Information Processing in Sensor Networks

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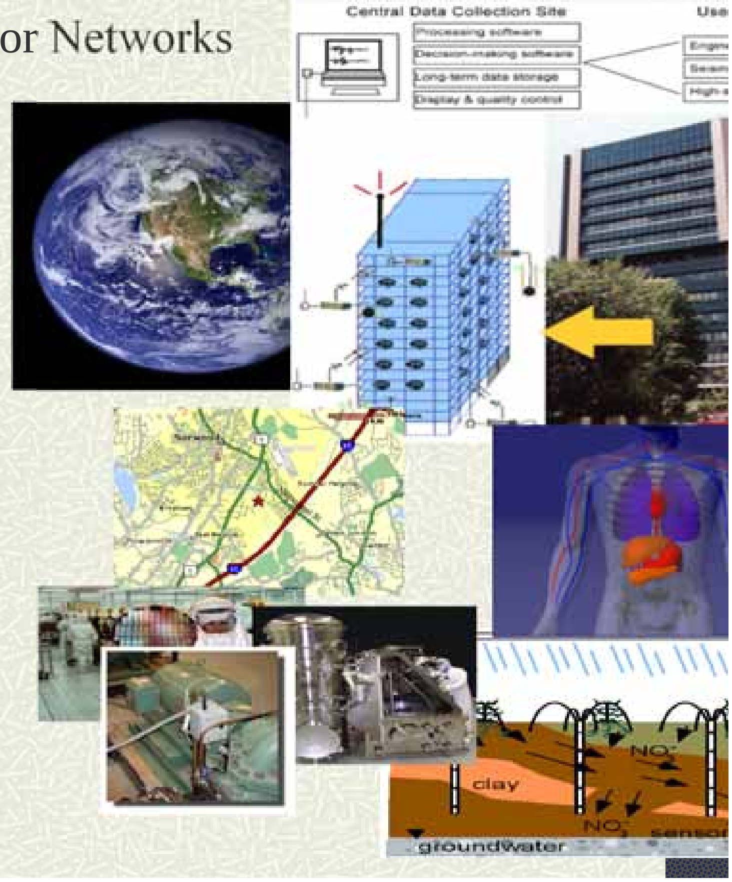
Part 1:

Introduction/Motivation and Hardware Platforms

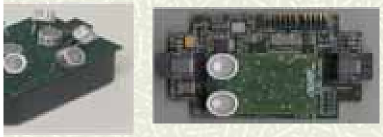
The Vision Behind Sensor Networks

- Embed numerous distributed sensor nodes to onitor and interact with physical world
- Exploit spatially and temporally dense, in situ, nsing and actuation

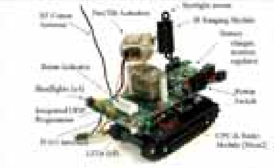
- etwork these devices so that they can ordinate to perform higher-level identification d tasks.
- ptimize and adapt runtime behavior across distributed system, taking advantage of signed in heterogeneity



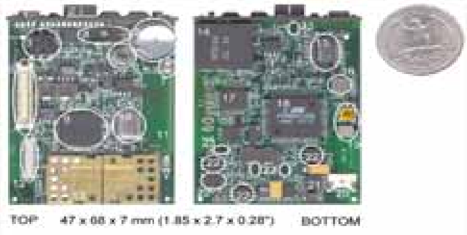
A Rich Ecology of Platforms: Static, Mobile, Flying, Wearable, Submersible…



lusa MK-2 *(UCLA)*



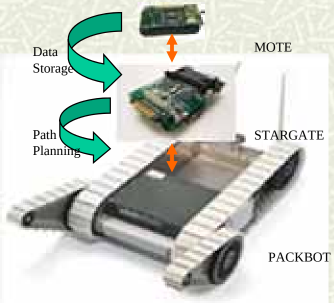
RagoBot *(UCLA)*



iBadge *(UCLA)*

otes *(UCB)*

Heliomote
(UCLA)



Data Mule
(UCLA)

Helicopter Imager
(UCLA)

StarGate
(Intel)

CHARACTERISTICS OF WSNs

- Large number of nodes (100s, and even 1000s)
- Nodes need to be close to each other – communication range
- Densities as high as 20 nodes/m3
- Asymmetric flow of information, from sensor nodes to sink
- Communications are triggered by queries or events
- Limited amount of energy (in many applications it is impossible to replace or recharge)
- Low cost*, size, and weight per node
- Prone to failures
- More use of broadcast communications instead of point-to-point
- Nodes do not have a global ID such as an IP address
- The security, both on physical and communication level, is more limited than in classical wireless networks

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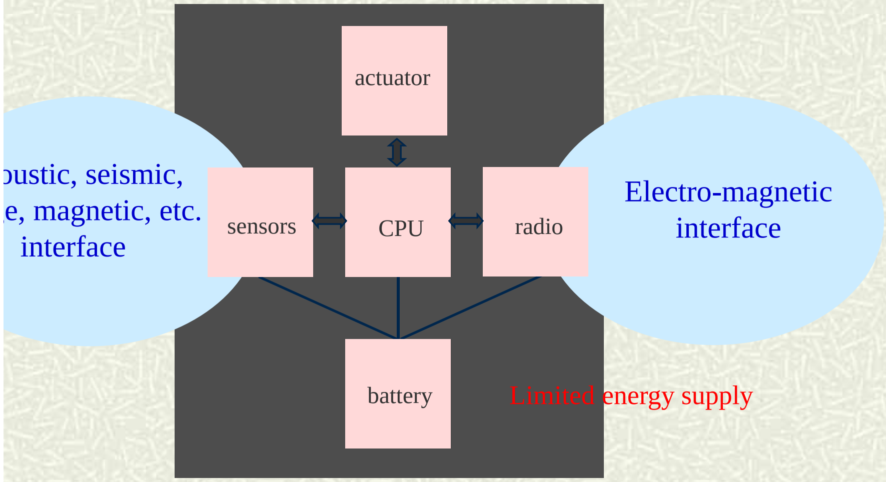
DIFFERENCES FROM AD-HOC NETWORKS

Number of sensor nodes can be several orders of magnitude higher
Sensor nodes are densely deployed and are prone to failures
The topology of a sensor network may change frequently due to node failure and node mobility
Sensor nodes are limited in power, computational capacities, and memory
May not have global ID like IP address
Need tight integration with sensing tasks

Canonical Sensor and Actuator Node



In the future, all integrated on a single chip!

