Wireless Embedded Systems and Networking

Foundations of IP-based Ubiquitous Sensor Networks

WSN Technology and Hardware Architectures

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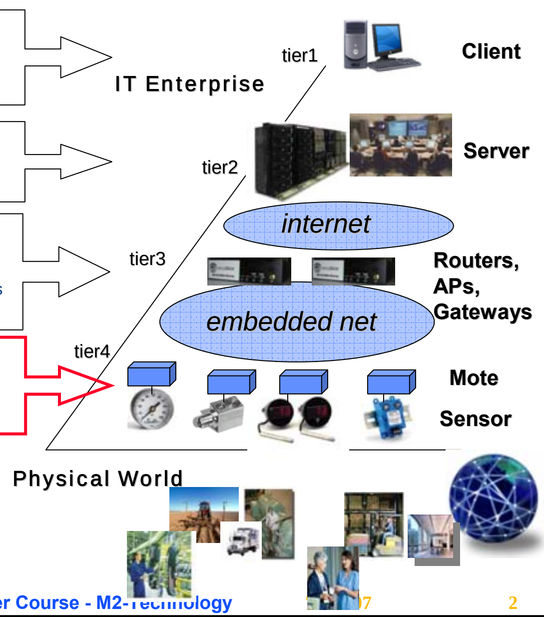
Technology Perspective

Client Tier: (desk,lap,PDA,phone)
- Interactivity, Human Interface, Form Factor, Ergonomics, Diversity of usage

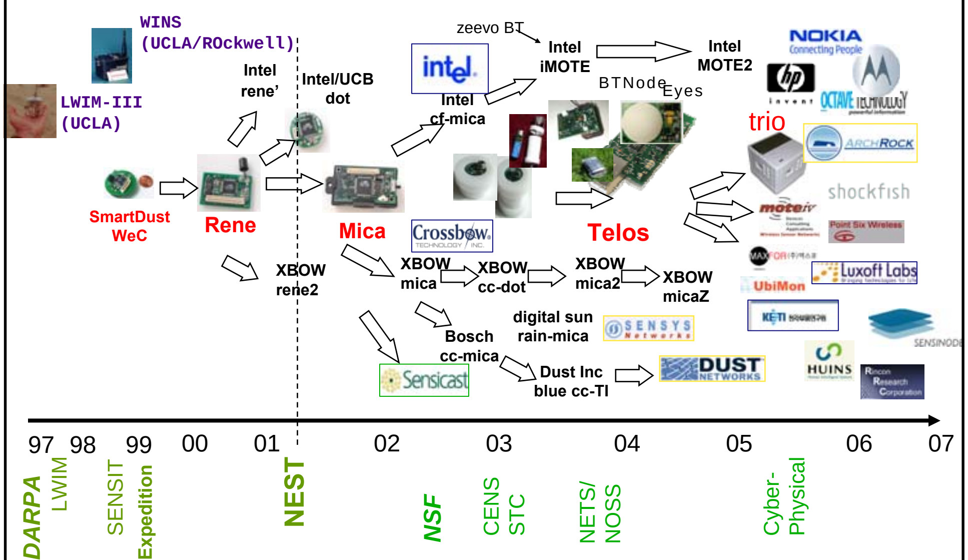
Server Tier:
- Massive compute, storage, bandwidth
- Scalability, reliability, redundancy

Router/Gateway Tier:
- Bridging: 802.15.4 ←→ (802.11, 802.3, GPRS)
- Routing: Embedded IP and IPv6/IPv4
- Caching, Transcoding, Logging, Gateway adapters
- Packet Processing

Embedded Tier: (mote)
- Low-power, cost-effective, robust embedded devices. Digital and analog interfaces, converters.
- Self-organized network communication



The Mote Lineage …



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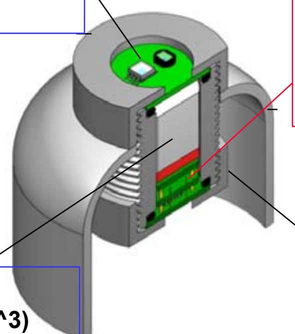
Anatomy of a Mote

Sensors/actuators*
- **MEMs – Silicon/CMOS**
- **Mechanical/Magnetic/Electrical**
- **Chemical**
- **Biological**

Processing & Storage
- **1M transistors < 1mm^2**
- **mwatt active, uwatt passive power**

