# A System Architecture for Networked Sensors

Jason Hill, Robert Szewczyk, Alec Woo,
Seth Hollar, David Culler, Kris Pister

**http://tinyos.millennium.berkeley.edu**

U.C. Berkeley

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# Computing in a cubic millimeter:

- Advances in low power wireless communication technology and micro-electromechanical sensors (MEMS) transducers make this possible
- How do you combine sensing, communication and computation into a complete architecture
- What are the requirements of the software?
- How do you evaluate a given design?

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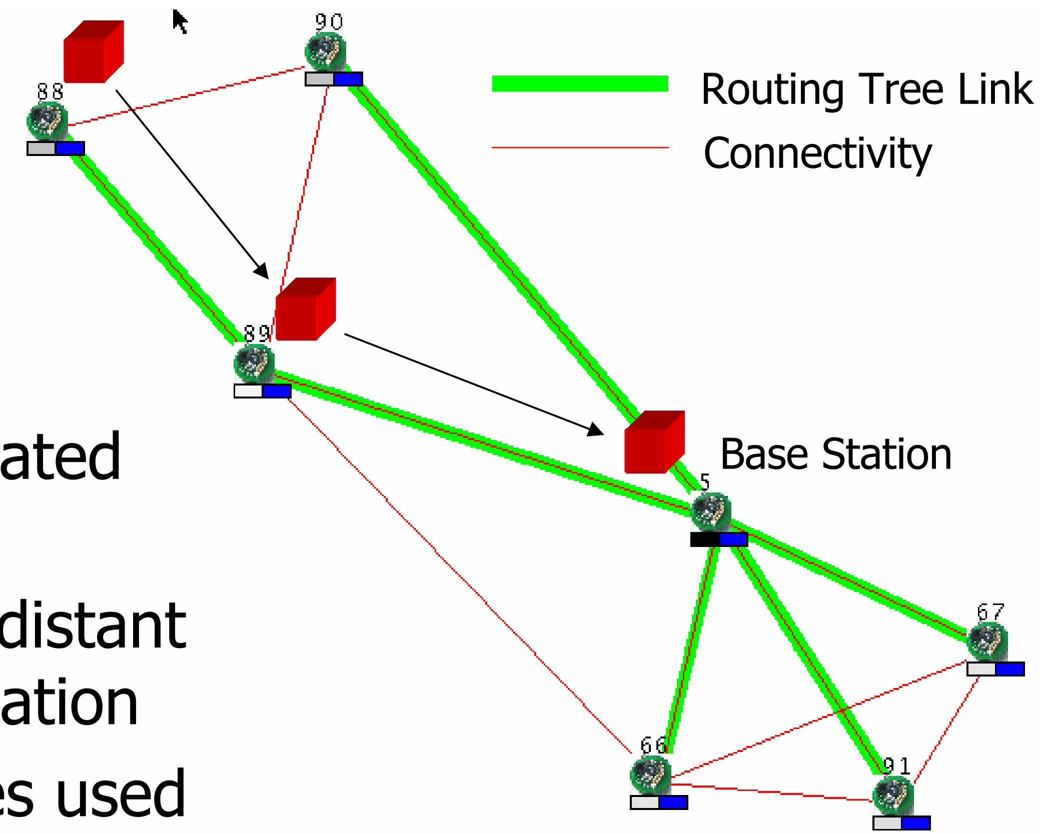
# Ad hoc sensing

- Autonomous nodes self assembling into a network of sensors
- Sensor information propagated to central collection point
- Intermediate nodes assist distant nodes to reach the base station
- Connectivity and error rates used to infer distance

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# Organization

- The Vision
- Hardware of today
- Software Requirements
- TinyOS system architecture
- System evaluation

# Today's Hardware

1.5″ x 1.5″

- Assembled from off-the-shelf components
- 4Mhz, 8bit MCU (ATMEL)
  - 512 bytes RAM, 8K ROM
- 900Mhz Radio (RF Monolithics)
  - 10-100 ft. range
- Temperature Sensor & Light Sensor
- LED outputs
- Serial Port

