The Mote Revolution:
Low Power Wireless Sensor Network Devices

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"The Mote Revolution: Low Power Wireless Sensor Network Devices"
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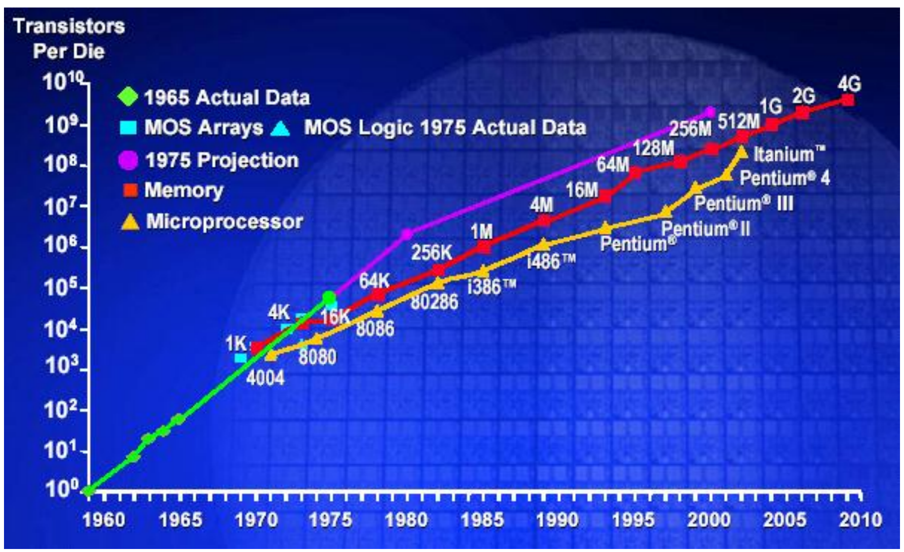
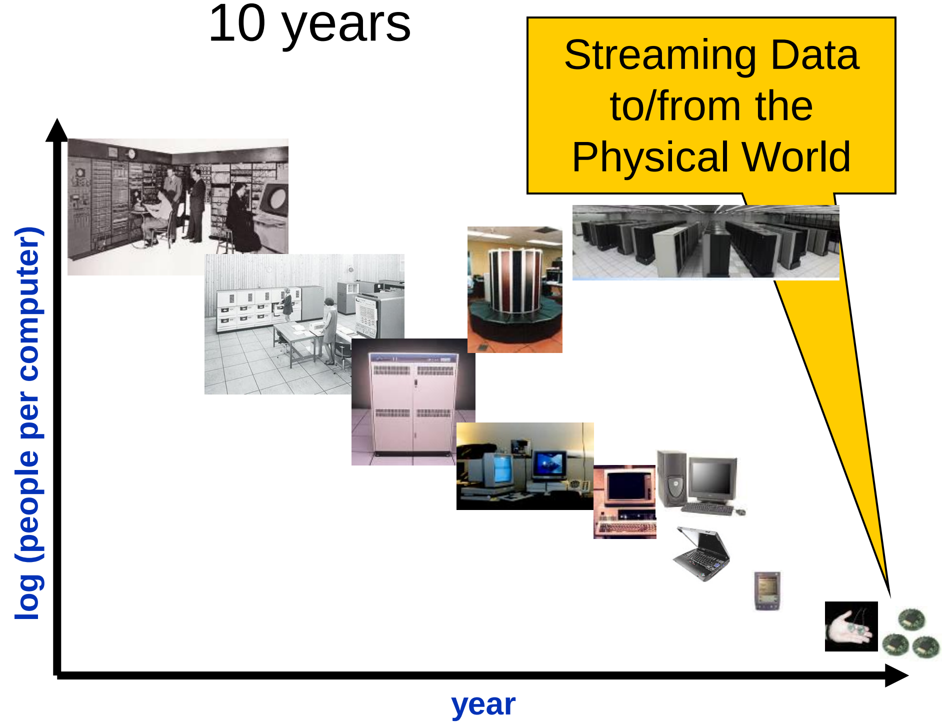
Outline

- Trends and Applications
- Mote History and Evolution
- Design Principles
- Telos

Faster, Smaller, Numerous

- Moore's Law
  - "Stuff" (transistors, etc) doubling every 1-2 years
- Bell's Law
  - New computing class every 10 years

