schemes exploit this
e.g. Schurgers et. al. @ ACM MobiHoc ‘02

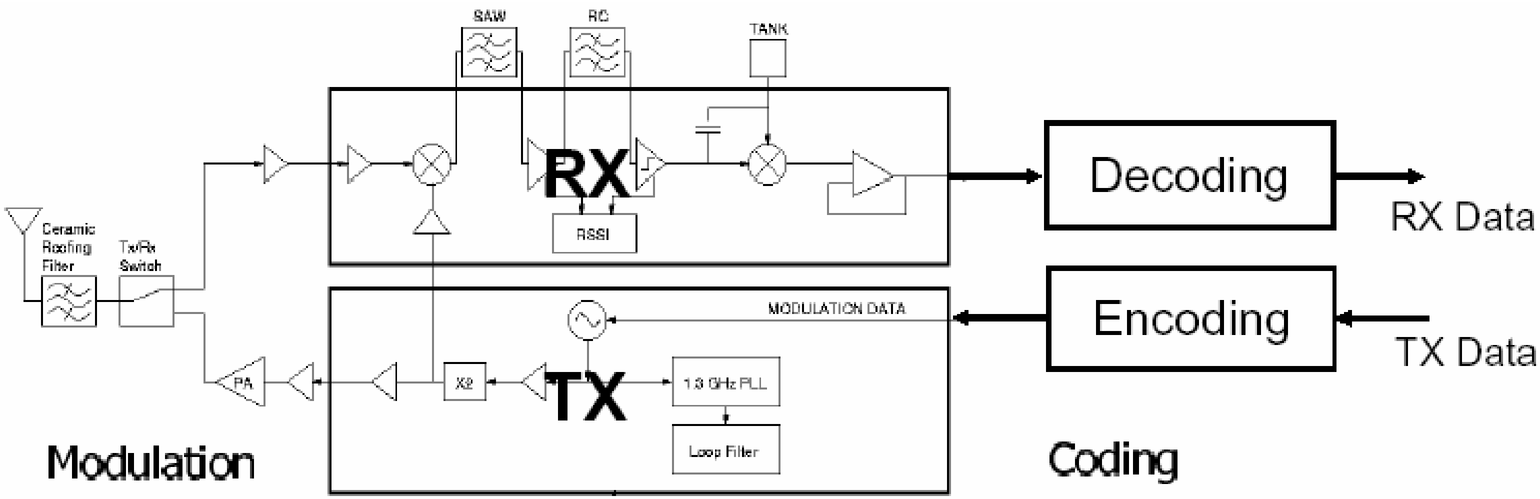


Long-range links

- Scaling based
- Slow down transmissions
- Energy-aware packet schedulers exploit this
e.g. Raghunathan et. al. @ ACM ISLPED ‘02