Communication
- **Low bit rate**
- **Short distance**
- **CMOS RF/DSP**
- **Low power – ~10mwatt**

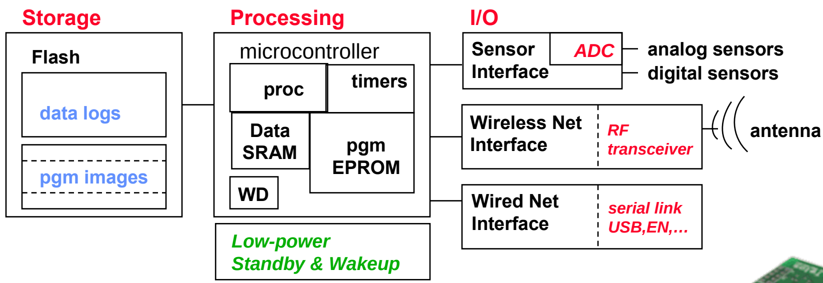


* Application Specific

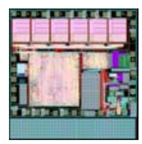
Power*
- **Batteries (10mw*day/cm^3)**
- **Fuel cells (100mw*day/cm^3)**
- **Scavenging**
  - **Solar (10mw/cm^2 outside)**
  - **Vibration (~1 uw/gm)**
  - **Flow**

Mechanical Design*
- **Enclosure**
- **Attachment**
- **Shielding & Exposure**

Architecture of a Mote



- Efficient wireless protocol *primitives*
- Flexible sensor interface
- Ultra-low power standby
- Very Fast wakeup
- Watchdog and Monitoring
- Data SRAM is critical limiting resource



System Architecture Directions for Networked Sensors, Hill,. Szewcyk, Woo, Culler, Hollar, Pister, ASPLOS 2000

Hands-on Examples

What we mean by "Low Power"

- **2 AA => 1.5 amp hours (~4 watt hours)**
- **Cell => 1 amp hour (3.5 watt hours)**

Cell: 500 -1000 mW => few hours active
WiFi: 300 - 500 mW => several hours
GPS: 50 – 100 mW => couple days

WSN: 50 mW active, 20 uW passive
450 uW => one year
45 uW => ~10 years

Ave Power = $f_{act} * P_{act} + f_{sleep} * P_{sleep} + f_{waking} * P_{waking}$

* System design
* Leakage (~RAM)
* Nobody fools mother nature

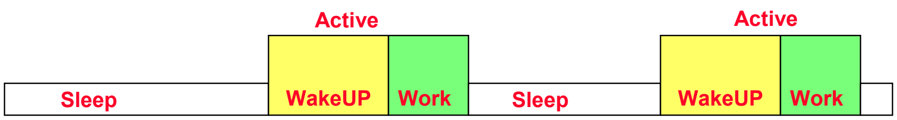
Mote Platform Summary

Mote Type / Year	*WeC* 1998	*René* 1999	*René 2* 2000	*Dot* 2000	*Mica* 2001	*Mica2Dot* * 2002	*Mica 2* * 2002	*Telos* 2004
								
Microcontroller								
Type	AT90LS8535		ATmega163		ATmega128			TI MSP430
Program memory (KB)	8		16		128			48
RAM (KB)	0.5		1		4			10
Active Power (mW)	15		15		15		60	0.5
Sleep Power (W)	45		45		75		75	2
Wakeup Time (s)	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	38.5
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

* Crossbow variation

*** Newer options discussed later

Power: Model of operation



- Sleep – Active [Wakeup / Work]
- Peak Power
  - Essentially sum of subsystem components
  - MW in supercomputer, kW in server, Watts in PDA
  - milliwatts in "mote" class device
- Sleep power
  - Minimal running components + leakage
  - Microwatts in mote-class
- Average power
  - $P_{ave} = = (1-f_{active})*P_{sleep} + f_{active}*P_{active}$ (Duty Cycle: f_{active})
  - $P_{ave} = f_{sleep}*P_{sleep} + f_{wakeup}*P_{wakeup} + f_{work}*P_{work}$
- Lifetime
  - EnergyStore / (P_{ave} - P_{gen})

Initial 802.15.4 Mote Platforms

- Focused on low power
- **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
- **Process**
  - Get your work done and get back to sleep
  - Telos: 4MHz 16-bit
  - MicaZ: 8MHz 8-bit
- **TI MSP430**
  - Ultra low power
    - » 1.6µA sleep
    - » 460µA active
    - » 1.8V operation

