Wireless Monitoring Technology

From Smart Dust to Reliable Networks

Kris Pister
Prof. EECS, UC Berkeley
Founder & CTO, Dust Networks

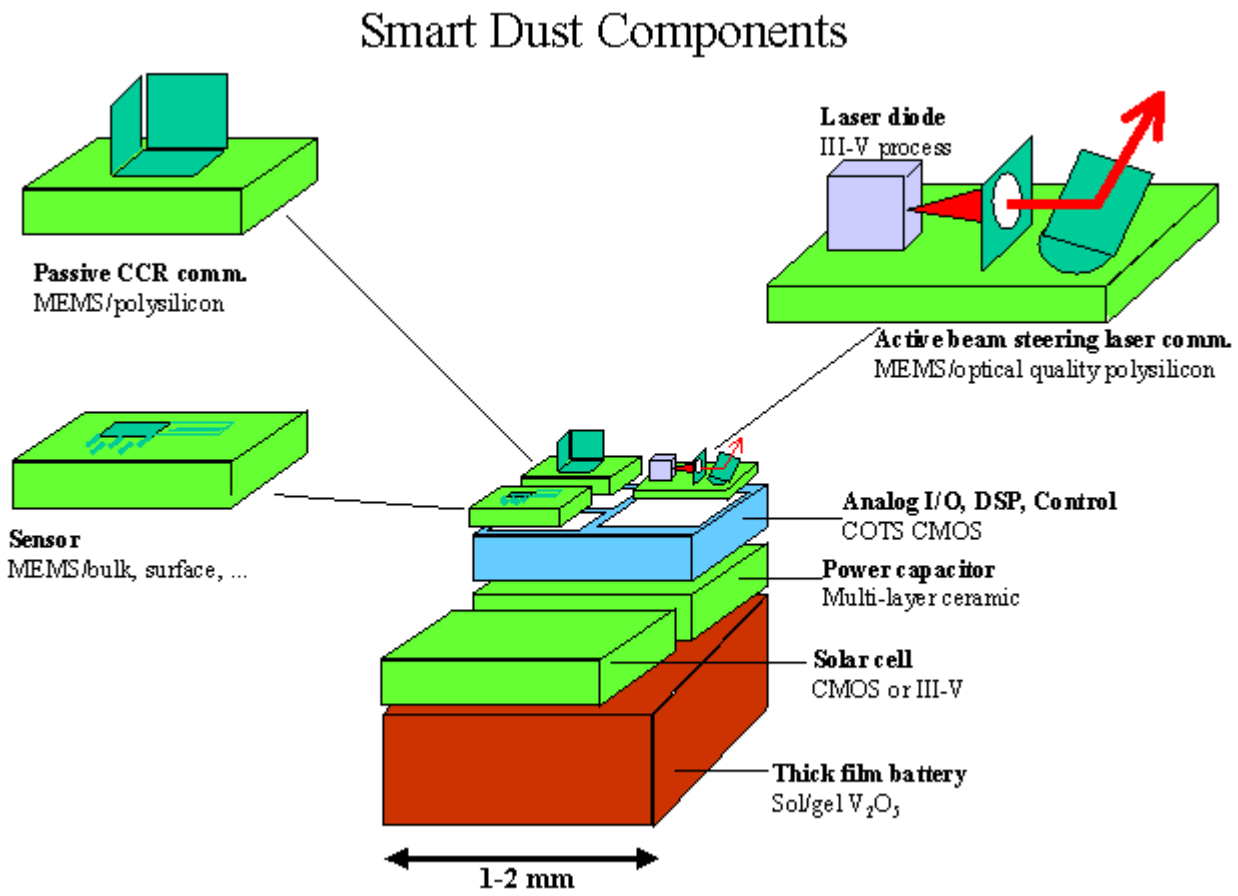
DUST™ NETWORKS

Outline

- History
- Academic research
- Commercial availability

Smart Dust Goal

c. 1997



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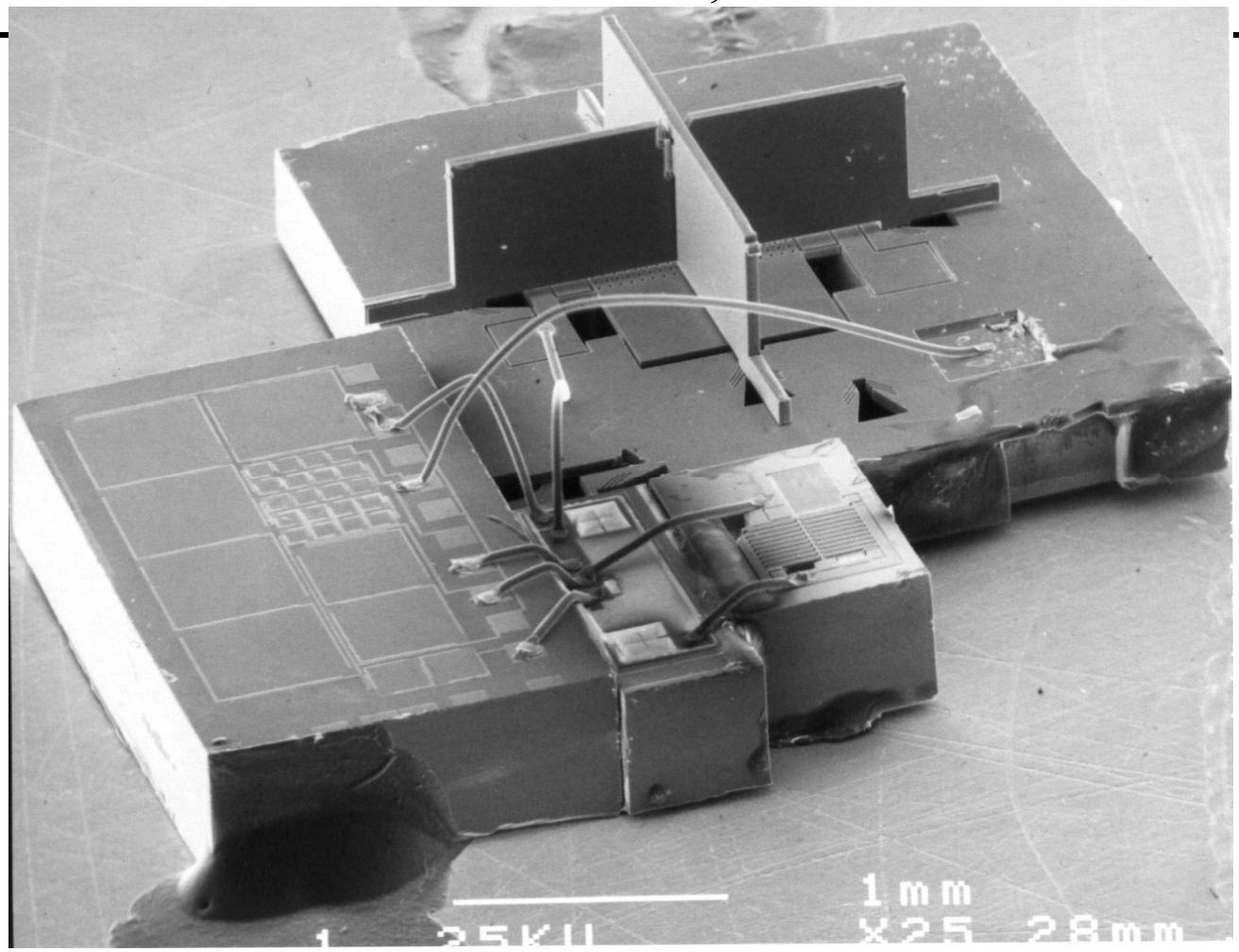