Far cry from gene
purpose compute

- **CPUs**
- **8 b / 8 MHz to 32 b / 400**
- **Storage**
- **2 KB - 64 MB RAM**
- **1 MB - 1 GB Flash**
- **No disk**
- **Radio**
- **38 Kbps / 10 m - 802.11b / m**
- **Power**
- **30 mW - 3 W**

Processing System: Memory

Considerations: Speed, capacity, price, power consumption, memory protection

- SRAM: typical, 0.5KB-64MB
  - Typical power consumption
    - retained: ~100ua; read/write: ~10ma if separate chip
    - retained: 2ua-100ua, read/write:~5ma if in core
- DRAM: high power consumption in retained mode
- EEPROM:4KB-512KB, often used as program store
- Flash: 256KB-1GB or beyond
  - Typically used when SRAM power is down and for buffering data
  - Large flashes are outside of core

Sensor Subsystem

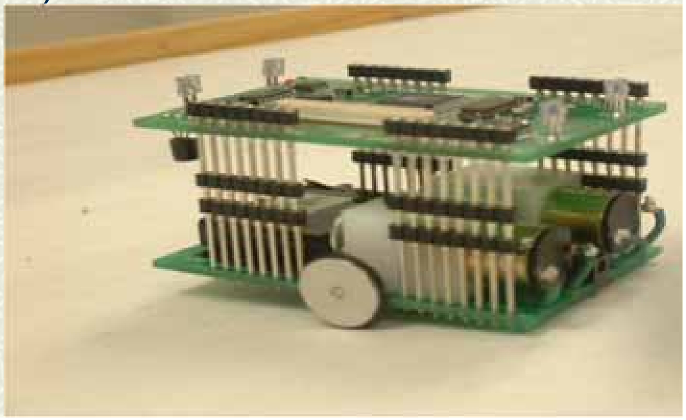
- Multiple types of sensors may be used:
    - Environmental: pressure, gas composition, humidity, light...
    - Motion or force: accelerometers, rotation, microphone, piezoresistive strain, position...
    - Electromagnetic: magnetometers, antenna, cameras...
    - Chemical/biochemical
- Digital or analog output
- Components:
    - Transducer
    - Analog signal conditioning circuits
    - Analog to digital converter (ADC)
    - Digital signal processing

Transceiver (Radio)

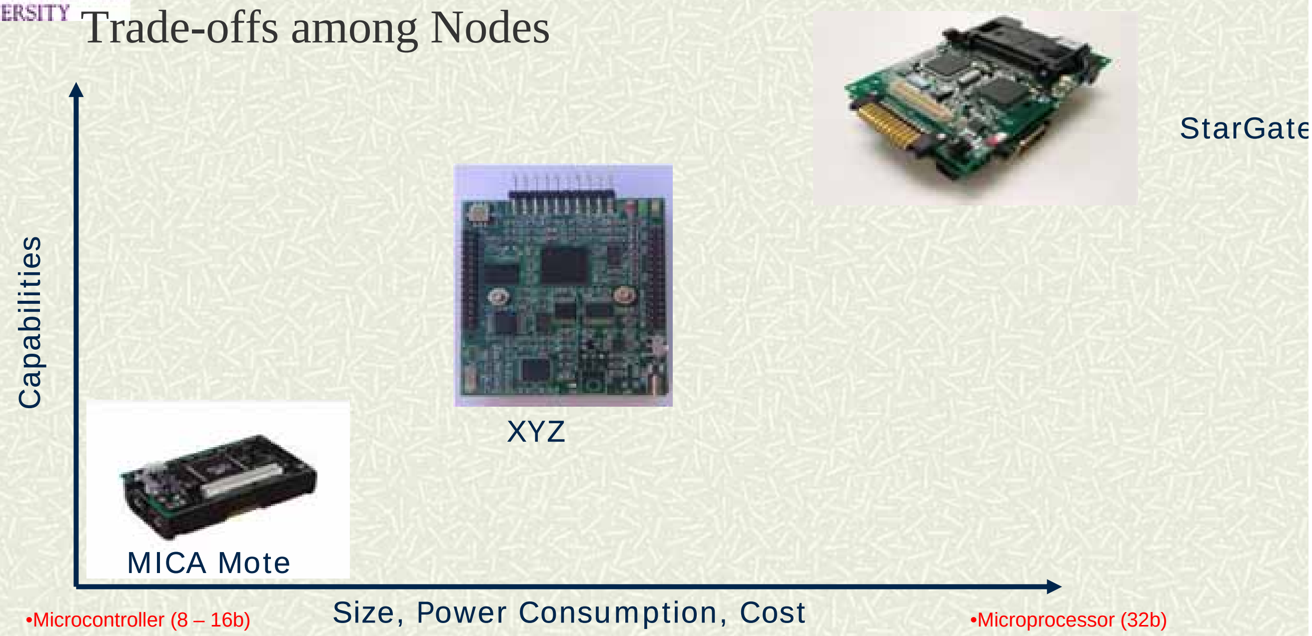
- Transceiver unit implements the procedures to convert bits to be transmitted into radio frequency (RF) waves and recovers them at other end.
    - Energy efficiency measure : the energy required to transmit or receive one bit joules/bit
    - signal propagation and interference characteristics
    - difference between receive power versus transmit power
    - antenna design issues : omnidirectional versus directed

Actuation System

- Types:
  - Leds, buzzers, motors, sliders, pumps, gears, solenoids…
- Energy consumption (idle: O(uW); active ~1-40 mW)
- Startup time (~1ms-1000ms or higher)
- Higher voltage planes and noise
- Coupling:
  - Opto-coupler for control communications, with encoders for feedback



Trade-offs among Nodes



- Microcontroller (8 – 16b)
- Narrow Band radio
- Low bit rate, low performance sensors
- *Long* relative lifetime at continuous operation

- Microprocessor (32b)
- Broad Band radio
- High performance sensors
- *Short* relative lifetime at continuous operation

Design Principles

- Key to Low Duty Cycle Operation:
  - Sleep – majority of the time
  - Wakeup – quickly start processing
  - Active – minimize work & return to sleep
  - Transceiver –when not active it is in idle state or sleep state