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# No dedicated I/O controllers

- Bit by bit interaction with Radio
- Software must process bit every 100µs
- No buffering
  - missed deadline → lost data
- Must time share on granularity of 2x sampling rate

# Key Software Requirements

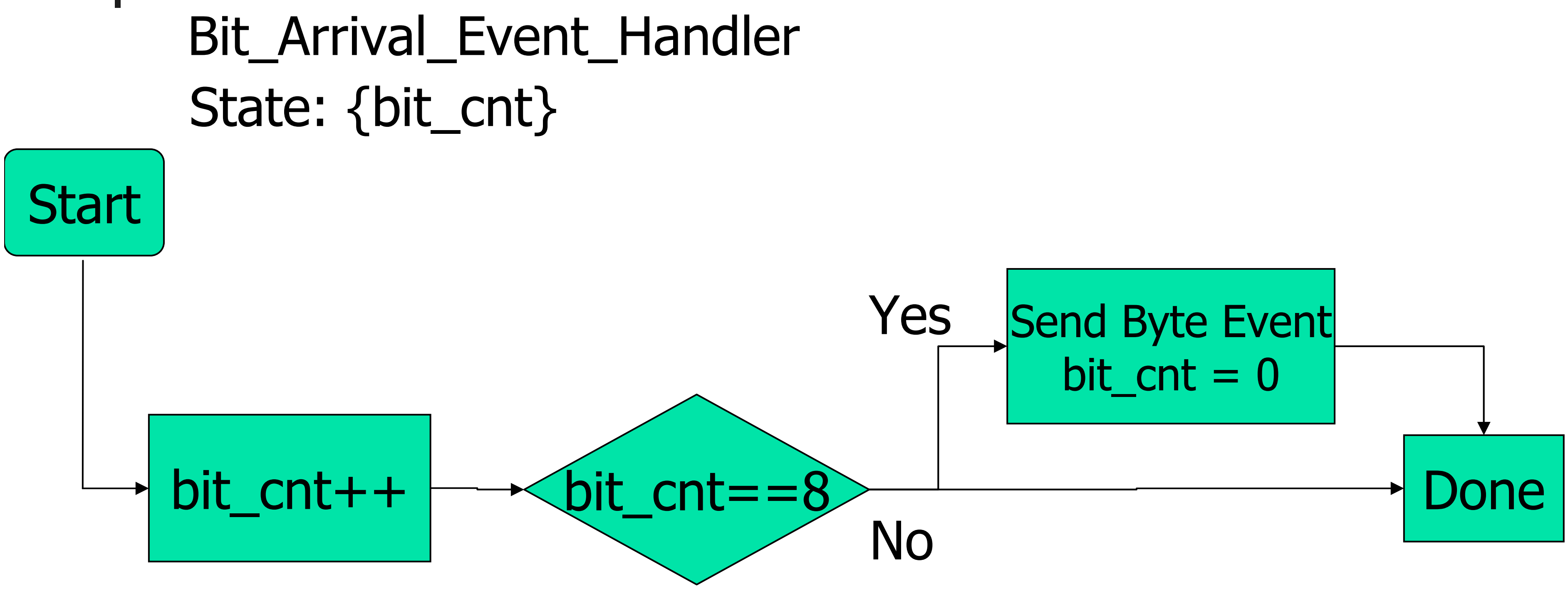
- Capable of fine grained concurrency
- Small physical size
- Efficient Resource Utilization
- Highly Modular

# TinyOS system architecture

# State Machine Programming Model

- System composed of state machines
- Command and event handlers transition a module from one state to another
  - Quick, low overhead, non-blocking state transitions
- Many independent modules allowed to efficiently share a single execution context

# Simple State Machine Logic




- Don't you have to do computational work eventually?
- "Tasks" used to perform computational work