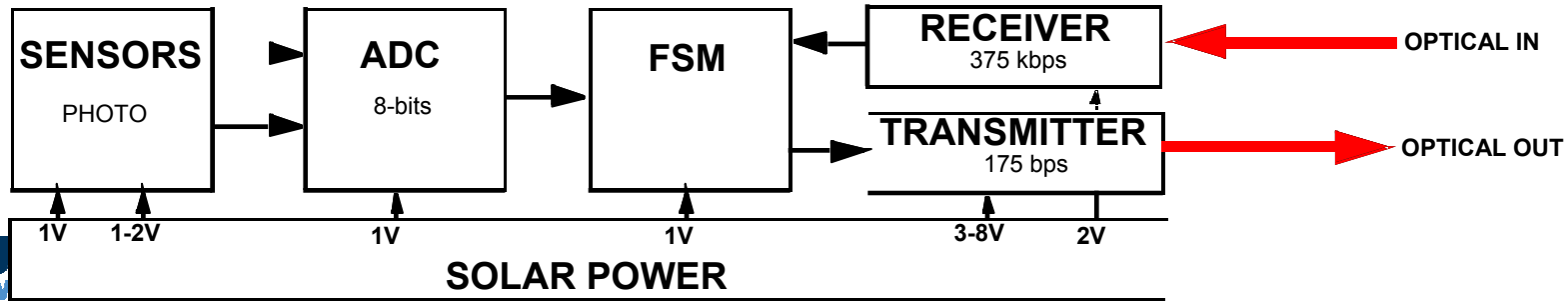
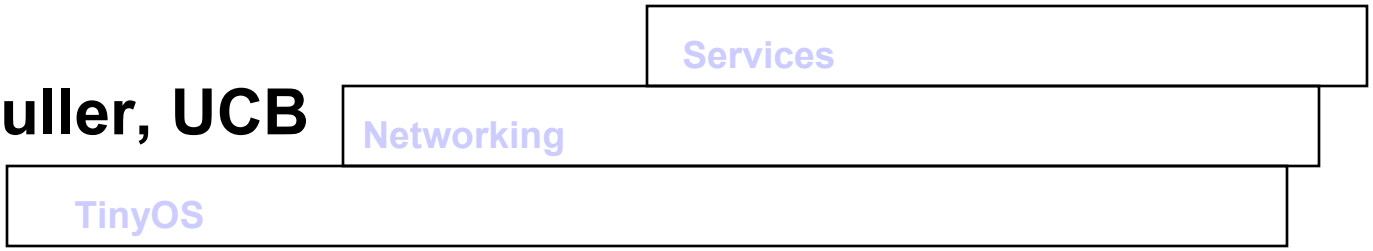
Smart Dust, 2002





UCB "COTS Dust" Macro Motes

David Culler, UCB



WeC 99
James McLurkin MS

Small microcontroller

- 8 kb code, 512 B data

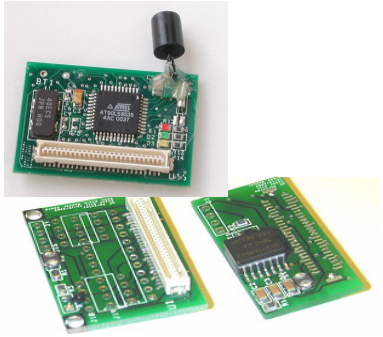
Simple, low-power radio

- 10 kbps

EEPROM storage (32 KB)