    Idle state—ready to receive but not currently receiving anything

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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

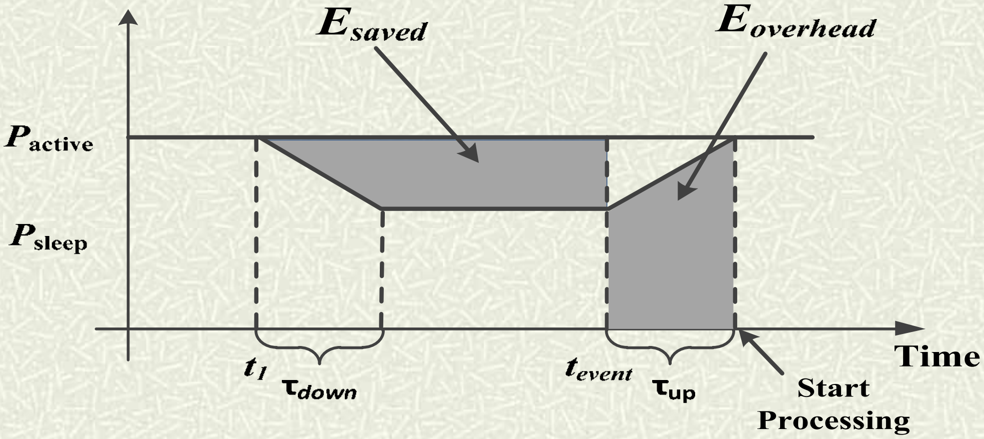
Energy Efficiency vs. Duty Cycling Efficiency

Mote
ATMega128
: CC1000

jate
PA255
): 802.11b

CPU			Radio		
Energy per computation	Sleep Power	Startup Cost	Energy per bit	Idle Power	Star Co
4 nJ/instr (8b) 31 mJ/beamform	30 uW	4 ms 7.2 uJ	430 nJ/b	7 mA	Low (~ 10 m
↑ 1.1 nJ/instr (32b) 1 mJ/beamform	↓ 20 mW	↓ 10.6 ms 4.17 mJ	↑ 90 nJ/b	↓ 160 mA	↓ High (~ 10 s)

Energy Savings and Overheads for Sleep Modes



If component remains active, energy spent for uselessly idling is:

$$E_{active} = P_{active}(t_{event} - t_1)$$

utting the component into sleep mode requires power consumption $(P_{active}+P_{sleep})/2$ and P_{sleep}
s consumed until t_{event} , then energy spent is:

$$\tau_{down}(P_{active} + P_{sleep})/2 + (t_{event} - t_1 - \tau_{down})P_{sleep}$$

Energy Savings and Overheads for Sleep Modes

nergy saving:

$$_{saved} = P_{active}(t_{event} - t_1) - (\tau_{down}(P_{active} + P_{sleep})/2 + (t_{event} - t_1 - \tau_{down})P_{s}$$

dditional overhead required to activate the component:

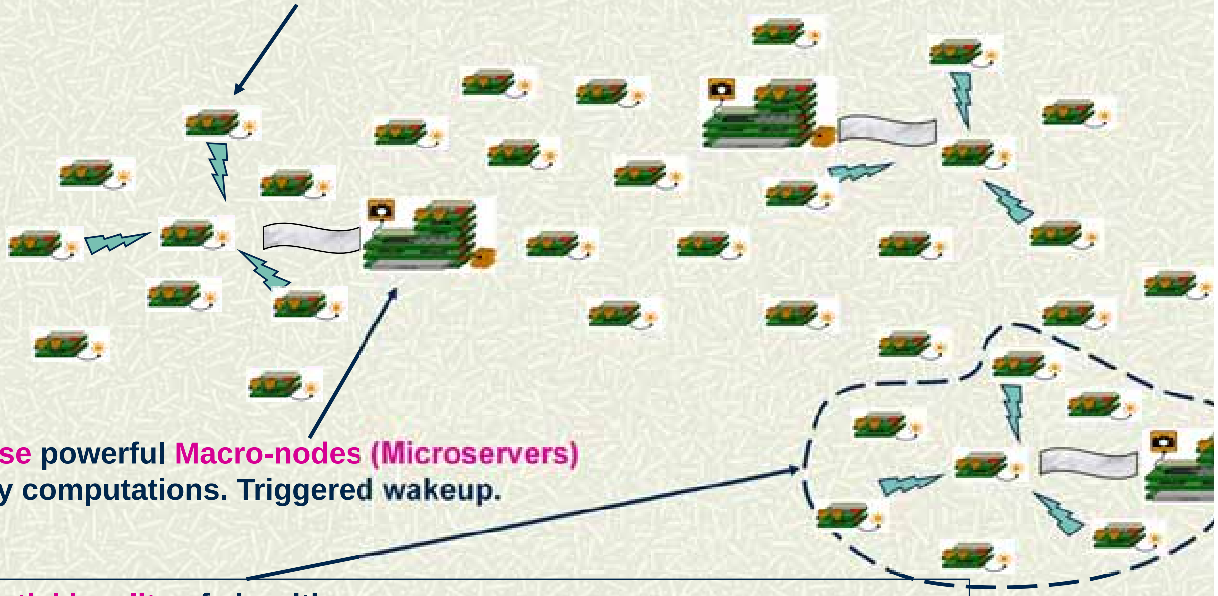
$$E_{overhead} = \tau_{up}(P_{active} + P_{sleep})/2$$

utting component into sleep mode is only beneficial if

$$_{overhead} < E_{saved}$$

$$(t_{event} - t_1) > \frac{1}{2}(\tau_{down} + \frac{P_{active} + P_{sleep}}{P_{active} - P_{sleep}}\tau_{up})$$

Tiered Architectures for Increased Lifetime: Mote Herds with Microserver Shepherds



Dense resource constrained Micro-nodes (Tripwires or Sentries)
Low duty cycle tasks. Mostly vigilant.