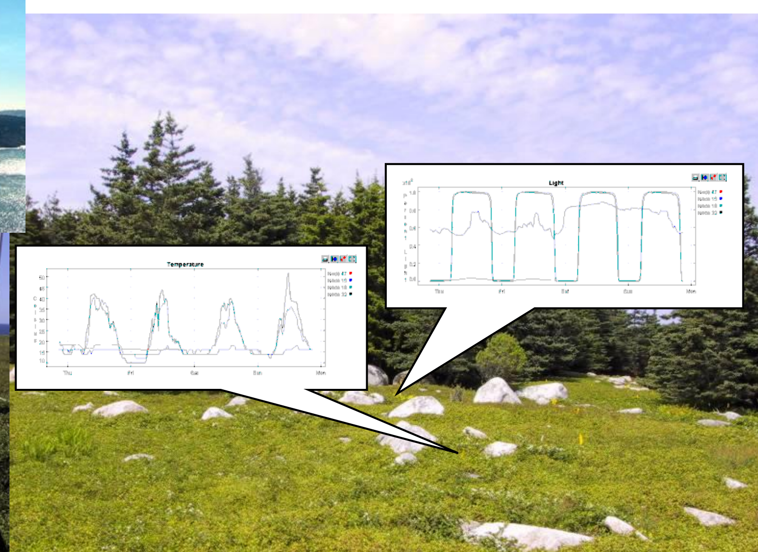


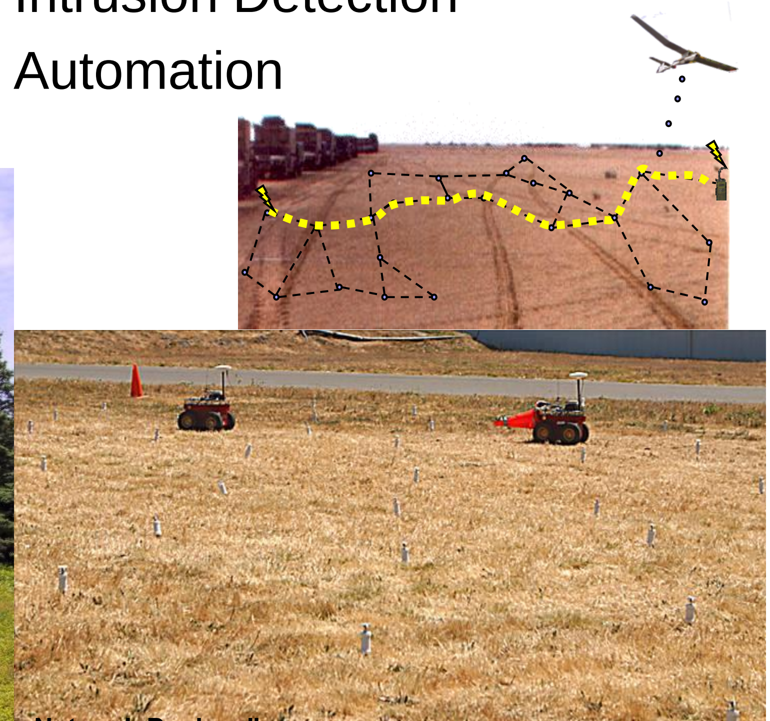


Applications

Density & Scale
Sample Rate & Precision
Disconnection & Lifetime
Mobility
Low Latency

- Environmental Monitoring
  - Habitat Monitoring
  - Integrated Biology
  - Structural Monitoring
- Interactive and Control
  - Pursuer-Evader
  - Intrusion Detection
  - Automation





Open Experimental Platform

Services

Networking

TinyOS

Telos 4/04
Robust
Low Power
250kbps
Easy to use

WeC 99
"Smart Rock"

Small microcontroller
- **8 kB code**
- **512 B data**

Simple, low-power radio
- **10 kbps ASK**

EEPROM (32 KB)

Simple sensors

Rene 11/00

Designed for experimentation

-sensor boards

-power boards

Dot 9/01

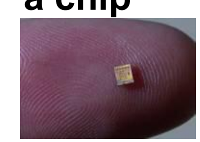
Demonstrate scale

Mica 1/02

NEST open exp. Platform
128 kB code, 4 kB data
40kbps OOK/ASK radio
512 kB Flash

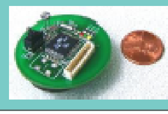
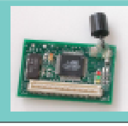
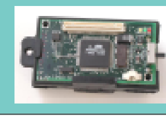
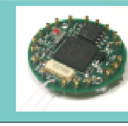
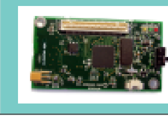
Mica2 12/02
38.4kbps radio
FSK