Another Issue: Start-up Time



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

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

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

Fixed Parameters

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

Tunable Parameters

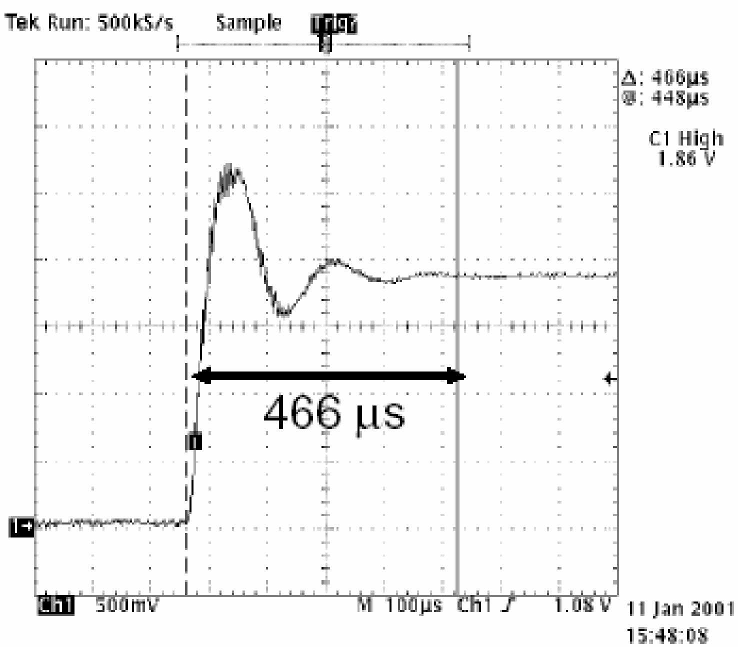
P_{out}
T_{on}
E_{FEC}

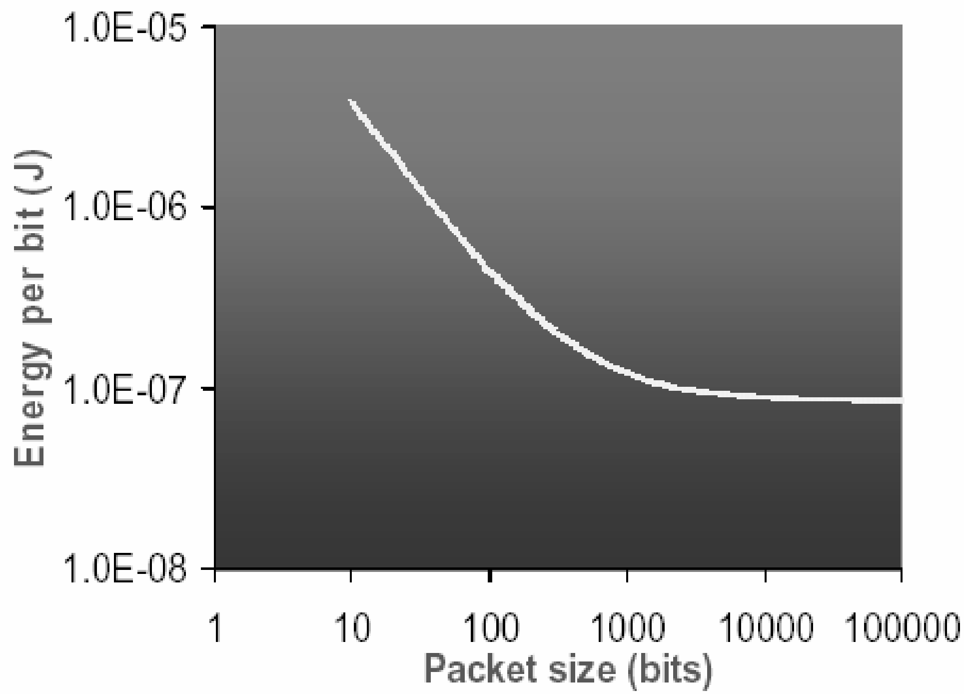
Ref: Shih et. al., Mobicom 2001

Wasted Energy

- Fixed cost of communication: startup time
  - High energy per bit for small packets