Sparse powerful Macro-nodes (Microservers)
Bulky computations. Triggered wakeup.

xploit spatial locality of algorithms
ne grained coverage, higher performance and lower power

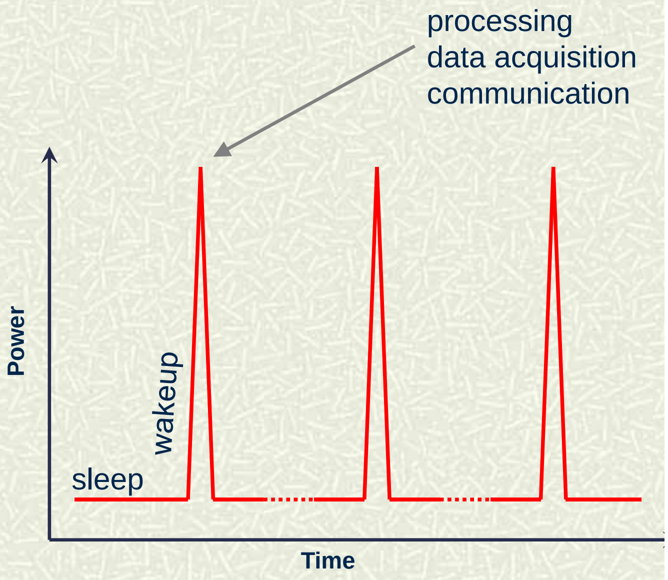
Diversity of Application Characteristics

	Seismology	Ecology	Battlefield
Sampling Rate	KHz	< Hz	KHz
Sampling Density	Km	Meters	Meters
Sample resolution	24 bit	8 bit	8 bit
Spatial Extent	100 Km^2	1 Km^2	10 Km^2
Estimation Fidelity	High	High	High
Latency	Minutes-Days	Hours-Months	Seconds
Lifetime	Months	Years	Weeks
Access Cost	Medium	Medium	High
Platform Cost	High	Medium \High	High
Platform mobility	No	Yes	Yes
Where is the answer needed?	Centrally	Centrally	Distributed
Nature of Task	Source	Field	Source

..Are there reusable architectures, platforms, design tools, run-time services, estimation algorithms etc.?

Typical Sensing 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 success
- Design principles
  - Sleep: majority of the time (>99%)
    - Need to optimize for this!
  - Wakeup: quickly start processing
  - Active: minimize work & return to sleep

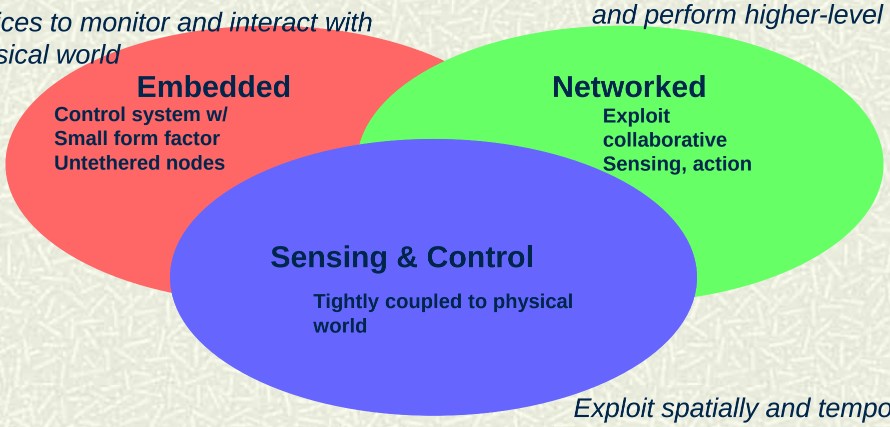


From Polastre et. al.at Hot Chips 2004

Multidisciplinary Challenges

Embed numerous distributed devices to monitor and interact with physical world

Network devices to coordinate and perform higher-level tasks



Embedded

Control system w/
Small form factor
Untethered nodes

Networked

Exploit
collaborative
Sensing, action

Sensing & Control

Tightly coupled to physical world

Exploit spatially and temporally dense, in situ, sensing and actuation

- Large-scale
- Distributed
- Real-time (control, events)
- Physically-coupled

- Unattended
- Resource-constrained
- Wireless
- Collaborative computations

Combines the hard problems of the Internet, Embedded Systems, Wireless Networks, and Distributed Computing!

Touch of history

- 3 Platform Perspectives
  - WINS – estimation theory
  - SmartDust – analog design, chip technology
  - Mica - systems
- WINS vision
  - bi-part architecture for passive vigilance
- PicoRadio
  - Incorporate programmable logic for protocol processing, as well as signal processing
- Smart Dust
  - Really serious about energy limits
  - Simple, un-partitioned architecture
- Berkeley TinyOS motes take off
- Mica
  - accelerate primitives not solutions
  - Rich interfaces and flexible composition for cross-layer optimization

Emergences of WINS

1994 Pottie and Kaiser propose Low Power Wireless Integrated Microsensor
- LWIM nodes built around 1996

DARPA Sensit Program

Late 97-98 handhelds emerge
- palm
- ITSY, BWRC PicoRadio, Srivastava UCLA, Chandrakasan MIT, …
- Matchbox PCs
- Bluetooth promised

Berkeley SmartDust
- 1999 WeC mote offshoot

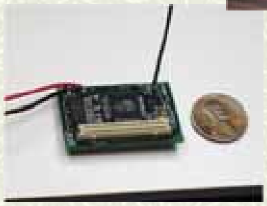
SCADDS (USC/UCLA) pc104s & tags

00 Mote / TinyOS platforms

WINS ng finally appears in Linux for Sensit

02 Mica NEST OEP creates de facto platform

03 Bluetooth revival



WINS case for distributed sensor nets

- **Must distribute to detect reliably regardless of $**
  - **All signals decay with distance (r^2) + absorption, scattering, dispersion, …even with line of sight**
  - **Often need to track multiple objects**
  - **Obstructions, clustering**
- **Detection and estimation theory**
  - **observables $\{X_j\}$ – sample outputs of sensors**
    - **target signal plus background noise & interference**
  - **features $\{f_k\}$ – reduced representation of observations**
    - **Fourier, LPC, wavelet coefficients**
  - **hypotheses $\{h_i\}$ – presence/absence based on estimates of feature set**
  - **Choose h_i if $P(h_i \mid \{f_k\}) > P(h_j \mid \{f_k\})$ for $j \neq i$**
  - **Complexity: dimensions of feature space, # hypotheses**

  => More observations, rather than more processing per observation

  => Short range means better SNR

  => Fewer targets (hypotheses) in range of set of sensors

  => Nearly homogeneous over small regions
  - **Reliability: number of independent observations and SNR**