Simple sensors

Rene 00



Designed for experimentation

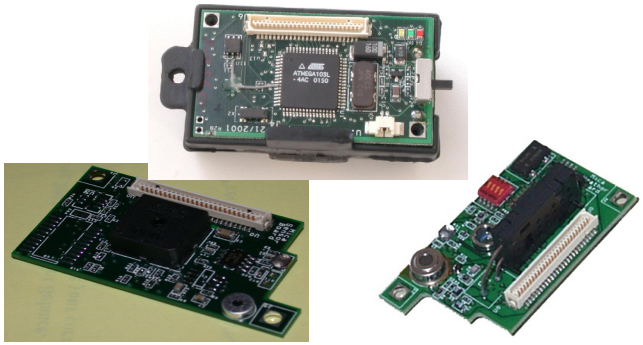
-sensor boards

-power boards

Dot 01

Demonstrate scale

Mica 02



NEST open exp. platform

128 KB code, 4 KB data

50 KB radio

512 KB Flash

comm accelerators

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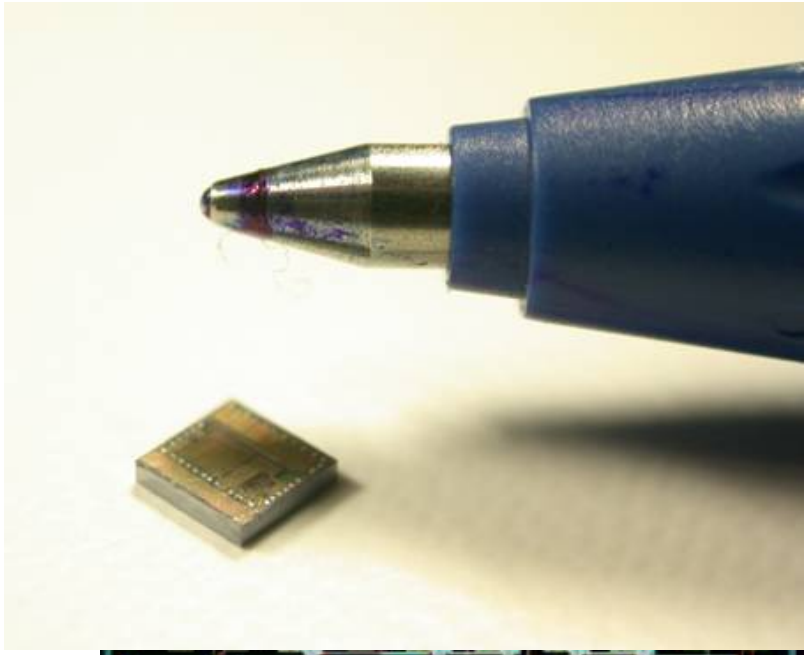
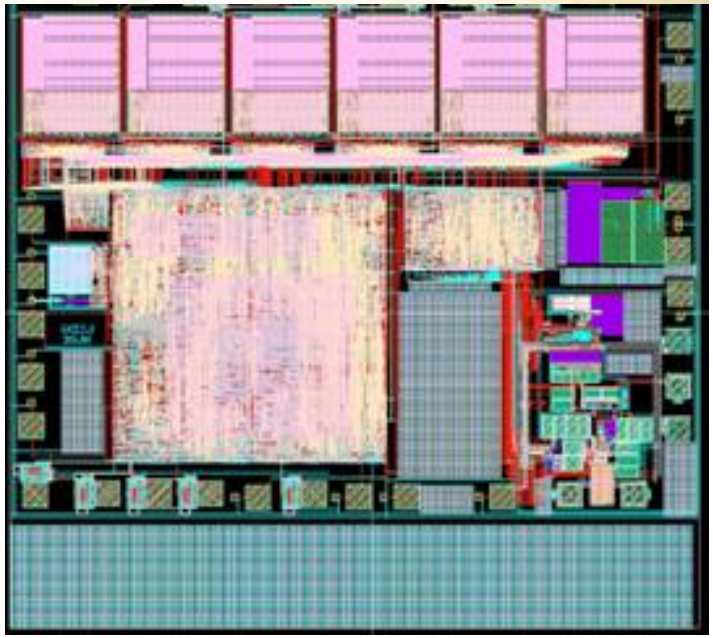
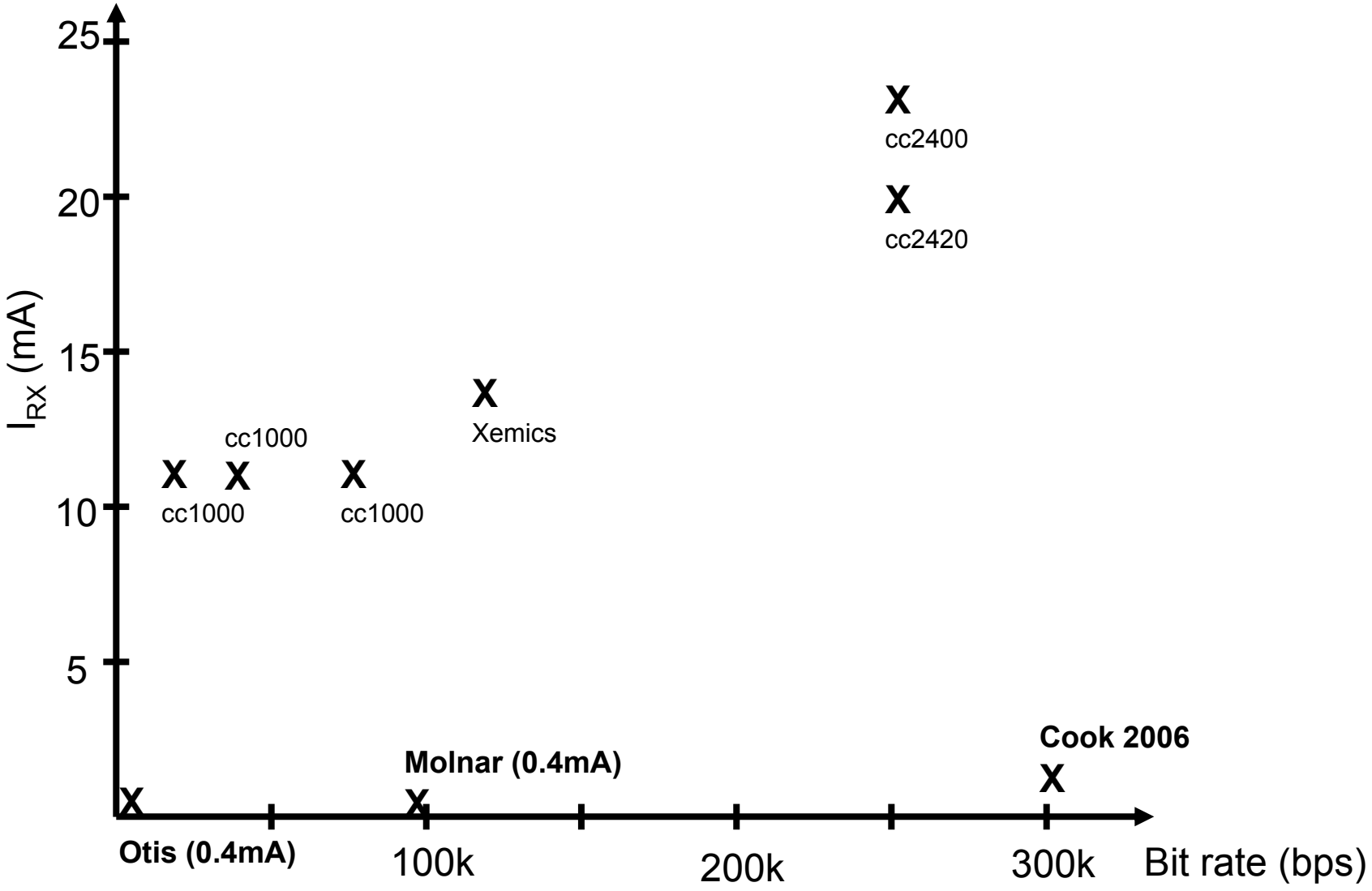
UCB Hardware Results ~2003