Spec 6/03
"Mote on a chip"



Commercial Off The Shelf Components (COTS)

Mote Evolution

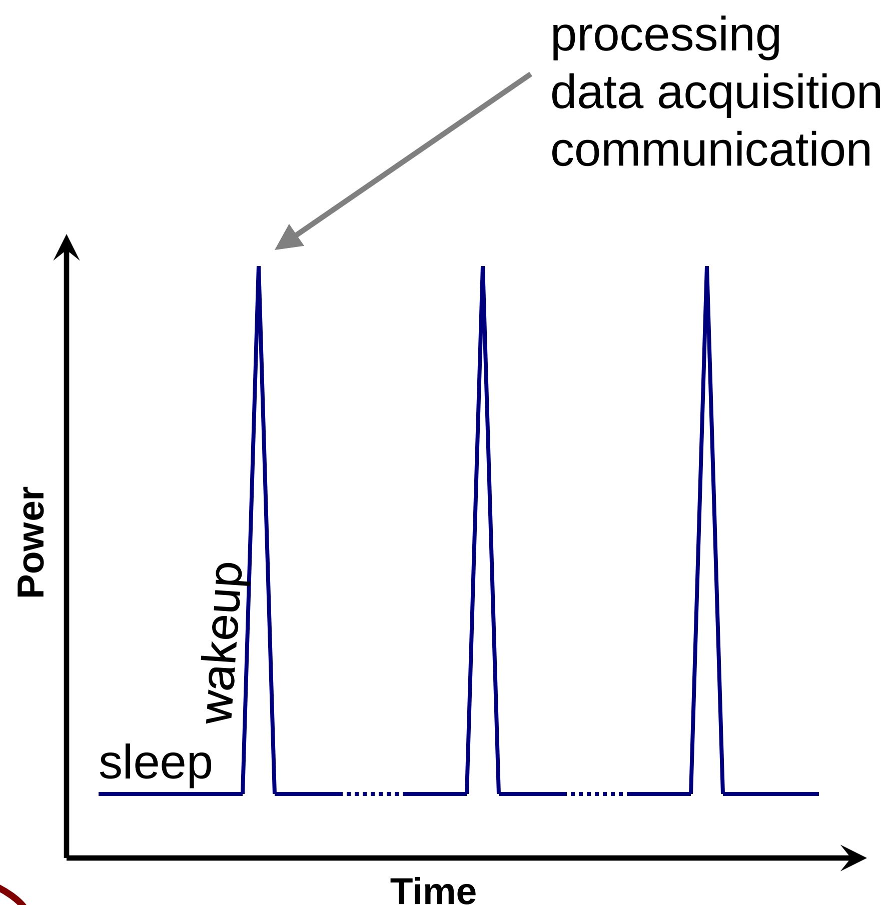
Mote Type	*WeC*	*René*	*René 2*	*Dot*	*Mica*	*Mica2Dot*	*Mica 2*	*Telos*
Year	1998	1999	2000	2000	2001	2002	2002	2004
								
Microcontroller								
Type	AT90LS8535		ATmega163		ATmega128			TI MSP430
Program memory (KB)	8		16		128			60
RAM (KB)	0.5		1		4			2
Active Power (mW)	15		15		8		33	3
Sleep Power (μW)	45		45		75		75	6
Wakeup Time (μs)	1000		36		180		180	6
Nonvolatile storage								
Chip	24LC256				AT45DB041B			ST M24M01S
Connection type	I^2C				SPI			I^2C
Size (KB)	32				512			128
Communication								
Radio	TR1000				TR1000	CC1000		CC2420
Data rate (kbps)	10				40	38.4		250
Modulation type	OOK				ASK	FSK		O-QPSK
Receive Power (mW)	9				12	29		38
Transmit Power at 0dBm (mW)	36				36	42		35
Power Consumption								
Minimum Operation (V)	2.7		2.7		2.7			1.8
Total Active Power (mW)	24				27	44	89	41
Programming and Sensor Interface								
Expansion	none	51-pin	51-pin	none	51-pin	19-pin	51-pin	10-pin
Communication	IEEE 1284 (programming) and RS232 (requires additional hardware)							USB
Integrated Sensors	no	no	no	yes	no	no	no	yes