Radio propagation

- Energy required to transmit distance d
  - $E_t = \beta d^n$
  - n is about 2 in freespace, about 4 near ground
  - Indoor has lots of other complications
- Small energy => short range
  - + Allows spatial multiplexing
  - Multihop routing required to achieve distance
    - Energy per hop is more
  - + routes around obstacles
  - Requires discovery, topology formation, maintenance
    - may dominate cost of communication
  - Requires media access control
    - Time, space, frequency, …
- WINS asserts diversity through spreading & coding

Passive Vigilance

Parts of the system must be sampling environment all the time

- Reliable detection costs too much energy

⇒ use low-cost, low resolution techniques to detect potential event

⇒ Bring in more powerful, more costly options (infrequently) when important

Example: seismic sensor triggering camera

Processing hierarchy

⇒ Introduces processing, storage, and communication issues

WINS node architecture

Figure 2. WINS network architecture.

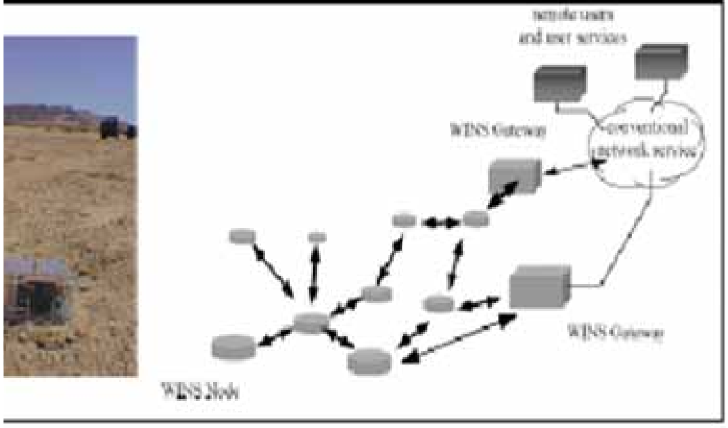
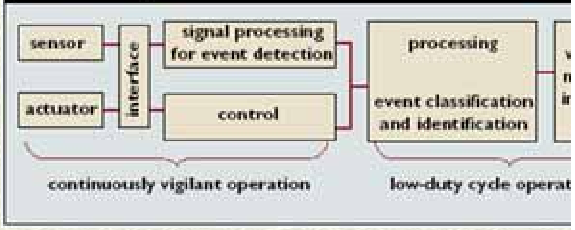


Figure 3. WINS node architecture.

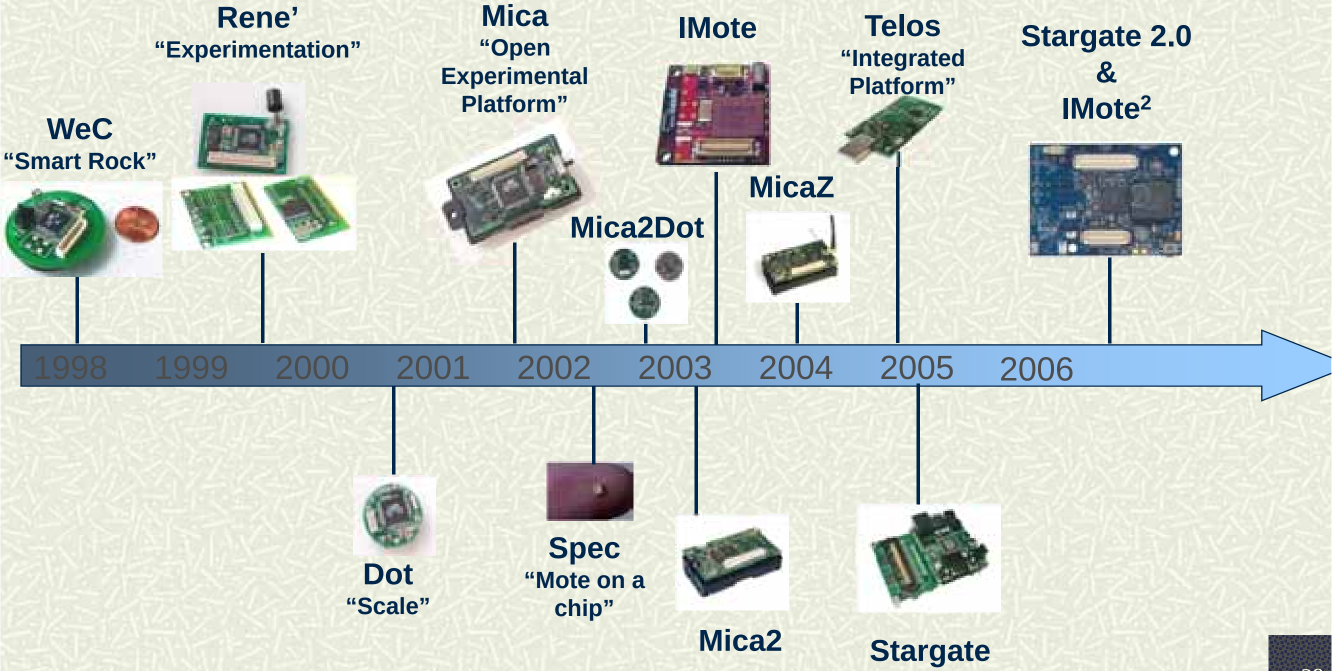


- Two-part architecture
- Combine network performance info, synch, BW reservations, into data messages
- Morphed into Sensoria automotive telematics
  - www.sensoria.com
- Observe variant on classical partitioning

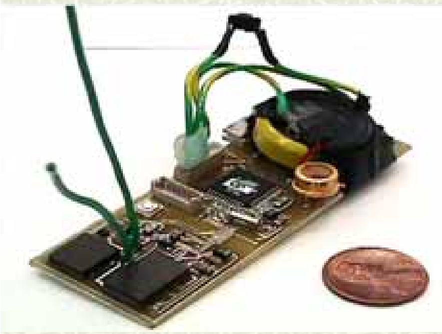
SENSOR NODE FEATURES (Generic)