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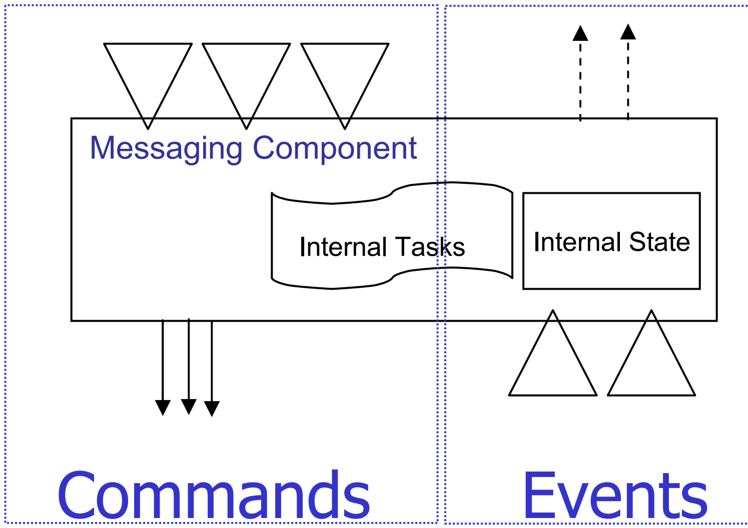
# TinyOS component model

- Component has:
  - Frame (storage)
  - Tasks (computation)
  - Command and Event Interface
- Constrained Storage Model allows compile time memory allocation
- Provides efficient modularity
- Explicit Interfaces help with robustness

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# TinyOS – The Software

- Scheduler and graph of components
  - constrained two-level scheduling model: tasks + events
- Provides a component based model abstracting hardware specifics from application programmer
- Capable of maintaining fine grained concurrency
- Can interchange system components to get application specific functionality

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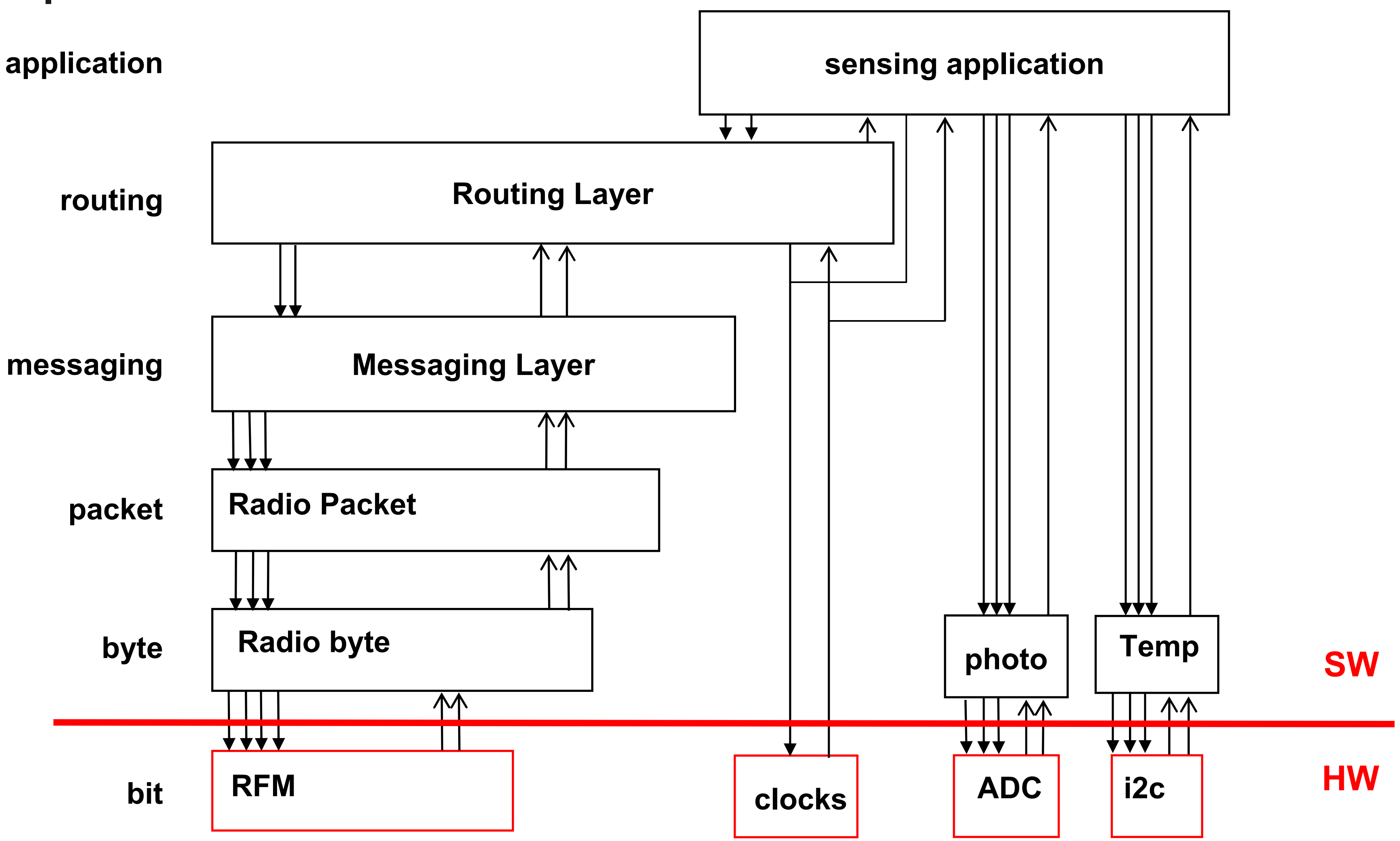
# Composition into a Complete Application