Low Power Operation

- Efficient Hardware
  - Integration and Isolation
    - Complementary functionality (DMA, USART, etc)
  - Selectable Power States (Off, Sleep, Standby)
  - Operate at low voltages and low current
    - Run to cut-off voltage of power source
- Efficient Software
  - Fine grained control of hardware
  - Utilize wireless broadcast medium
  - Aggregate

Typical WSN Application

- Periodic
  - Data Collection
  - Network Maintenance
  - *Majority of operation*
- Triggered Events
  - Detection/Notification
  - *Infrequently occurs*
    - *But… must be reported quickly and reliably*
- Long Lifetime
  - Months to Years without changing batteries
  - Power management is the key to WSN success



Design Principles

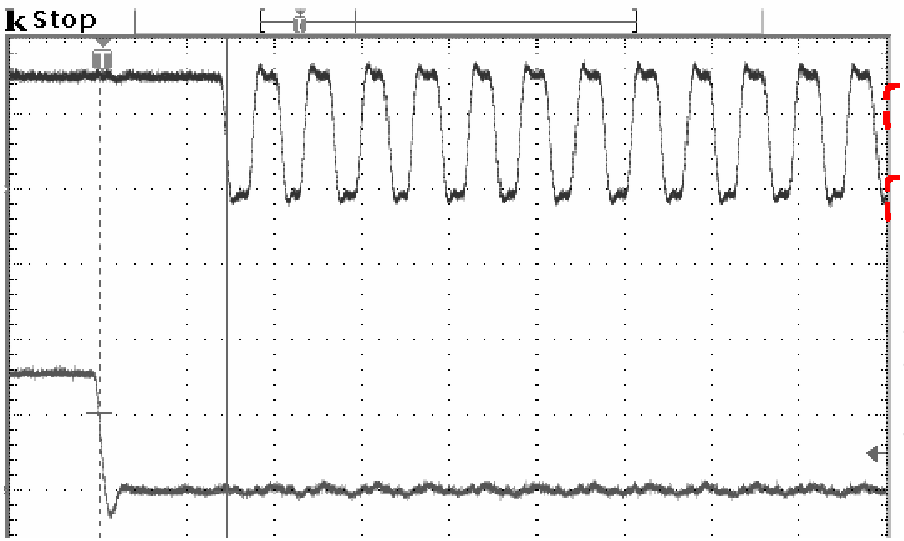
- Key to Low **Duty Cycle** Operation:
  - Sleep – majority of the time
  - Wakeup – quickly start processing
  - Active – minimize work & return to sleep

Sleep

- Majority of time, node is asleep
  - >99%
- Minimize sleep current through
  - Isolating and shutting down individual circuits
  - Using low power hardware
    - Need RAM retention
- Run auxiliary hardware components from low speed oscillators (typically 32kHz)
  - Perform ADC conversions, DMA transfers, and bus operations while microcontroller core is stopped