- **Standards Based**
  - IEEE 802.15.4, USB
- **IEEE 802.15.4**
  - CC2420 radio
  - 250kbps
  - 2.4GHz ISM band
- **TinyOS support**
  - New suite of radio stacks
  - Pushing hardware abstraction
  - Must conform to std link
- **Ease of development and Test**
  - Program over USB
  - Std connector header
- **Interoperability**
  - Telos / MicaZ / ChipCon dev

UCB Telos

Xbow MicaZ

Microcontrollers

- Memory starved
  - Far from Amdahl-Case 3M rule
  - 2005 => 4x improvement
- Fairly uniform active inst per nJ
  - Faster MCUs generally a bit better
  - Improving with feature size
- Min operating voltage
  - 1.8 volts => most of battery energy
  - 2.7 volts => lose half of battery energy
- Standby power
  - Recently a 10x improvement
  - Probably due to design focus
  - Fundamentally SRAM leakage
  - Wake-up time is key
- Trade sleep power for wake-up time
  - Memory restore
- DMA Support
  - permits ADC sampling while processor is sleeping

Manufacturer	Device	RAM (kB)	Flash (kB)	Active (mA)	Sleep (μA)	Release
Atmel	AT90LS8535	0.5	8	5	15	1998
	Mega128	4	128	8	20	2001
	Mega165/325/645	4	64	2.5	2	2004
General Instruments	PIC	0.025	0.5	19	1	1975
Microchip	PIC Modem	4	128	2.2	1	2002
Intel	4004	0.625	4	??	??	1971
	8051 Classic	0.5	32	30	5	1995
	8051 16-bit	1	16	45	10	1996
Philips	80C51 16-bit	2	60	15	3	2000
Motorola	HC05	0.5	32	6.6	90	1988
	HC08	2	32	8	100	1993
	HCS08	4	60	6.5	1	2003
Texas Instruments	TSS400 4-bit	0.03	1	15	??	1974
	MSP430F14x 16-bit	2	60	1.5	1	2000
	MSP430F16x 16-bit	10	48	2	1	2004
Atmel	AT91 ARM Thumb	256	1024	38	160	2004
Intel	XScale PXA27X	256	N/A	39	574	2004

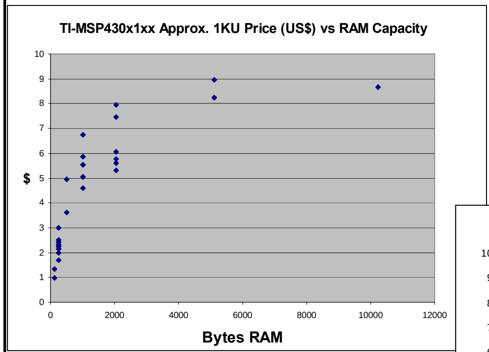
2004: Microcontroller market responded substantially to WSN requirements

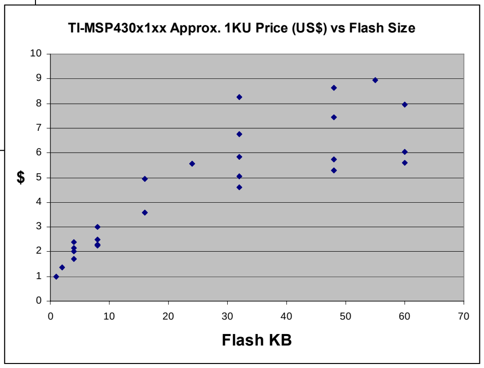
2005/6: Radio integration

2006/7: Proliferation and solidification

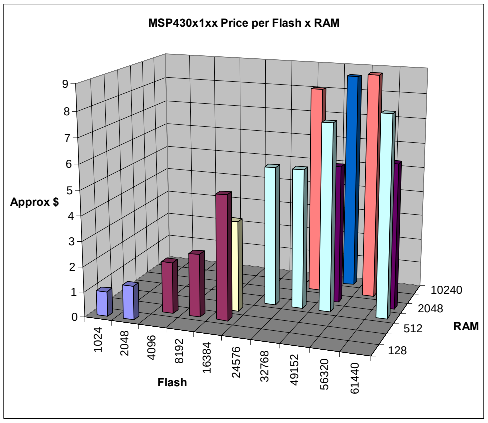
? - Complete SoC

Critical Memory Footprint





Memory Footprint continued



- Regression
  - RAM: $0.397 per kB
  - FLASH: $0.074 per kB
- Compare with standard SRAM/DRAM
  - 1M SRAM: $0.002 per kB
  - 256M DRAM ~ 10^{-5} per kB