Startup time screen capture

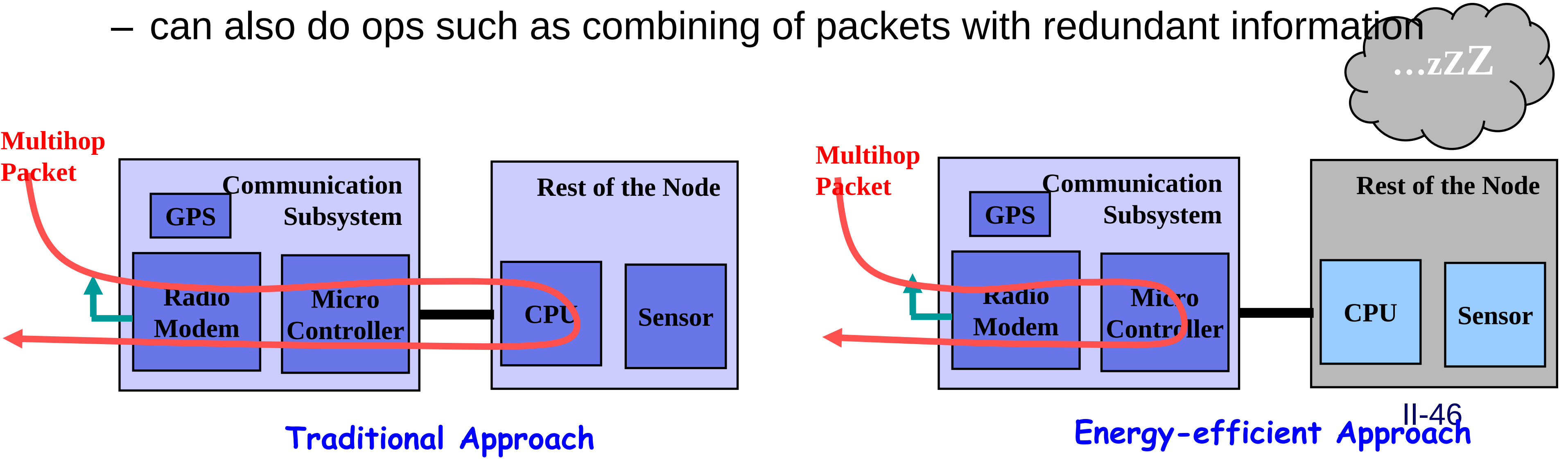




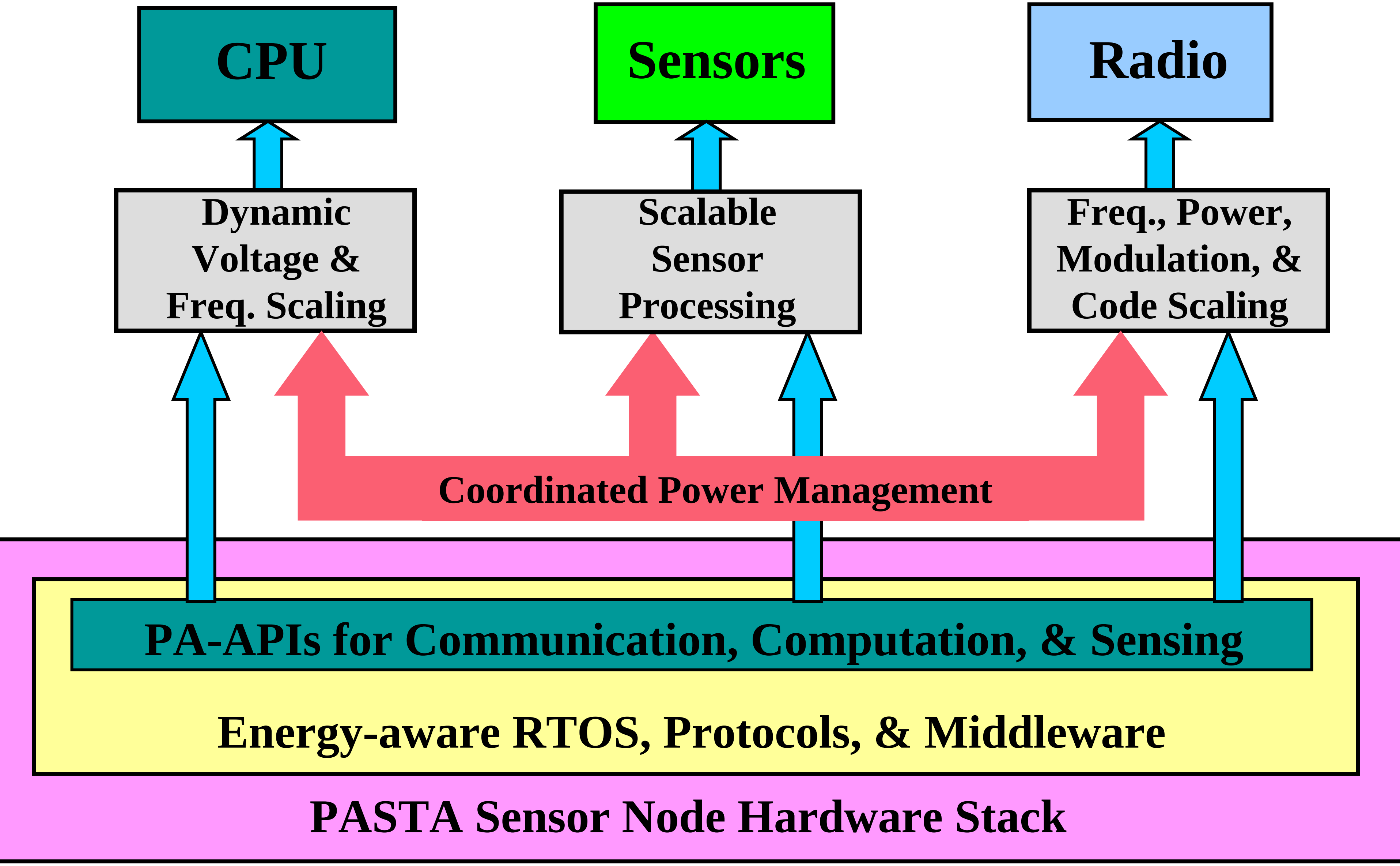
Ref: Shih et. al., Mobicom 2001

Sensor Node with Energy-efficient Packet Relaying [Tsiatsis01]

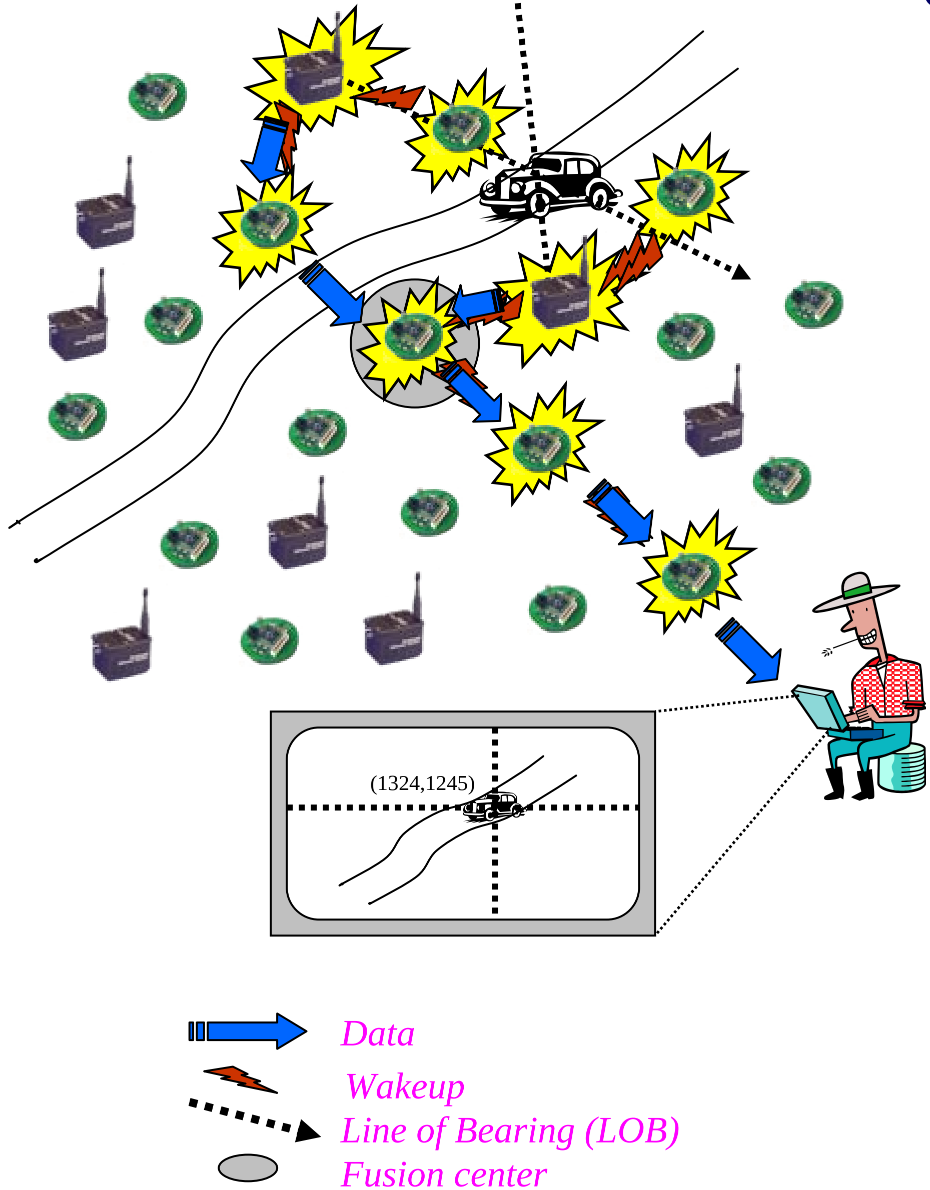
- Problem: sensor noes often simply relays packets
  - e.g. > 2/3-rd pkts. in some sample tracking simulations
- Traditional : main CPU woken up, packets sent across bus
  - power and latency penalty
- One fix: radio with a packet processor handles the common case of relaying
  - packets redirected as low in the protocol stack as possible
- Challenge: how to do it so that every new routing protocol will not require a new radio firmware or chip redesign?
  - packet processor classifies and modifies packets according to application-defined rules
  - can also do ops such as combining of packets with redundant information