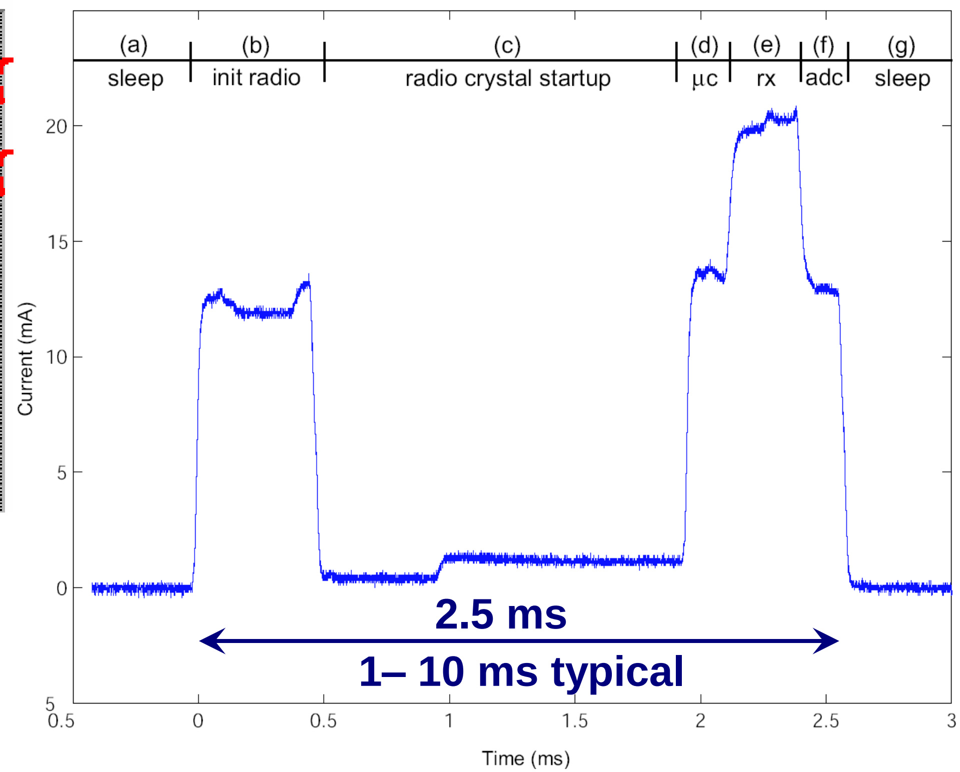
Wakeup

- Overhead of switching from Sleep to Active Mode
- Microcontroller
- Radio (FSK)



292 ns

10ns – 4ms typical



Active

- Microcontroller
  - Fast processing, low active power
  - Avoid external oscillators
- Radio
  - High data rate, low power tradeoffs
  - Narrowband radios
    - Low power, lower data rate, simple channel encoding, faster startup
  - Wideband radios
    - More robust to noise, higher power, high data rates
- External Flash (stable storage)
  - Data logging, network code reprogramming, aggregation
  - High power consumption
  - Long writes
- Radio vs. Flash
  - 250kbps radio sending 1 byte
    - Energy : 1.5μJ
    - Duration : 32μs
  - Atmel flash writing 1 byte
    - Energy : 3μJ
    - Duration : 78μs

Telos Platform

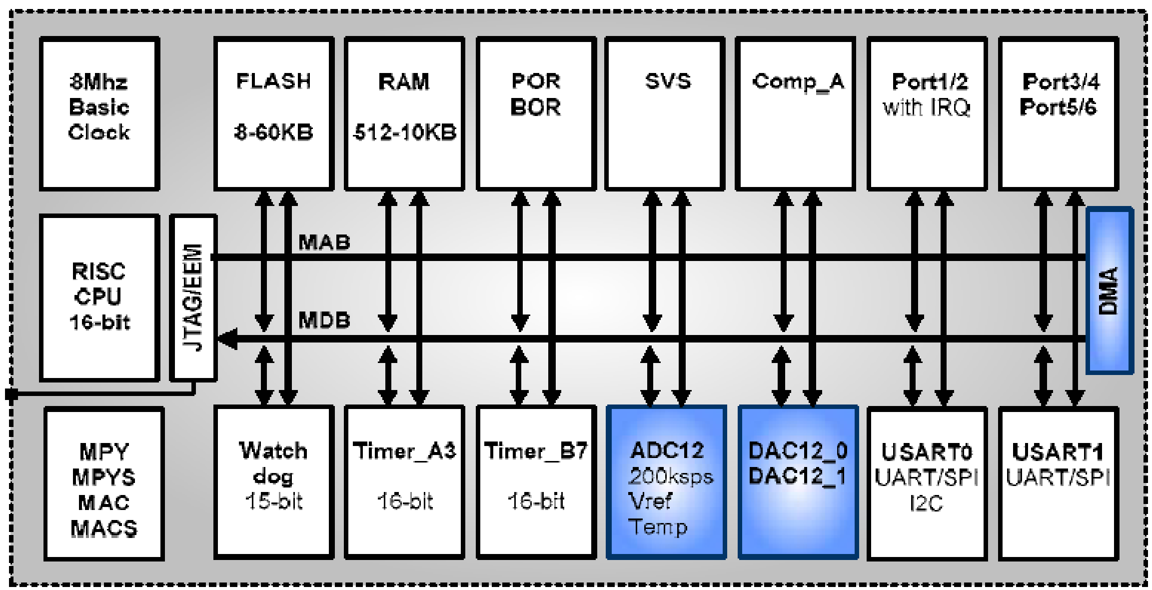
- A new platform for low power research
  - Monitoring applications:
    - Environmental
    - Building
    - Tracking
- Long lifetime, low power, low cost
- Built from application experiences and low duty cycle design principles
- Robustness
  - Integrated antenna
  - Integrated sensors
  - Soldered connections

- Standards Based
  - IEEE 802.15.4
  - USB
- IEEE 802.15.4 **ZigBee**
  - CC2420 radio
  - **Frame-based**
  - 250kbps
  - 2.4GHz ISM band
- TI MSP430
  - Ultra low power
    - 1.6μA sleep
    - 460μA active
    - 1.8V operation

Open embedded platform with open source tools, operating system (TinyOS), and designs.