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# The Application

- The single node application is just another state machine

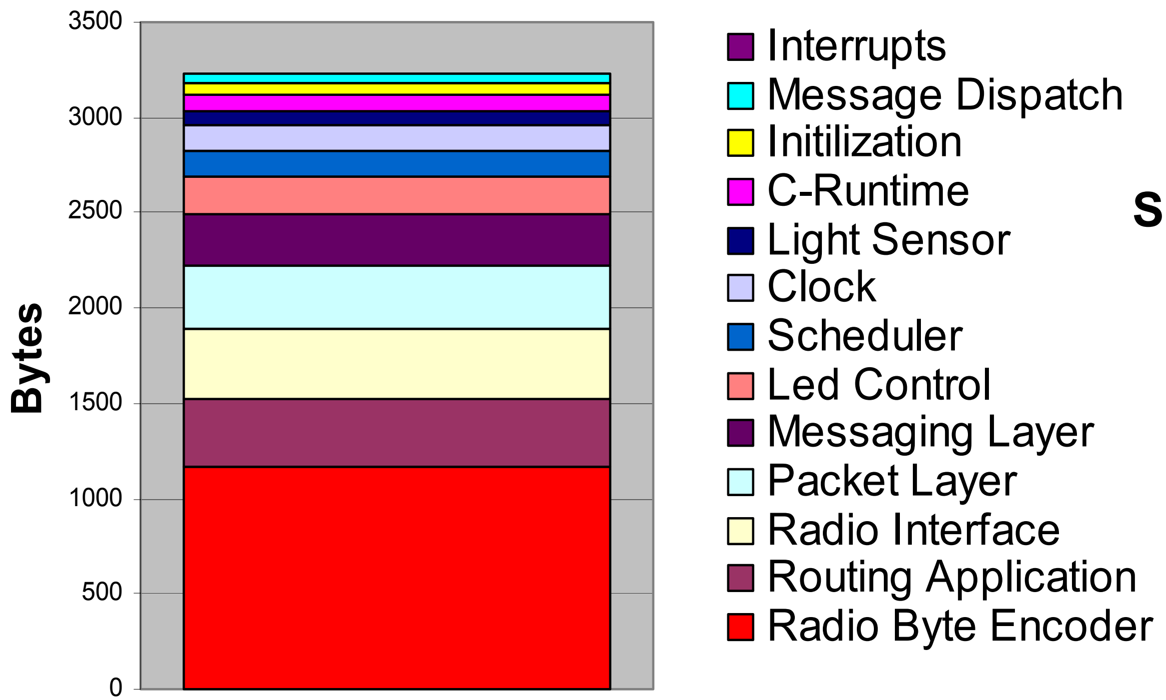
```
Message_Handler(incoming_message){
        if(sender_is_better_parent()){
                my_parent = sender();
        }else if(I_am_parent_of_sender(){
                forward_message(my_parent,
                                incoming_message);
        }
}
Clock_Event_Handler(){
        check_expire(my_parent);
        if(my_parent != null){
                send_data(my_parent);
        }
}
```