Radio

Type	Narrowband				Wideband		
Vendor Part no.	RFM TR1000	Chipcon CC1000	Chipcon CC2400	Nordic nRF2401	Chipcon CC2420	Motorola MC13191/92	Zeevo ZV4002
Max Data rate (kbps)	115.2	76.8	1000	1000	250	250	723.2
RX power (mA)	3.8	9.6	24	18 (25)	19.7	37(42)	65
TX power (mA/dBm)	12 / 1.5	16.5 / 10	19 / 0	13 / 0	17.4 / 0	34(30)/ 0	65 / 0
Powerdown power (μA)	1	1	1.5	0.4	1	1	140
Turn on time (ms)	0.02	2	1.13	3	0.58	20	*
Modulation	OOK/ASK	FSK	FSK,GFSK	GFSK	DSSS-O-QPSK	DSSS-O-QPSK	FHSS-GFSK
Packet detection	no	no	programmable	yes	yes	yes	yes
Address decoding	no	no	no	yes	yes	yes	yes
Encryption support	no	no	no	no	128-bit AES	no	128-bit SC
Error detection	no	no	yes	yes	yes	yes	yes
Error correction	no	no	no	no	yes	yes	yes
Acknowledgments	no	no	no	no	yes	yes	yes
Interface	bit	byte	packet/byte	packet/byte	packet/byte	packet/byte	packet
Buffering (bytes)	no	1	32	16	128	133	yes *
Time-sync	bit	SFD/byte	SFD/packet	packet	SFD	SFD	Bluetooth
Localization	RSSI	RSSI	RSSI	no	RSSI/LQI	RSSI/LQI	RSSI

* Manufacturer's documentation does not include additional information.

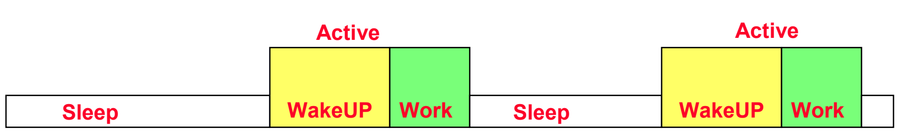
- Trade-offs:
  - resilience / performance => slow wake up
  - Wakeup vs interface level
  - Ability to optimize vs dedicated support

CMOS Radios

- CMOS radios now widely available
  - 1 mW transmit power
  - Consume 10s mW transmitting, receiving, or listening
  - Nominal range 10's of meters
    - » Power grows as R^3 or worse
- Substantial improvements in link coding
  - On/Off => Amplitude Shift => Frequency Shift narrow band => Frequency tunable spread spectrum (802.15.4)
- 802.15.4 radio has gained wide adoption
  - IEEE only standardizes Phy to MAC
  - Many competing higher level protocols
    - » ZIGBEE, several TinyOS Stacks, Ember, Dust, Sensicast, Millennial, … , IPv6
- Higher level hardware interfaces reduce processor load, but limit power optimizations
- Reliability must be addressed at higher levels too