Putting it All Together: Power-aware Sensor Node



Future Directions: Sensor-field Level Power Management



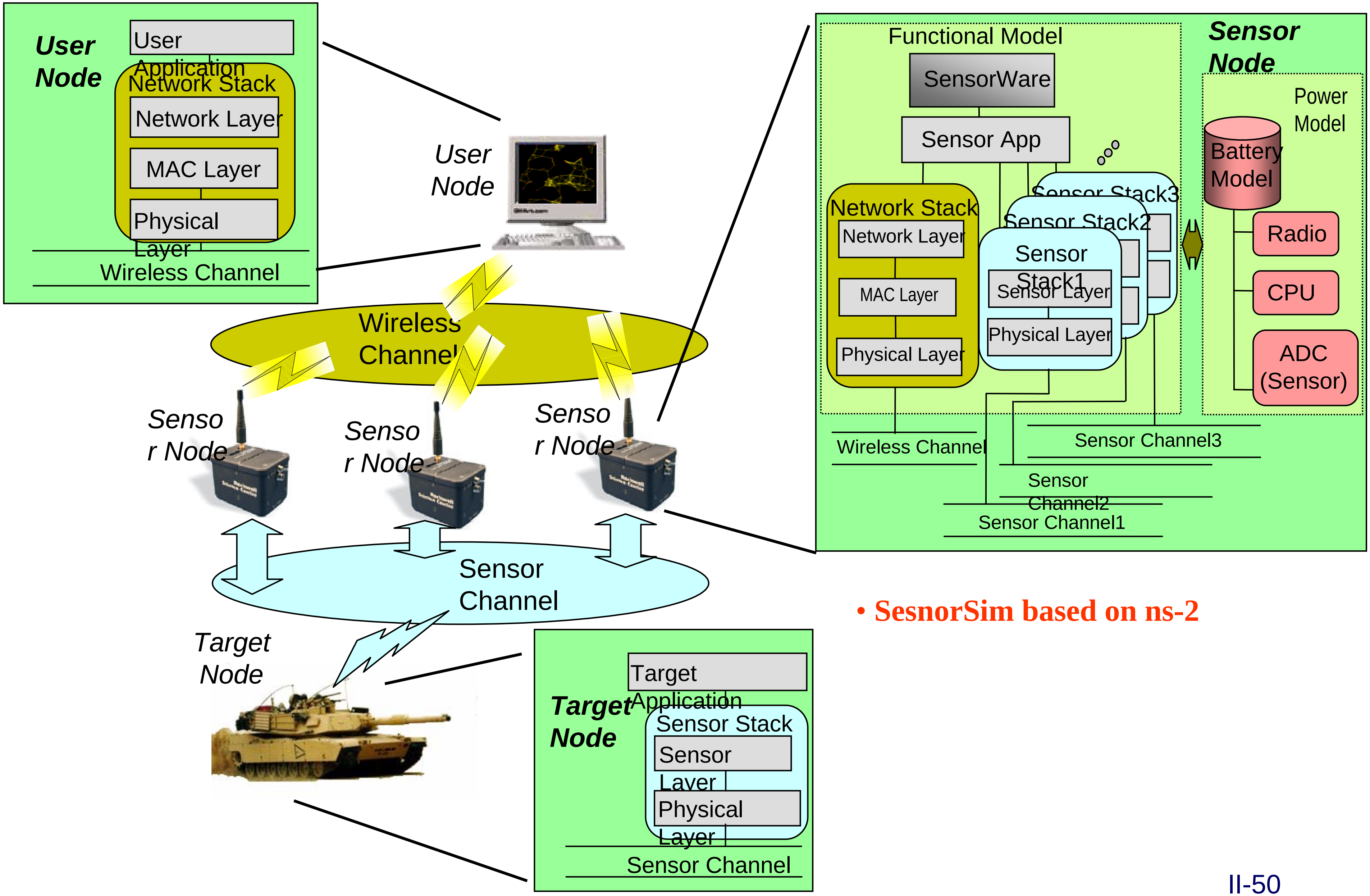
TYPE	STATE	SENS	CPU	COMM
Tripwire		ON	OFF	STEM
		ON	ON	ON
Tracker		OFF	OFF	STEM
		ON	ON	ON

- Two types of nodes
  - Tripwire nodes that are always sense
    - Low-power presence sensing modalities such as seismic or magnetic
  - Tracker nodes that sense on-demand
    - Higher power modalities such as LOB
- Approach
  - Network self-configures so that gradients are established from Tripwire nodes to nearby Tracker nodes
  - Radios are all managed via STEM
  - Event causes nearby Tripwire nodes to trip
  - Tripped Tripwire nodes collaboratively contact suitable Tracker nodes
    - Path established via STEM
    - Tracker nodes activate their sensors
  - Range or AoA information from Tracker Nodes is fused (e.g. Kalman Filter) to get location
    - In-network processing
      - Centralized : where should the fusion center be?
      - Distributed : fusion tree
  - Result of fusion sent to interested user nodes
  - Set of active Tracker Nodes changes as target moves
    - Process similar to hand-off