# Analysis

- Let’s take apart Space, Power and Time

# Space Breakdown…

Code size for ad hoc networking application




**Scheduler: 144 Bytes code**
**Totals: 3430 Bytes code**
**226 Bytes data**

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# Power Breakdown…

| | Active | Idle | Sleep |
|---|---|---|---|
| CPU | 5 mA | 2 mA | 5 μA |
| Radio | 7 mA (TX) | 4.5 mA (RX) | 5 μA |
| EE-Prom | 3 mA | 0 | 0 |
| LED's | 4 mA | 0 | 0 |
| Photo Diode | 200 μA | 0 | 0 |
| Temperature | 200 μA | 0 | 0 |

Panasonic
CR2354
560 mAh

- But what does this mean?
  - Lithium Battery runs for 35 hours at peak load and years at minimum load!
    - That's three orders of magnitude difference!
  - A one byte transmission uses the same energy as approx 11000 cycles of computation.

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# Time Breakdown…

| Components | Packet reception work breakdown | CPU Utilization | Energy (nj/Bit) |
|---|---|---|---|
| AM | 0.05% | 0.20% | 0.33 |
| Packet | 1.12% | 0.51% | 7.58 |
| Ratio handler | 26.87% | 12.16% | 182.38 |
| Radio decode thread | 5.48% | 2.48% | 37.2 |
| RFM | 66.48% | 30.08% | 451.17 |
| Radio Reception | - | - | 1350 |
| Idle | - | 54.75% | - |
| Total | 100.00% | 100.00% | 2028.66 |

- 50 cycle thread overhead (6 byte copies)
- 10 cycle event overhead (1.25 byte copes)

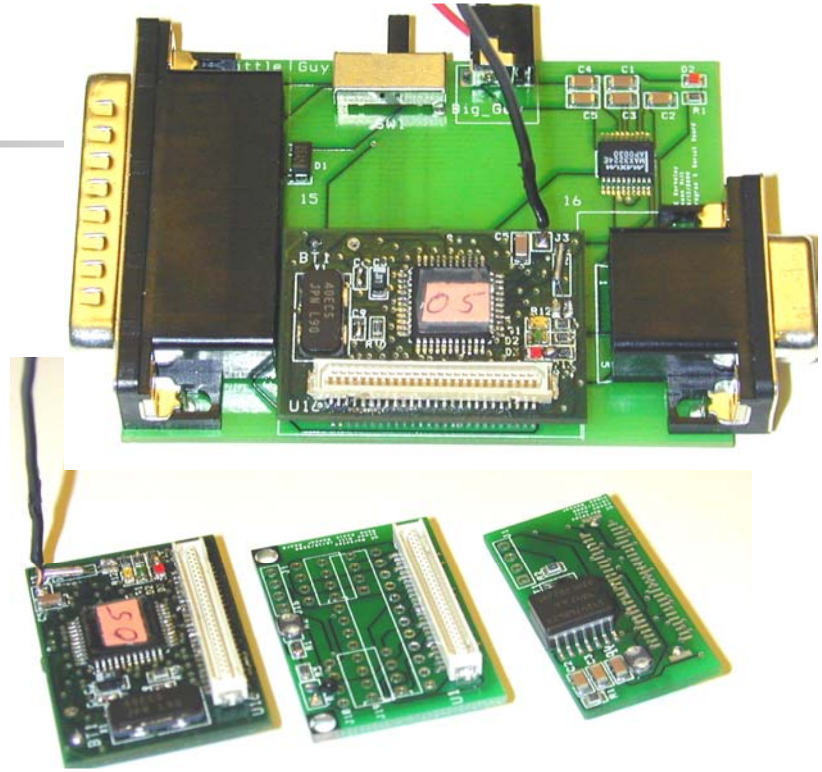
# How well did we meet the requirements?