- 2 chips fabbed in 0.25um CMOS
  - "Mote on a chip" worked, missing radio RX
  - 900 MHz transceiver worked
- Records set for low power CMOS
  - ADC
    - 8 bits, 100kS/s
    - 2uA@1V
  - Microprocessor
    - 8 bits, 1MIP
    - 10uA@1V
  - 900 MHz radio
    - 100kbps, "bits in, bits out"
    - 20 m indoors
    - 0.4mA @ 3V





Radio Performance



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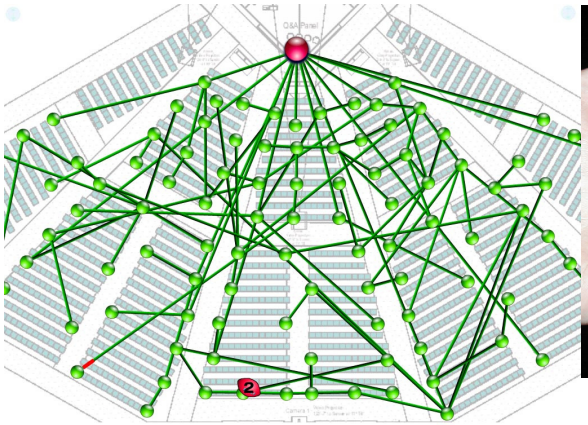
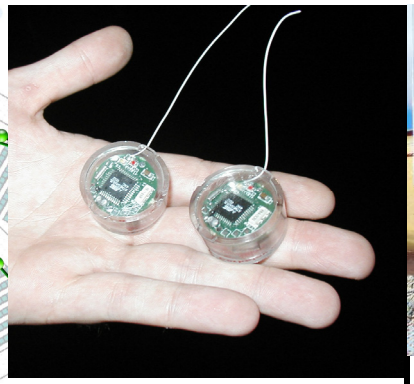
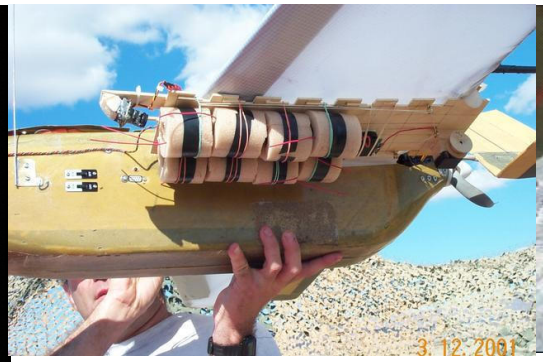
University Demos – Results of 100 man-years of research





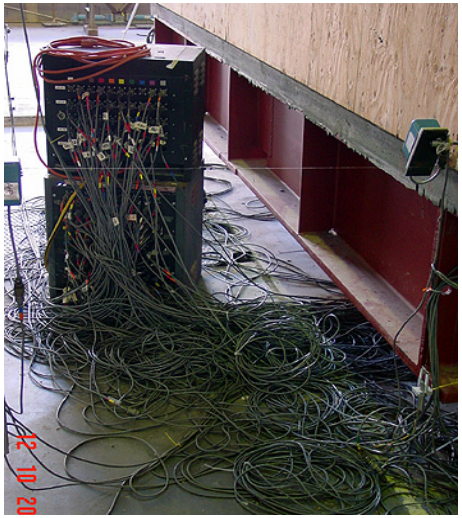
Intel Developers Forum, live demo 800 motes, 8 level dynamic network,