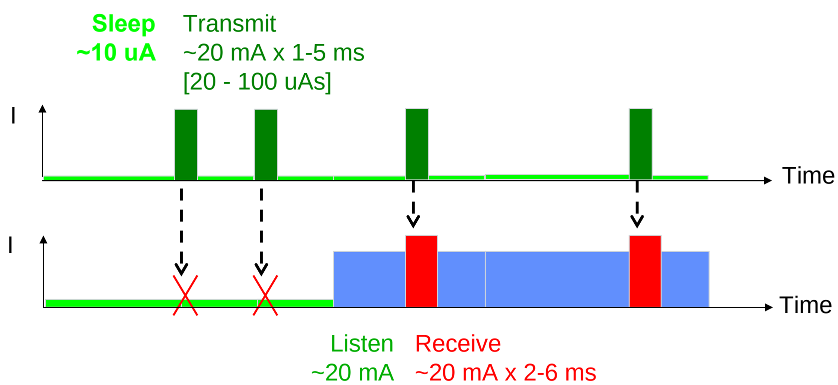
Power States at Node Level

Operation	Telos	Mica2	MicaZ
Minimum Voltage	1.8V	2.7V	2.7V
Module Standby	5.1 μA	19.0 μA	27.0 μA
MCU Idle	54.5 μA	3.2 mA	3.2 mA
MCU Active	1.8 mA	8.0 mA	8.0 mA
MCU + Radio RX	21.8 mA	15.1 mA	23.3 mA
MCU + Radio TX (0dBm)	19.5 mA	25.4 mA	21.0 mA
MCU + Flash Read	4.1 mA	9.4 mA	9.4 mA
MCU + Flash Write	15.1 mA	21.6 mA	21.6 mA
MCU Wakeup	6 μs	180 μs	180 μs
Radio Wakeup	580 μs	1800 μs	860 μs

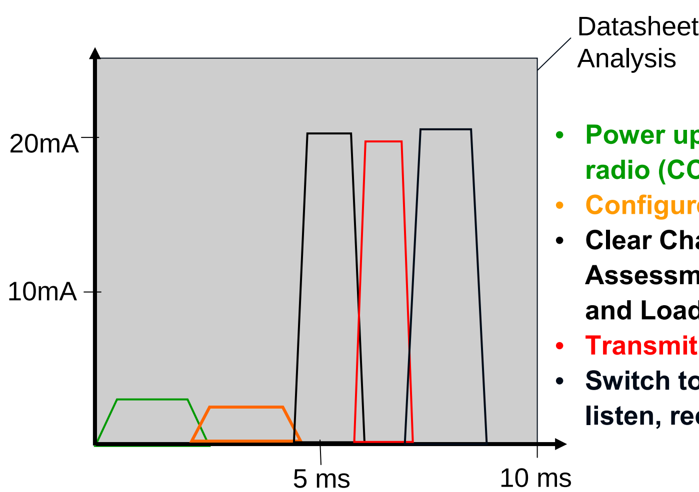


Telos: Enabling Ultra-Low Power Wireless Research, Polastre, Szewczyk, Culler, *IPSN/SPOTS 2005*

Communication Power Consumption

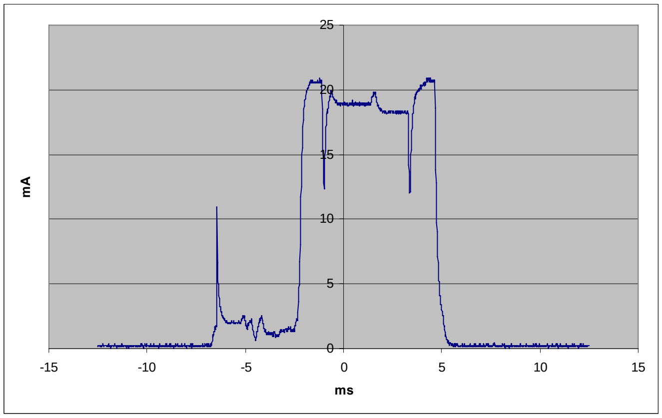


Energy Profile of a Transmission



- **Power up oscillator & radio (CC2420)**
- **Configure radio**
- **Clear Channel Assessment, Encrypt and Load TX buffer**
- **Transmit packet**
- **Switch to rcv mode, listen, receive ACK**

Example: TX maximum packet



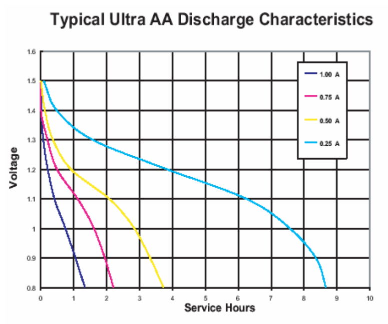
The "Idle Listening" Problem

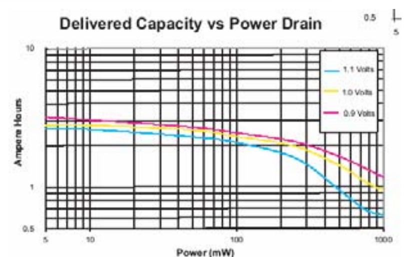
- The power consumption of "short range" (i.e., low-power) wireless communications devices is roughly the same whether the radio is transmitting, receiving, or simply ON, "listening" for potential reception
  - includes IEEE 802.15.4, Zwave, Bluetooth, and the many variants
  - WiFi too!
  - Circuit power dominated by core, rather than large amplifiers
- Radio must be ON (listening) in order receive anything.
  - Transmission is infrequent. Reception α Transmit x Density
  - Listening (potentially) happens all the time