- ✓ Capable of fine grained concurrency
- ✓ Small physical size
- ✓ Efficient Resource Utilization
- ✓ Highly Modular

# Conclusions

- People are working on shrinking sensors and communication, we need to focus on what brings them together
- TinyOS is a highly modular software environment tailored to the requirements of Network Sensors, stressing efficiency, modularity and concurrency
- We now have a whole new set of tradeoffs need to investigate

# Hardware Kits



- Two Board Sandwich
  - Main CPU board
    with Radio Communication
  - Secondary Sensor Board
- Allows for expansion and customization
- Current sensors include:
  Acceleration, Magnetic Field,
  Temperature, Pressure,
  Humidity, Light,  and RF Signal Strength
- Can control RF transmission strength & Sense Reception Strength

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# How to get more information:

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# Real time operating systems

| Name | Code Size | Target CPU |
|---|---|---|
| pOSEK | 2K | Microcontrollers |
| pSOSystem | | PII->ARM Thumb |
| VxWorks | 286K | Pentium -> Strong ARM |
| QNX Nutrino | >100K | Pentium II -> NEC |
| QNX RealTime | 100K | Pentium II -> SH4 |
| OS-9 | | Pentium -> SH4 |
| Chorus OS | 10K | Pentium -> Strong ARM |
| ARIEL | 19K | SH2, ARM Thumb |
| Creem | 560 bytes | ATMEL 8051 |

- QNX context switch = 2400 cycles on x86
- pOSEK context switch > 40 µs
- Creem -> no preemption

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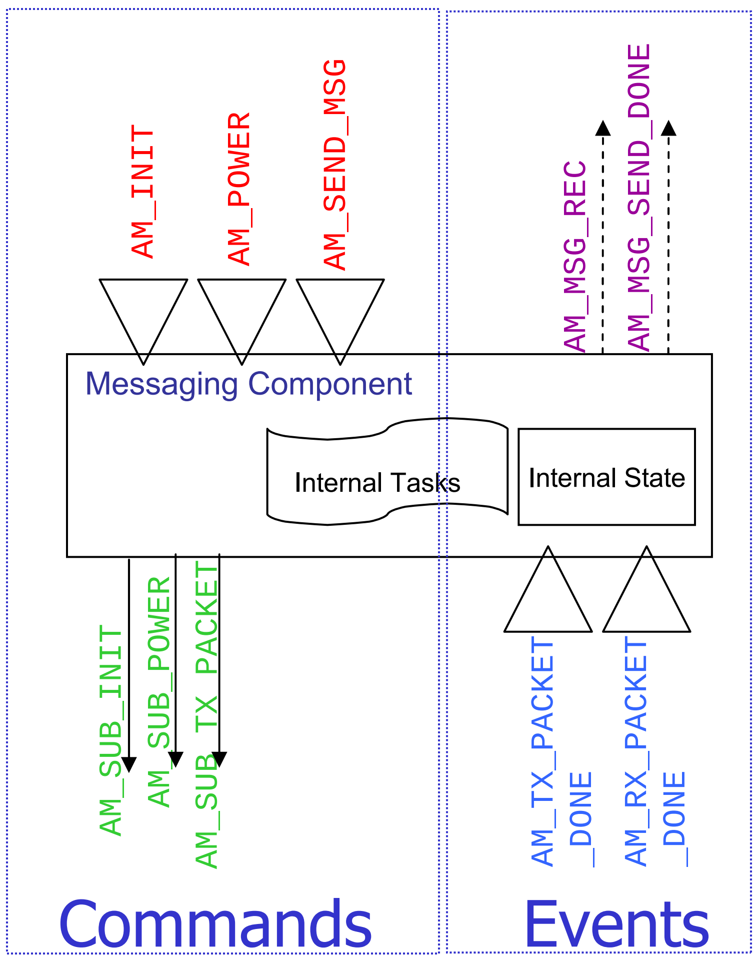
# TOS Component