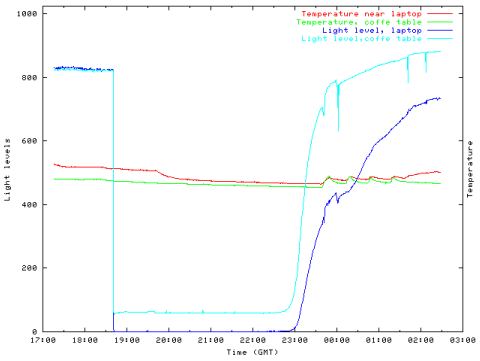
Motes dropped from UAV, detect vehicles, log and report direction and velocity

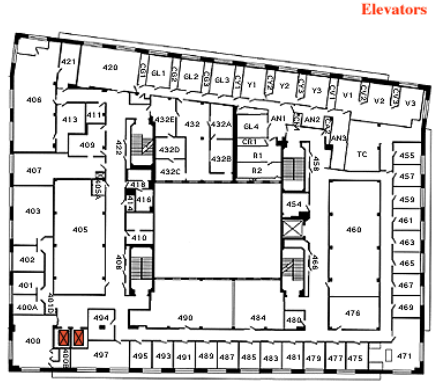
Seismic testing demo: real-time data acquisition, $200 vs. $5,000 per node

vs.

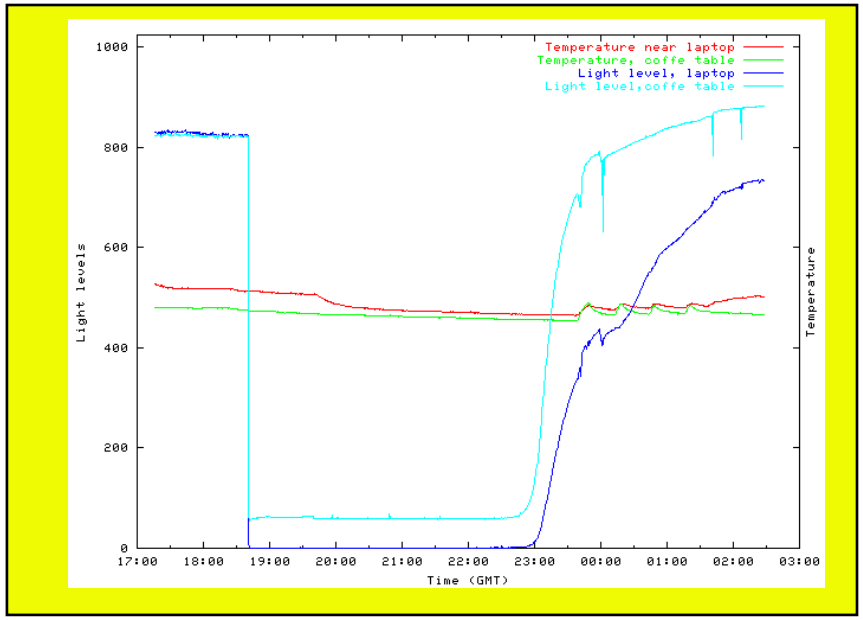


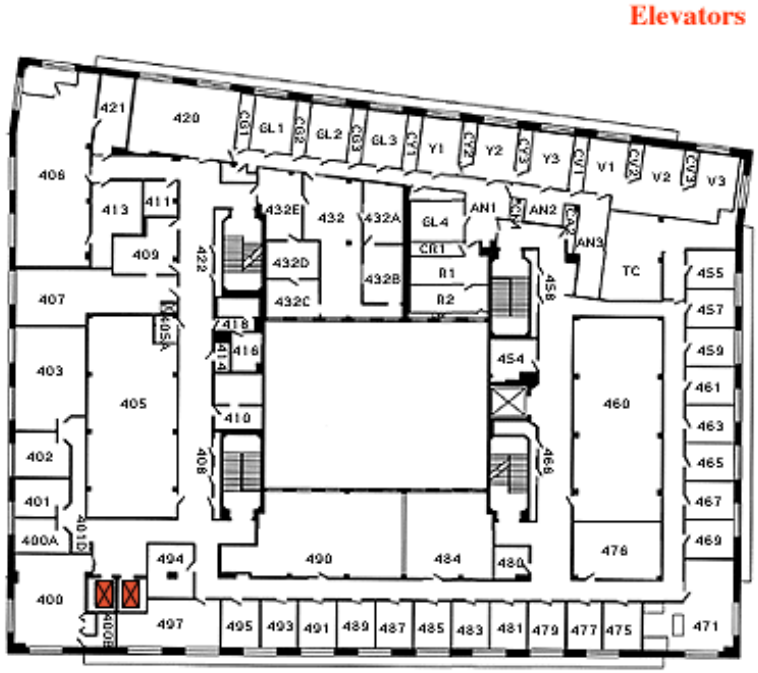
50 temperature sensors for HVAC deployed in 3 hours. $100 vs. $800 per node.





Building Energy System (ucb, 2001)





- 50 temperature sensors on 4th floor
- 5 electrical power monitors
- 1 relay controlling a Trane rooftop chiller