Processor/Radio Board	MPR300CB
Speed	4 MHz
Flash	128K bytes
SRAM	4K bytes
EEPROM	4K bytes
Radio Frequency	2.4 GHz, 916MHz or 433MHz
Data Rate	40 kbits/sec
Power	0.75 mW
Radio Range	100 feet
Power	2 x AA batteries; Solar Energy

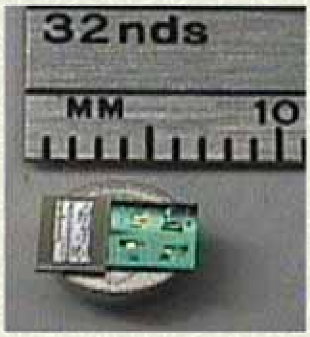
Sensor Motes Timeline



Examples for Sensor Nodes



Dust



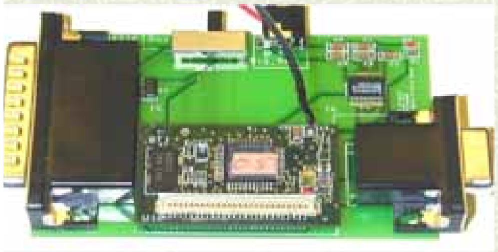
Smart Dust

ckwell WINS

JPL Sensor Webs

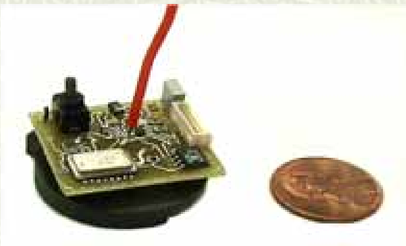
Examples for Sensor Nodes

Rene Mote



Dot Mote

MICA Mote



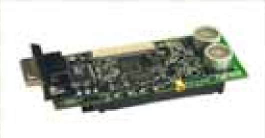
weC Mote

Current Platforms: 1st Generation

ica2DOT (2003)
- 16Kb program mem
- RFM TR1000 (CSMA/ASK)
- Lightweight and small

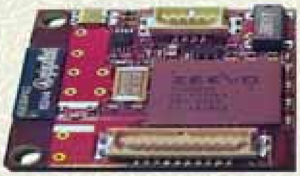
ica2 & Cricket platform (2003)
- 128Kb program mem
- ChipconCC1000 (CSMA/FSK)
- 40Khz Ultrasounders (Cricket only)

icaZ (2004) & Telos (2005)
- 802.15.4/Zigbee stack
- Spread Spectrum radio handles multipath better
- Integrated antenna (Telos only)



Current Platforms: 2nd Generation

- Imote (2003) & Imote^2
  - Higher processing power
  - Bluetooth & 802.11 capable (Imote^2 only)
- Stargate (2005) & Stargate 2.0
  - Pentium class processor
  - Linux OS => easy development (C/C++)
  - More processing capabilities => energy intensive
  - 802.11 capable

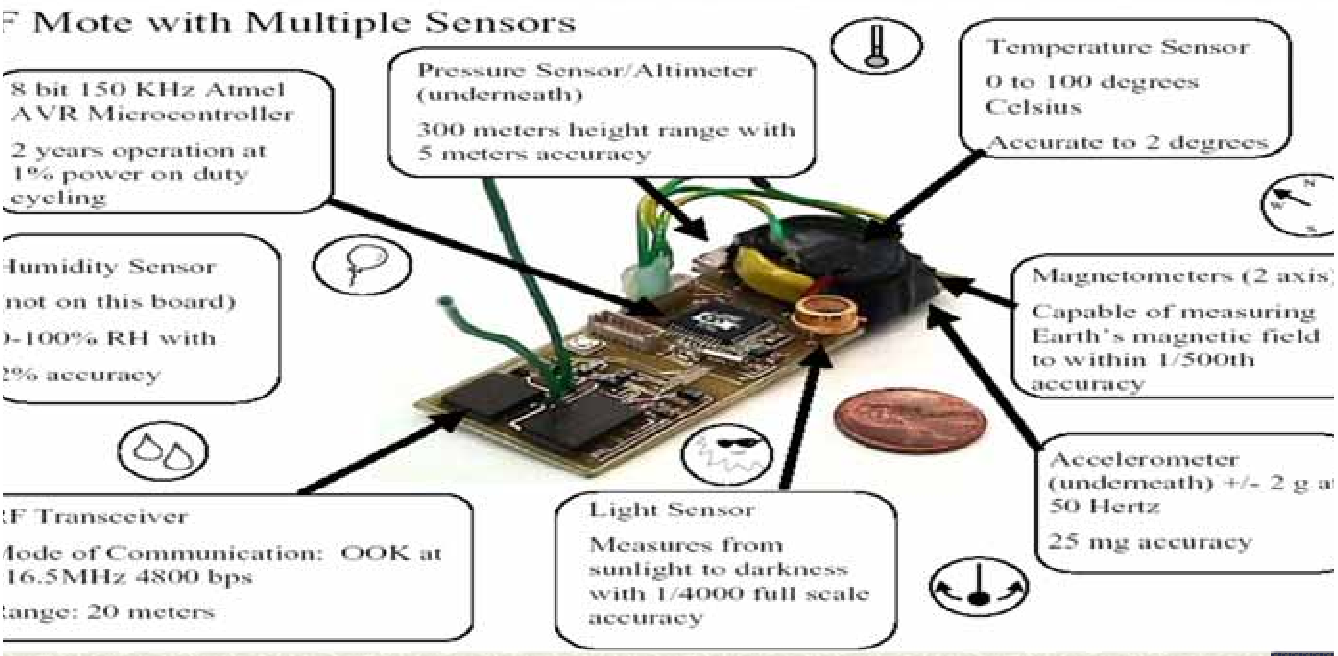


The Mote Family

ype	WeC 1998	René 1999	René 2 2000	Dot 2000	Mica 2001	Mica2Dot 2002	Mica 2 2002	Telos 2004
ontroller								
	AT90LS8535		ATmega163		ATmega128			TI MSP
m memory (KB)	8		16		128			60
KB)	0.5		1		4			2
Power (mW)	15		15		8		33	3
ower (μW)	45		45		75		75	6
p Time (μs)	1000		36		180		180	6
latile storage								
	24LC256				AT45DB041B			ST M24M
ction type	I^{2}C				SPI			I^{2}C
B)	32				512			128
unication								
	TR1000				TR1000	CC1000		CC242
te (kbps)	10				40	38.4		250
ation type	OOK				ASK	FSK		O-QPS
e Power (mW)	9				12	29		38
it Power at 0dBm (mW)	36				36	42		35
Consumption								
um Operation (V)	2.7		2.7		2.7			1.8
ctive Power (mW)	24				27	44	89	41
mming and Sensor Interface								
sion	none	51-pin	51-pin	none	51-pin	19-pin	51-pin	10-pi
unication	IEEE 1284 (programming) and RS232 (requires additional hardware)							USB
ted Sensors	no	no	no	yes	no	no	no	yes