⇒Total energy consumption dominated by *idle listening*

Energy Sources

- Batteries still the best energy store
  - Voltage
  - Source current
  - Leakage
  - Voltage profile
  - Recharge
- SuperCaps have improved dramatically
  - High leakage
- Power-harvesting
  - Nearby AC
  - Solar
  - Vibration
  - Mechanical
- Introduces new control loop on the node





Sensors

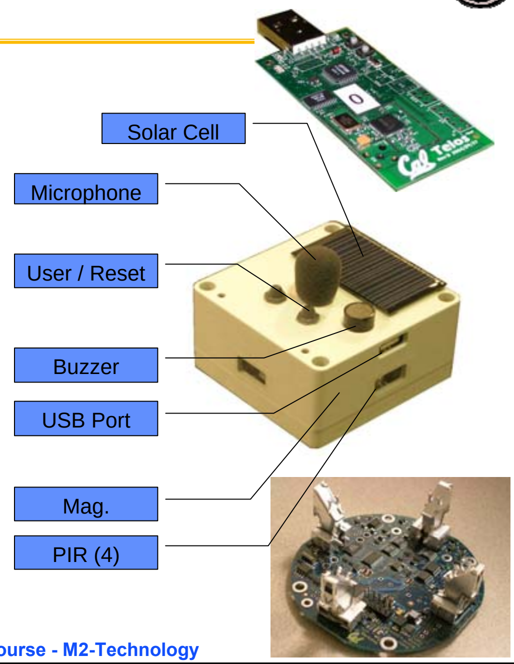
- Wide array of low-power micro sensors available
  - Temp, Light, Humidity, Acceleration, Mag, Pressure, …
- Several digital interfaces
  - RS232, SPI, I2C, …
- Too many analog interfaces
- Conventional external sensor very diverse
  - Excitation voltage
  - Bandpass, Op Amps, sensitivity, range, …
- In all cases, mechanical design is critical
  - Expose sensors, protect electronics

=> Hassle for node developers

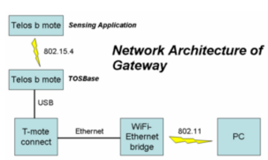
=> Vastly easier to integrate wireless (or wired) sensor modules than the sensors themselves

Trio Node

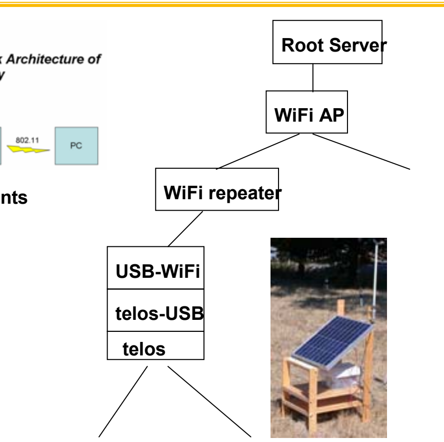
- Platform Goals
  - Permanent deployment
  - Weather resistance
  - Research-friendly
- Features
  - Telos (MCU, radio, flash)
  - Rich sensor-board
    - » Solar Harvesting
    - » Passive Infrared
    - » Microphone
    - » Magnetometer
    - » Grenade Timer
- Improved Usability
  - Pushbuttons
  - Integrated Antenna
  - Exposed USB Connector



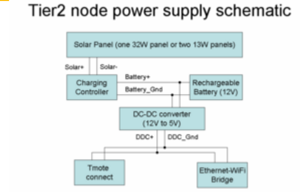
Self-powered MultiTier Network



COTS components



Tier2 node power supply schematic



The New Power Point

- Microcontrollers:
  - 1-10 mW active, 1 uW passive => 10-100 uW average
- Micro-sensors (MEMS, Materials, Circuits)
  - acceleration, vibration, gyroscope, tilt, magnetic, heat, motion, pressure, temp, light, moisture, humidity, barometric
  - chemical (CO, CO2, radon), biological, microradar, ...
  - actuators too (mirrors, motors, smart surfaces, micro-robots)
- Micro-Radios
  - CMOS, short range (10 m), low bit-rate (200 kbps), 10 mW
- Micro-Power
  - Batteries: 1,000 mW*s/mm^3, fuel cells
  - solar (10 mW/cm^2, 0.1 mW indoors), vibration (~uW/gm), flow
- 1 cm^3 battery => 1 year at 1 msgs/sec