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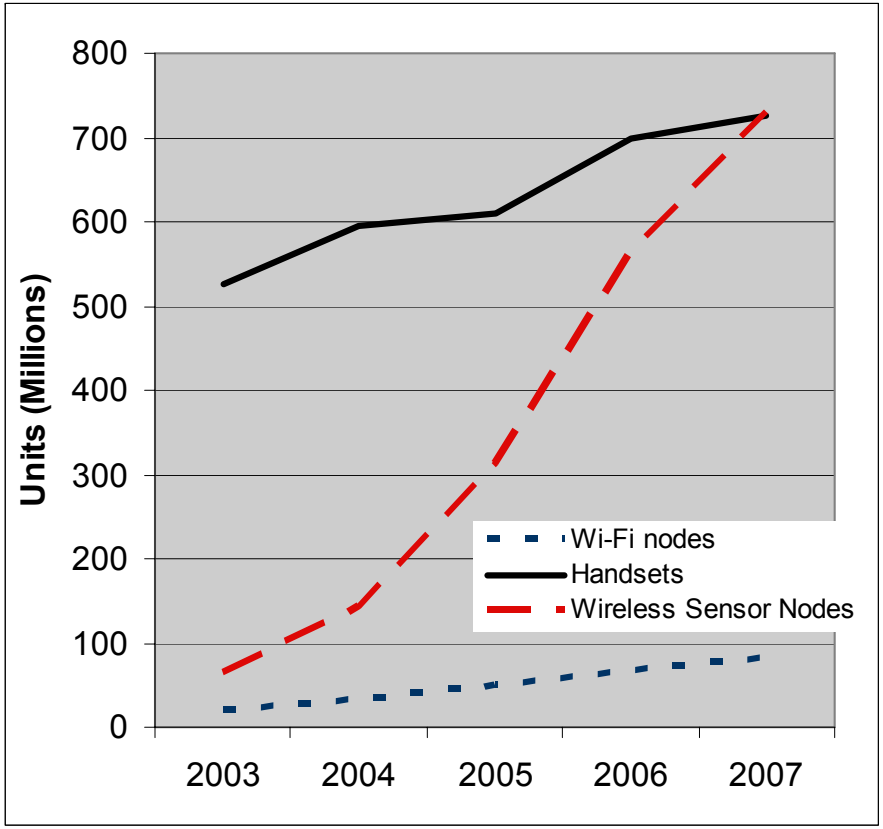
~~Sensor Networks Take Off!~~

Industry Analysts Take Off!



$8.1B market for Wireless Sensor Networks in 2007

Source: InStat/MDR 11/2003 (Wireless); Wireless Data Research Group 2003; InStat/MDR 7/2004 (Handsets)

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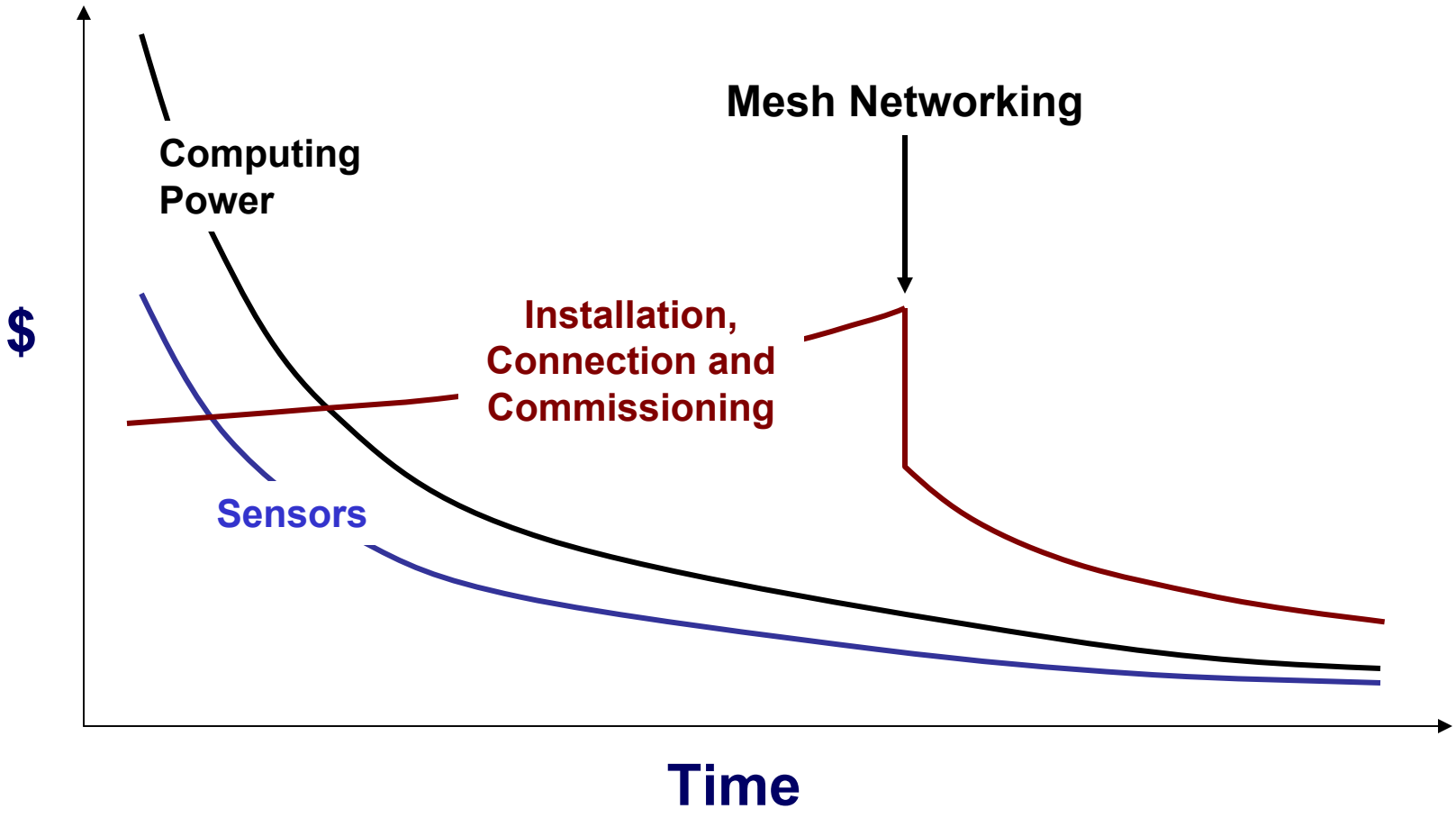
Cost of Sensor Networks



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What do OEMs and SIs want?

^ and scientists and and engineers and startups and grad students and….