From Polastre et. al.at Hot Chips 2004

Berkeley Motes (Details)



F Mote with Multiple Sensors

8 bit 150 KHz Atmel AVR Microcontroller

2 years operation at 1% power on duty cycling

Pressure Sensor/Altimeter (underneath)

300 meters height range with 5 meters accuracy

Temperature Sensor

0 to 100 degrees Celsius

Accurate to 2 degrees

Iumidity Sensor

not on this board)

)-100% RH with

2% accuracy

Magnetometers (2 axis)

Capable of measuring Earth's magnetic field to within 1/500th accuracy

Accelerometer (underneath) +/- 2 g a

50 Hertz

25 mg accuracy

F Transceiver

Iode of Communication: OOK at 16.5MHz 4800 bps

ange: 20 meters

Light Sensor

Measures from sunlight to darkness with 1/4000 full scale accuracy

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MICAz Platform

icroprocessor: Atmel ATmega128L
  - 7.3728 MHz clock
  - 128 kB of Flash for program memory
  - 4 kB of SRAM for data and variables
  - 2 UARTs (Universal Asynchronous Receive and Transmit)
  - Serial Port Interface (SPI) bus
  - Dedicated hardware I2C bus

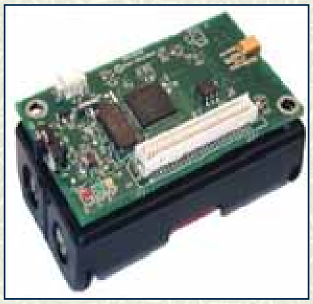
adio: Chipcon's CC2420 (IEEE 802.15.4)
  - 250 kbit/s

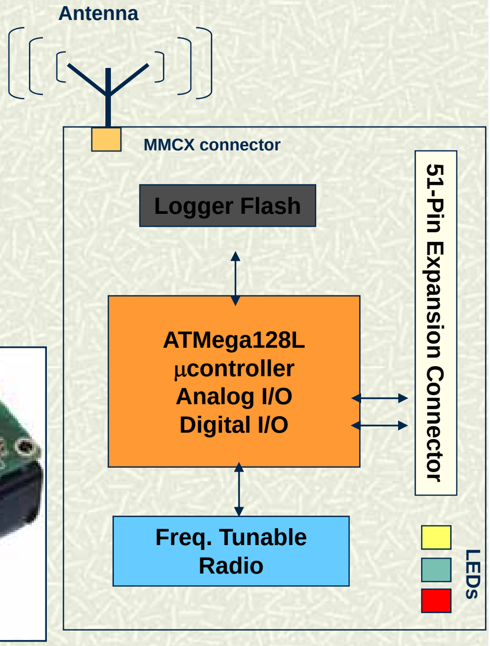
xternal serial flash memory: 512 Kb
  - xbow estimates > 100000 samples

1-pin expansion connector
  - Eight 10-bit analog I/O
  - 21 general purpose digital I/O

ser interface: 3 programmable LEDs

owered by two AA batteries
  - 1850 mAh capacity





Antenna

MMCX connector

Logger Flash

ATMega128L
µcontroller
Analog I/O
Digital I/O

Freq. Tunable Radio

51-Pin Expansion Connector

LEDs

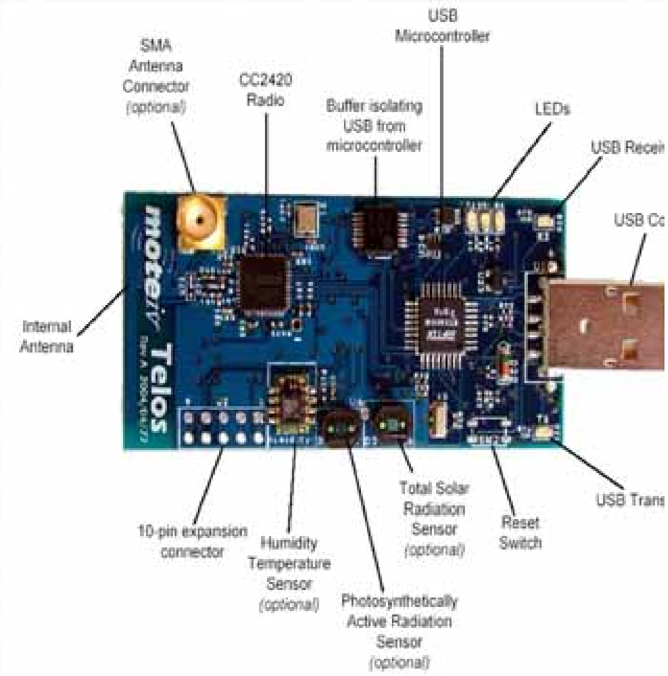
Telos Platform

Robust

- USB interface
- Integrated antenna (30m-125m)
- External antenna capability (~500m)

High Performance

- 10kB RAM, 48 KB ROM
- 12-bit ADC and DAC (200ksamples/sec)
- Hardware link-layer encryption



Telos by MOTEIV.com

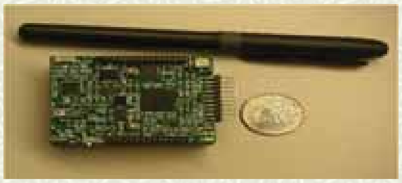
Single board philosophy
- Robustness, Ease of use, Lower Cost
- Integrated Humidity & Temperature sensor