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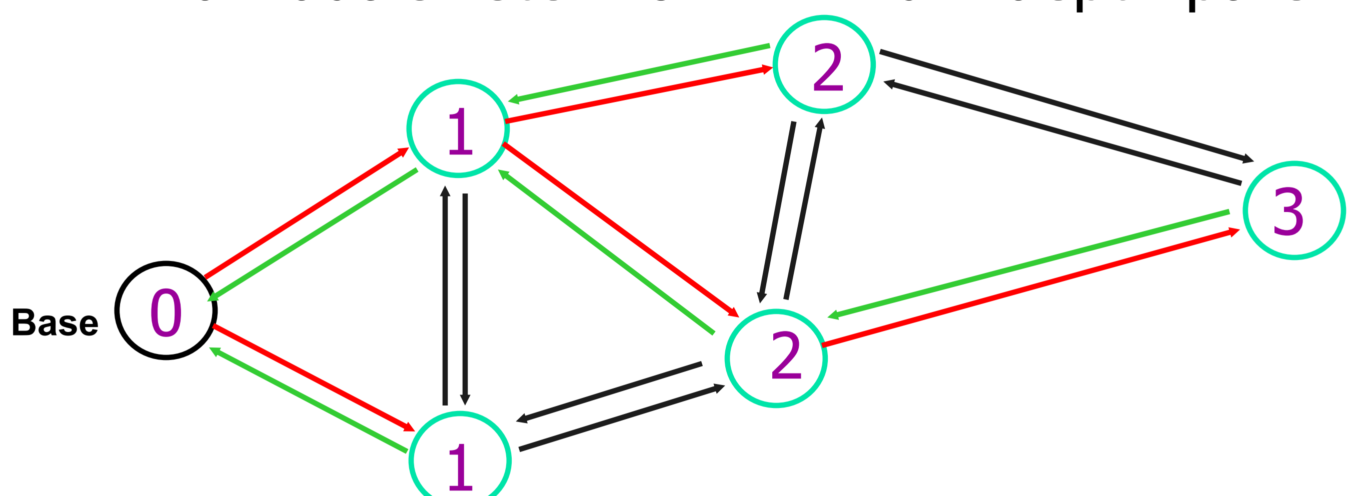
```
//AM.comp//
TOS_MODULE AM;
ACCEPTS{
  char AM_SEND_MSG(char addr, char type,
                   char* data);
  void AM_POWER(char mode);
  char AM_INIT();
};
SIGNALS{
  char AM_MSG_REC(char type,
                  char* data);
  char AM_MSG_SEND_DONE(char success);
};
HANDLES{
  char AM_TX_PACKET_DONE(char success);
  char AM_RX_PACKET_DONE(char* packet);
};
USES{
  char AM_SUB_TX_PACKET(char* data);
  void AM_SUB_POWER(char mode);
  char AM_SUB_INIT();
};
```

# Ad hoc networking

- Each node needs to determine it's parent and its depth in the tree
- Each node broadcasts out <identity, depth, data> when parent is known
- At start, Base Station knows it is at depth 0
  - It send out <Base ID, 0, **>
- Individuals listen for minimum depth parent

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# Easy Migration of the Hardware Software Boundary