Low Power Operation

- TI MSP430 -- Advantages over previous motes
  - 16-bit core
  - 12-bit ADC
    - 16 conversion store registers
    - Sequence and repeat sequence programmable
  - < 50nA port leakage (vs. 1μA for Atmels)
  - Double buffered data buses
  - Interrupt priorities
  - Calibrated DCO
- Buffers and Transistors
  - Switch on/off each sensor and component subsystem

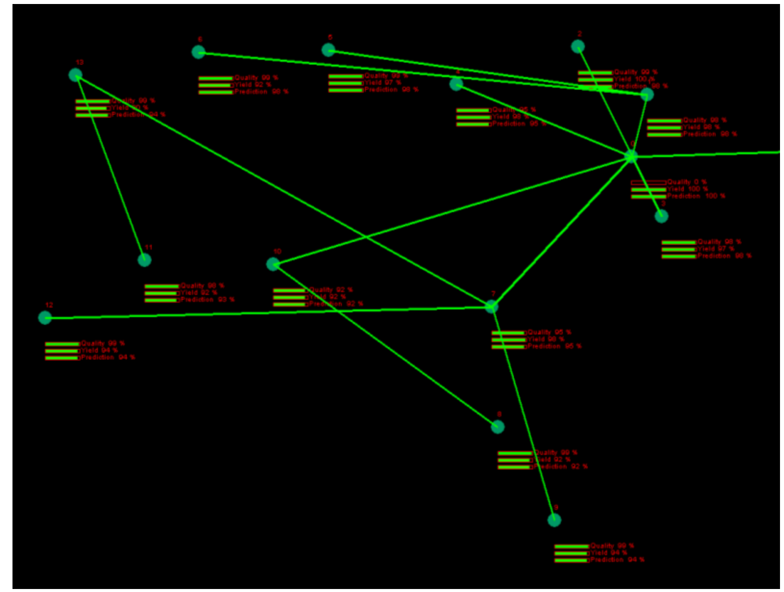


Minimize Power Consumption

- Compare to MicaZ: a Mica2 mote with AVR mcu and 802.15.4 radio
- Sleep
  - Majority of the time
  - Telos: 2.4μA
  - MicaZ: 30μA
- Wakeup
  - As quickly as possible to process and return to sleep
  - Telos: 290ns typical, 6μs max
  - MicaZ: 60μs max internal oscillator, 4ms external
- Active
  - Get your work done and get back to sleep
  - Telos: 4-8MHz 16-bit
  - MicaZ: 8MHz 8-bit

CC2420 Radio

IEEE 802.15.4 Compliant



- CC2420
  - Fast data rate, robust signal
    - 250kbps : 2Mchip/s : DSSS
    - 2.4GHz : Offset QPSK : 5MHz
    - 16 channels in 802.15.4
    - -94dBm sensitivity
  - Low Voltage Operation
    - 1.8V minimum supply
  - Software Assistance for Low Power Microcontrollers
    - 128byte TX/RX buffers for full packet support
    - Automatic address decoding and automatic acknowledgements
    - Hardware encryption/authentication
    - Link quality indicator (assist software link estimation)
      - samples error rate of first 8 chips of packet (8 chips/bit)

Power Calculation Comparison

Design for low power

- Mica2 (AVR)
  - 0.2 ms wakeup
  - 30 μW sleep
  - 33 mW active
  - 21 mW radio
  - 19 kbps
  - 2.5V min
    - 2/3 of AA capacity
- MicaZ (AVR)
  - 0.2 ms wakeup
  - 30 μW sleep
  - 33 mW active
  - 45 mW radio
  - 250 kbps
  - 2.5V min
    - 2/3 of AA capacity
- Telos (TI MSP)
  - 0.006 ms wakeup
  - 2 μW sleep
  - 3 mW active
  - 45 mW radio
  - 250 kbps
  - 1.8V min
    - 8/8 of AA capacity