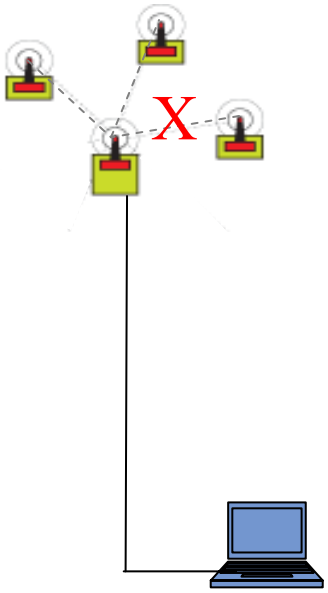
- Reliability
- Reliability
- Reliability
- Low installation and ownership costs
  - No wires; >5 year battery life
  - No network configuration
  - No network management
- Typically “trivial” data flow
  - Regular data collection
    - 1 sample/minute…1 sample/day?
  - Event detection
    - Threshold and alarm

Reliability

- Hardware
  - Temperature, humidity, shock
  - Aging
  - MTBF = 5 centuries
- Software
  - Linux yes (manager/gateway)
  - TinyOS no (motes)
- Networking
  - RF interference
  - RF variability

Network Types

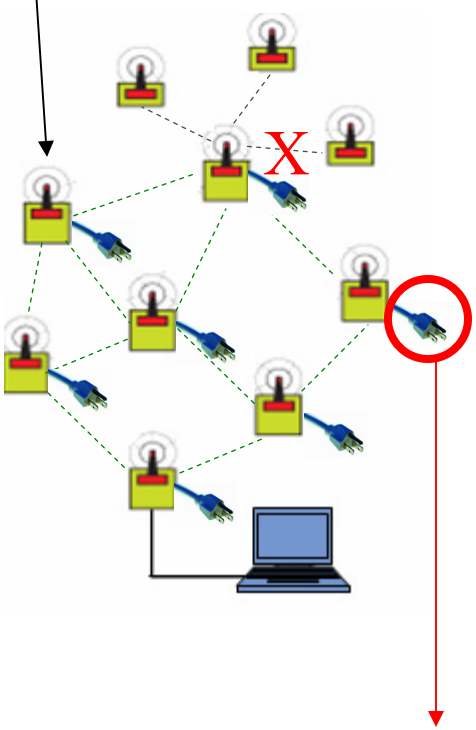
Star



Star-Mesh

Powered mesh infrastructure

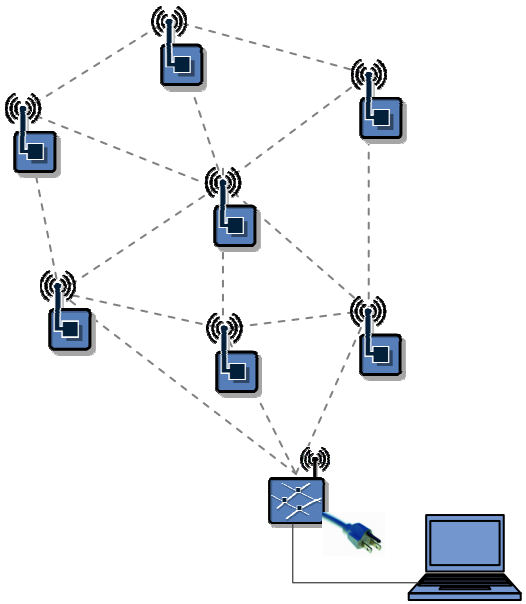
Star-connected sensors



Full Mesh

No infrastructure

Mesh-connected sensors



Why not use 802.11?