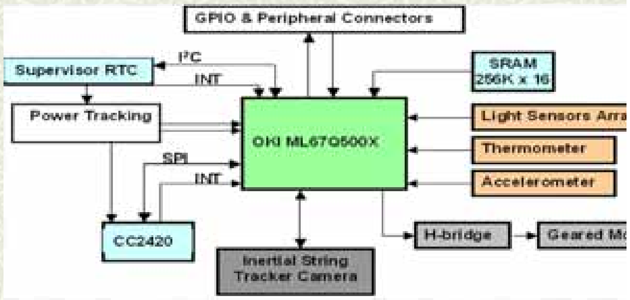
First platform to use 802.15.4
- CC2420 radio, 2.4 GHz, 250 kbps

Motorola HCS08 processor
- Lower power consumption, 1.8V operation, faster wakeup time
- 40 MHz CPU clock, 10K RAM; 48K Flash
- 50m indoor; 125m outdoor ranges

Beyond Motes: XYZ for Low-cost Computationally-Intensive Applications

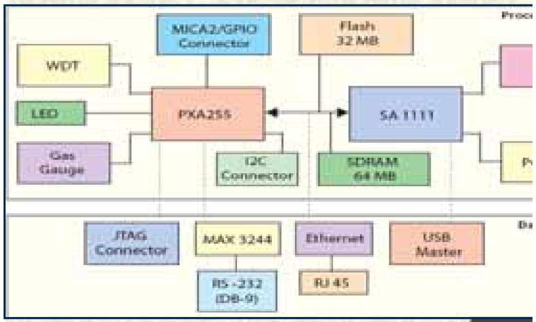
- ’s ENALAB, marketed by Cogent
- ARM Thumb Processor
  - core processor
  - KB FLASH, 32KB RAM
  - K x 16 External RAM
  - ax clock speed 58MHz, scales down to 2MHz
  - ltiple power management functions
- E 802.15.4 compliant radio
  - ipcon CC2420 radio
- ered with 3AA batteries
- elerometer, temperature and light sensors on board





Microserver-class Node: Stargate for High-performance and Mote Coordination

- Embedded platform from Intel
- Compute engine: PXA255 (32bit, 2.3 nJ/instruction, 200 MHz, 1.5V), several sleep modes, 4 dynamically selectable voltage-frequency settings, rich set of peripherals
- Communication: built-on Bluetooth (0-20 dBm, ARM7TDMI core with 64KB RAM, 512MB Flash), 802.11 via PC or CF connector, and Mica2 or MicaZ mote via mote connector (can wake up Stargate)
- Software: Compaq bootloader, Linux 2.4 series kernel



SENSOR NETWORKS FEATURES

APPLICATIONS:

Military, Environmental, Health, Home, Space Exploration,
Chemical Processing, Volcanoes, Mining, Disaster Relief….

SENSOR TYPES:

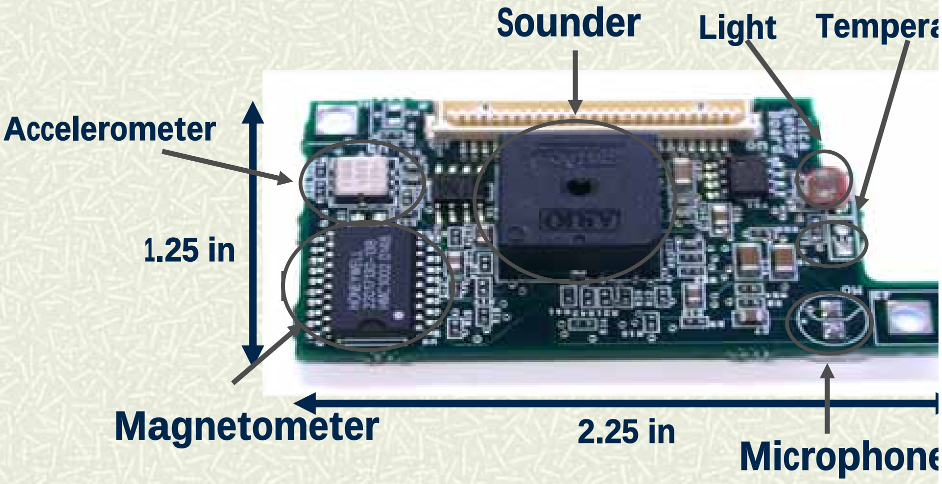
Seismic, Low Sampling Rate Magnetic, Thermal, Visual, Infrared, Acoustic,
Radar…

SENSOR TASKS:

Temperature, Humidity, Vehicular Movement, Lightning Condition,
Pressure, Soil Makeup, Noise Levels, Presence or Absence of Certain Types of
Objects, Mechanical Stress Levels on Attached Objects, Current Characteristics
(Speed, Direction, Size) of an Object ….

Sensor Types

- Light
  - Thermopile
  - Ultraviolet
  - IR
  - Visible Light
  - Color sensors
- Magnetic
- Sound
  - Ultrasound
- Accelerometers
- Temperature sensors
- Pressure sensors
- Humidity
- Touch sensors



Dot Weather Boards

- “Dot” sensorboards (1” diameter)
  - HoneyDot: Magnetometer
    - Resolution: 134 μGauss
  - Ultrasonic Transceiver
  - Weather Station

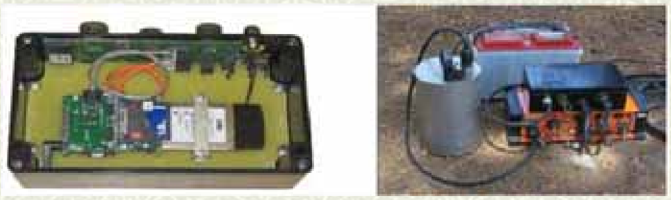
Applications of Stargate

- Seismic monitoring, personal exploration rover, mobile micro-servers, networked info-mechanical system hierarchical wireless sensor networks

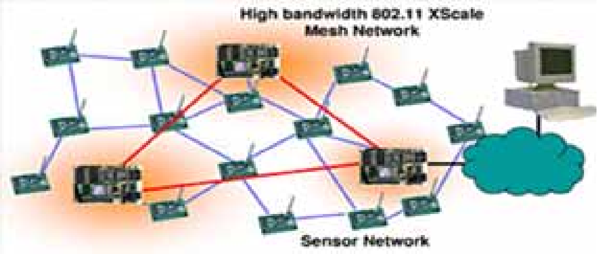
NIMS, UCLA]

[Robotics, CMU]

[NESL, UCLA]



[CENS, UCLA]



[Intel + UCLA]