Tools

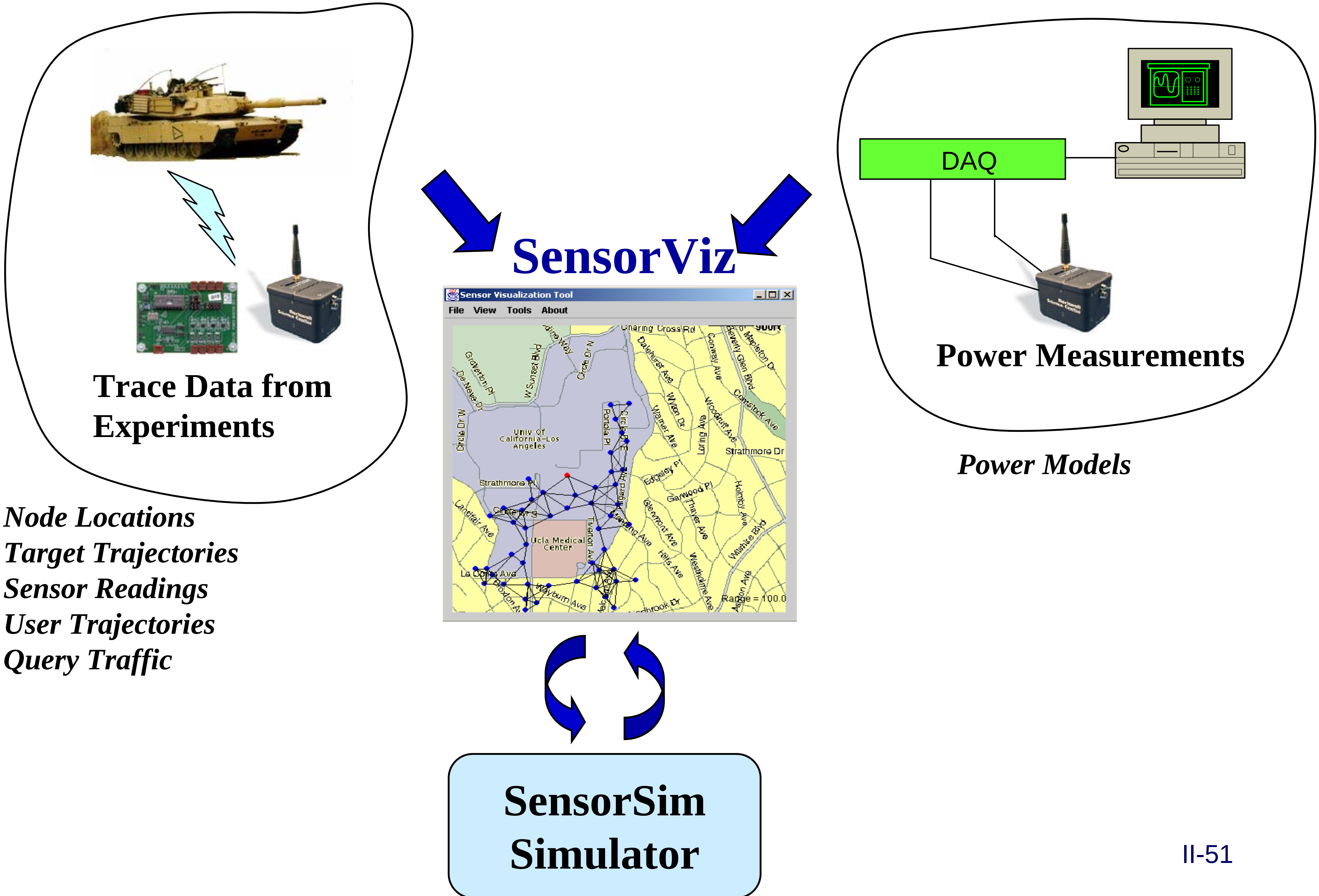
- Sensor Network-level Simulation Tools
  - Ns-2 enhancements by ISI
  - Ns-2 based SensorSim/SensorViz by UCLA
  - C++-based LECSim by UCLA
  - PARSEC-based NESLsim by UCLA
- Node-level Simulation Tools
  - MILAN by USC for WINS and μAMPS
  - ToS-Sim for Motes
- Processor-level Simulation Tools
  - JoulesTrack by MIT

SensorSim



- SesnorSim based on ns-2

SensorViz



Trace Data from Experiments
Node Locations
Target Trajectories
Sensor Readings
User Trajectories
Query Traffic
SensorViz
Sensor Visualization Tool
File View Tools About
DAQ
Power Measurements
Power Models
SensorSim Simulator