Passive Vigilance

- Sense only when there is something useful to detect
- Listen only when there is something useful to hear
- How do you know?
  - By arrangement
  - By cascade of lower power triggers

Trends and issues

- 2006-7 integrate 802.15.4 radio with microcontroller
  - 8051 or XAP2 1-address arch. with poor compilers
- Rapid migration of RISC cores
  - ARM and XSCALE moving down
- Improved system support

- Microcontrolller + Radio + Flash is universal
- Sensor suite, power subsystem, mechanical design are application specific

⇒ Mote will be *manufactured in* to end devices and building fixtures (or materials)

⇒ Solution integrated through software

Recent Developments

- ATMEL 1281 – more data RAM
- ATMEL RF230 – more TX and RX
  - Crossbow IRIS, Meshnetics Zigbit
- CC2430 – integrated 8051
  - Sensinode
- EM250 / EM260 – integrated XAP + zigbee stack
- Jennic – 32-bit processor + MB
- ARM Cortex – 32-bit Processor

Brief Comparison

Vendor	TI	Crossbow	MeshNetics	Ember	DustNetworks
Model	CC2430	IRIS M2110CA	ZigBit ZDM-A1281	EM250	SmartMesh-XT M2030
Type	System-on-Chip	OEM module	OEM module	System-on-Chip	OEM module
Link	http://www.ti.com/lit/gpn/cc2430	http://www.xbow.com/Products/productdetails.aspx?sid=264	http://www.meshnetics.com/zigbee-products/	http://www.ember.com/pdf/EM250/120-0082-000H_EM250_Datasheet.pdf	http://www.dustnetworks.com/docs/M2030.pdf
Micro Controller	8051 core integrated in CC2430	Atmega 1281	Atmega1281	Integrated 16-bt XAP2b MCU	Integrated
Program Memory (KB)	32/64/128	128	128	128	
SRAM (KB)	8	8	8	5	
Nominal Voltage (V)	3	3	3	1.8	3
MCU Active current (mA)	9.5	8	14	8.5	
MCU Active RX current (mA)	26.7	24	19	35.5	22
MCU Active TX current (mA)	26.9 (at 0 dBm)	25 (at 3 dBm)	18 (at 0 dBm)	35.5 (at 0 dBm)	20 (at -2 dBm)
Numer of power saving modes	3	1	1	1	2
Power mode 1 (uA)	190	8 (sleep mode)	6 (power save mode)	1 (deep sleep)	51 (low power networking)
Power mode 2 (uA)	0.5				10 (sleep)
Power mode 3 (uA)	0.3				
Number of timers	4	6	6	3	
Granularity of timers	one general 16-bit timer	four general 16-bit timers	four general 16-bit timers	two 16-bit general timer	
	two general 8-bit timers	two general 8-bit timers	two general 8-bit timers	one 16-bit sleep timer	
	one MAC timer				
ADC					
precision (bits)	12	10	10	12	
# channels	8	8	4	4	
DMA	Yes			Yes	
Radio	CC2430	AT86RF230	AT86RF230	EM250	Integrated
Data rate (kbps)	250	250	250	250	250
Receiver Sensitivity (dBm)	-92	-101	-101	-97	-90
Current at RX (mA)	17.2	16	16	27	
Current at TX at 0dBm (mA)	17.4 (at 0 dBm)			24.3 (at 0 dBm)	
Current at minimum TX (mA)	18.3 (at -25.2 dBm)	10 (at -17 dBm)	10 (at -17 dBm)	19.5 (at -32 dBm)	
Current at maximum TX (mA)	32.4 (at 0.6 dBm)	17 (at 3 dBm)	17 (at 3 dBm)	27 (at 3 dBm)	
Any link or signal indicator	RSSI, LQI	RSSI, LQI	RSSI, LQI	RSSI, LQI	
Non standard mode					
How high in the stack	802.15.4/ZigBee	802.15.4/XMesh	802.15.4/ZigBee	802.15.4/ZigBee	802.15.4/TSMP

Discussion