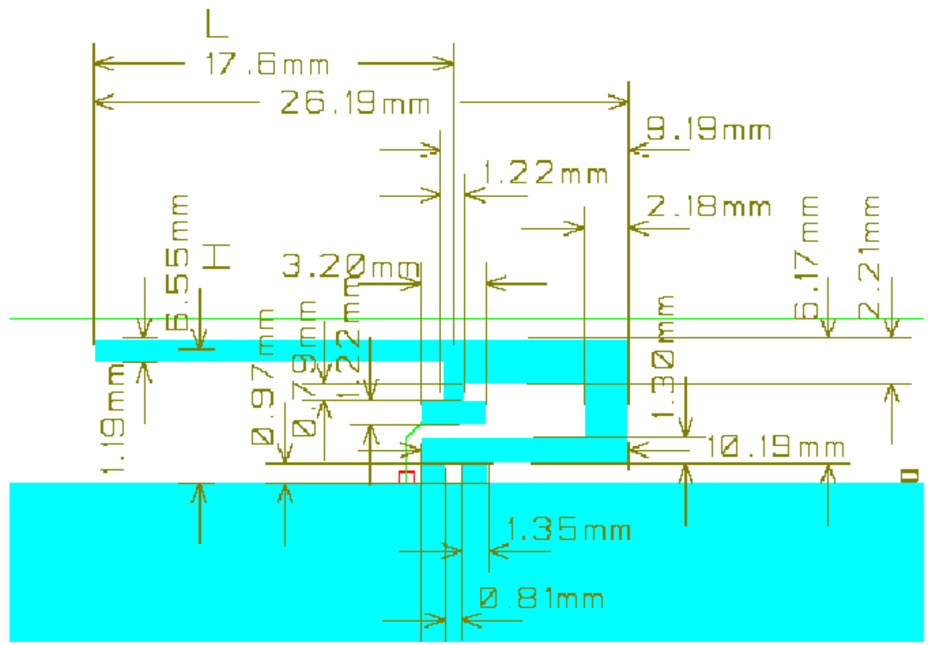
Supporting mesh networking with a pair of AA batteries reporting data once every 3 minutes using synchronization (<1% duty cycle)

453 days	328 days	945 days

Integrated Antenna

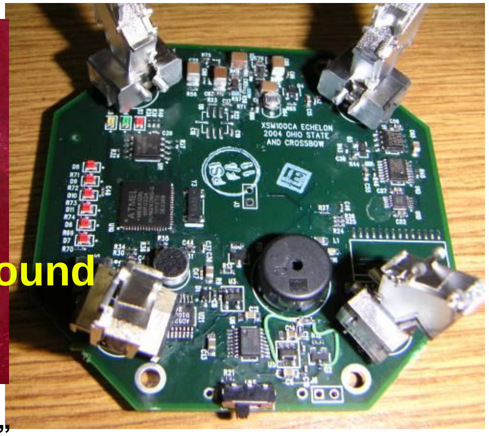
Inverted-F Microstrip Antenna and SMA Connector

- Inverted-F
  - Psuedo Omnidirectional
  - 50m range indoors
  - 125m range outdoors
  - Optimum at 2400-2460MHz
- SMA Connector
  - Enabled by moving a capacitor
  - > 125m range
  - Optimum at 2430-2483MHz



Sensors

- Integrated Sensors
  - Sensirion SHT11
    - Humidity (3.5%)
    - Temperature (0.5°C)
    - Digital sensor
  - Hamamatsu S1087
    - Photosynthetically active light
    - Silicon diode
  - Hamamatsu S1337-BQ
    - Total solar light
    - Silicon diode
- Expansion
  - 6 ADC channels
  - 4 digital I/O
  - Existing sensor boards
    - Magnetometer
    - Ultrasound
    - Accelerometer
    - 4 PIR sensors
    - Microphone
    - Buzzer



Conclusions

- New design approach derived from our experience with resource constrained wireless sensor networks
  - Active mode needs to run quickly to completion
  - Wakeup time is crucial for low power operation
    - Wakeup time and sleep current set the minimal energy consumption for an application
  - Sleep most of the time
- Tradeoffs between complexity/robustness and low power radios
- Careful integration of hardware and peripherals