- TinyOS component models hardware abstractions in software
- Component model allows migration of software components into hardware
- Example:
  - Bit level radio processing component could be implemented as specialized FIFO with complex pattern matching
  - Could reduce CPU utilization while sending by more than 50%

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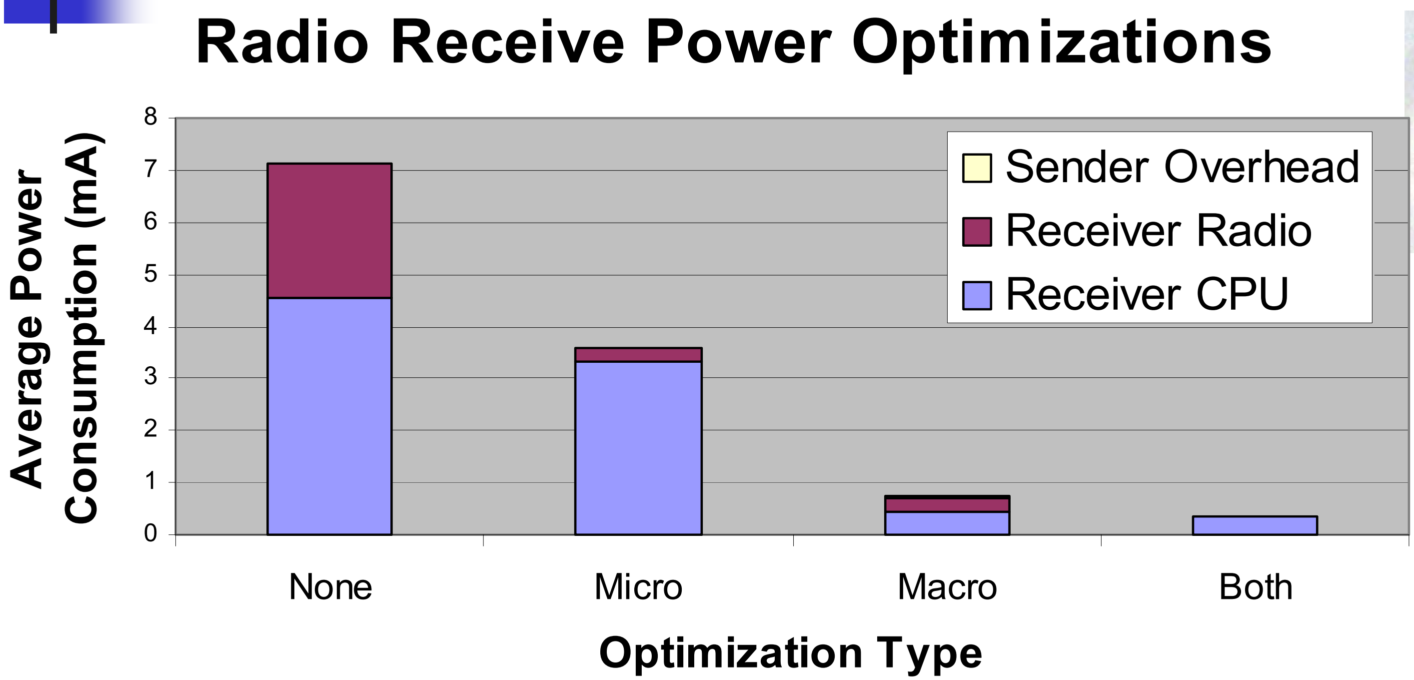
# Sample tradeoffs




Panasonic
CR2354
560 mAh

| Battery Lifetime for sensor reporting every minute | | |
|---|---|---|
| | Duty Cycle | Estimated Battery Life |
| Full Time Listen | 100% | 3 Days |
| Full Time Low_Power Listen | 100% | 6.54 Days |
| Periodic Multi-Hop Listening | 10% | 65 Days |
| No Listen (no Multi-hop) | 0.01% | Years |

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