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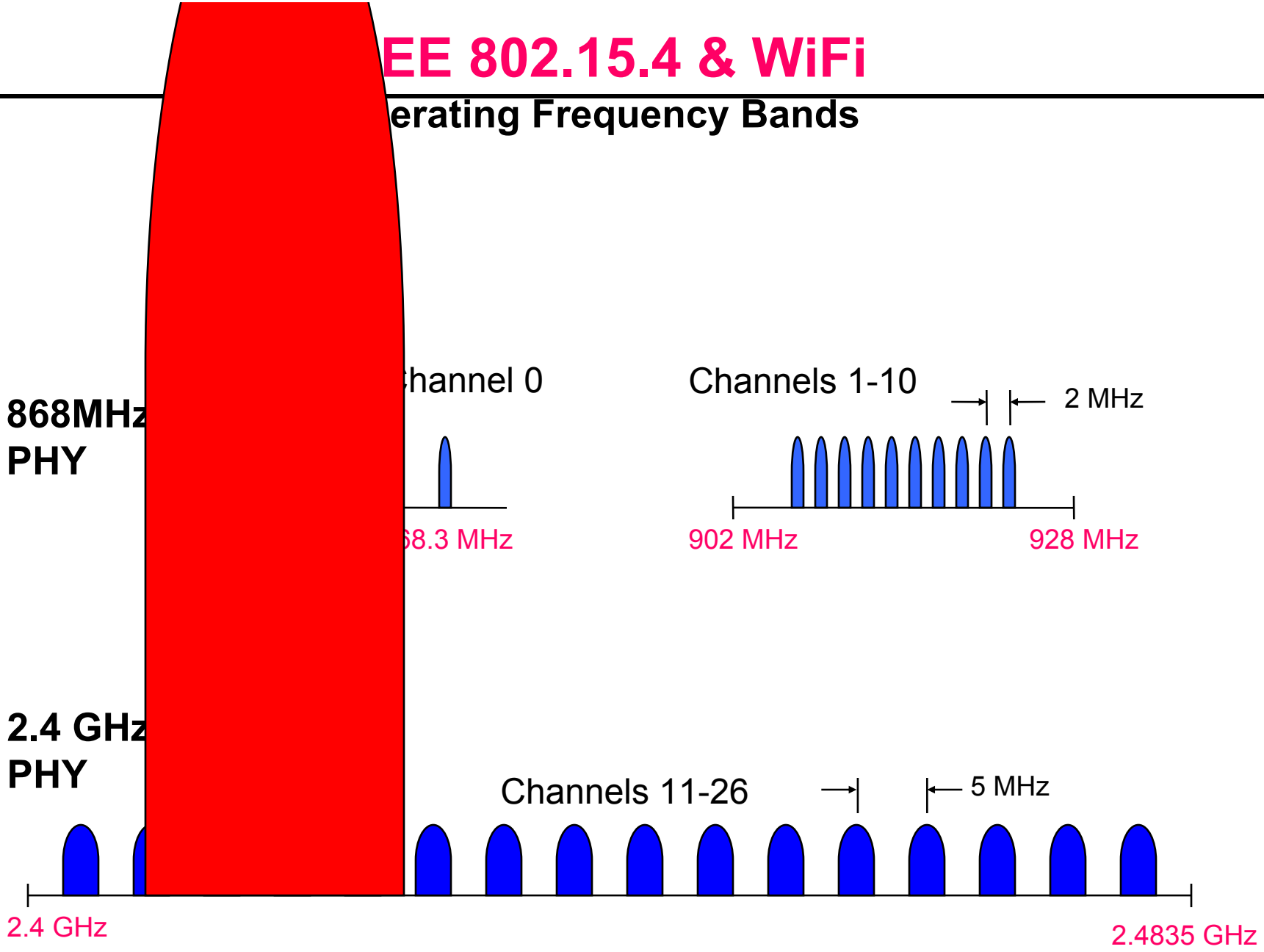
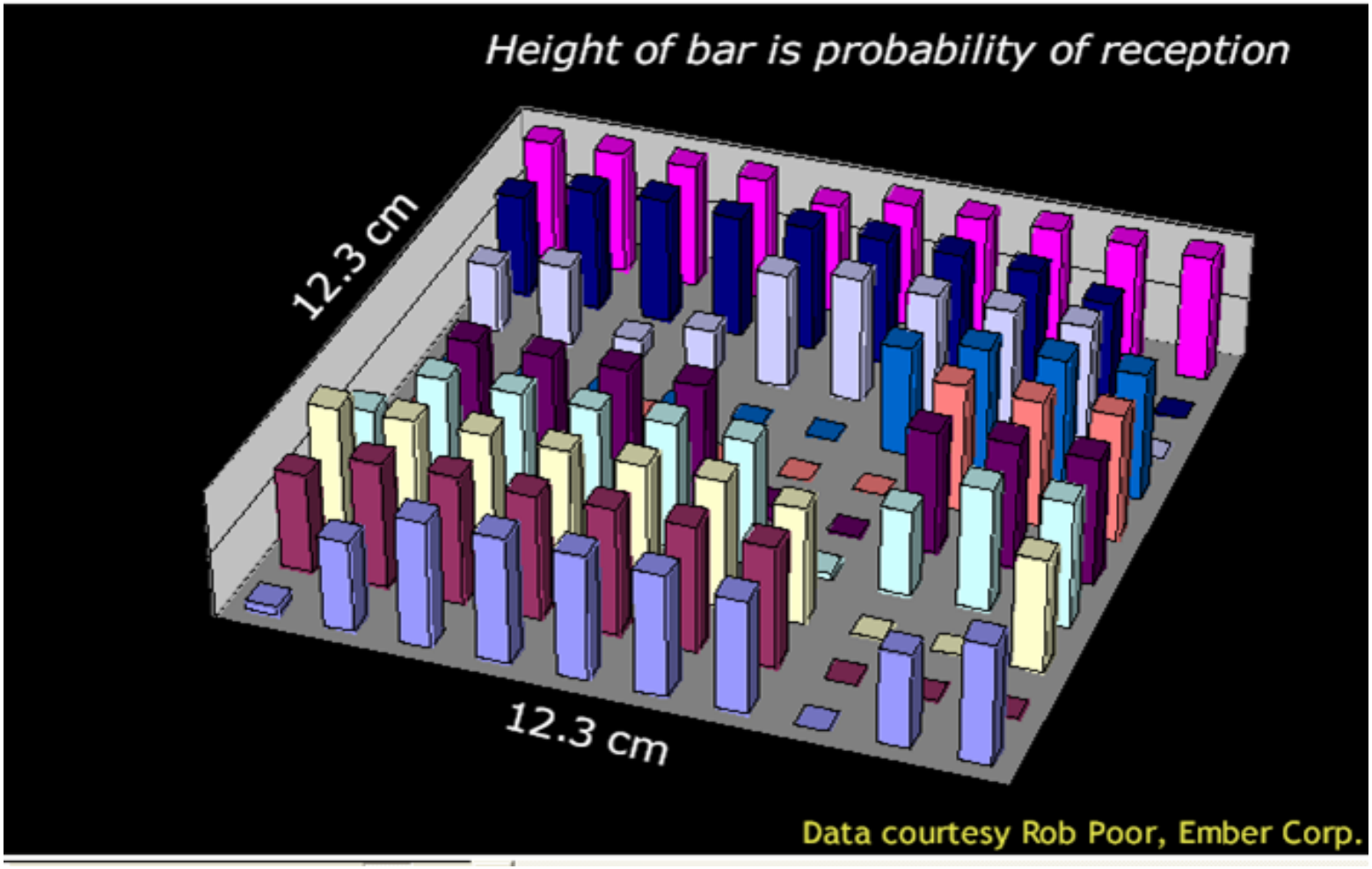
EE 802.15.4 & WiFi

erating Frequency Bands



Spatial effect of multipath



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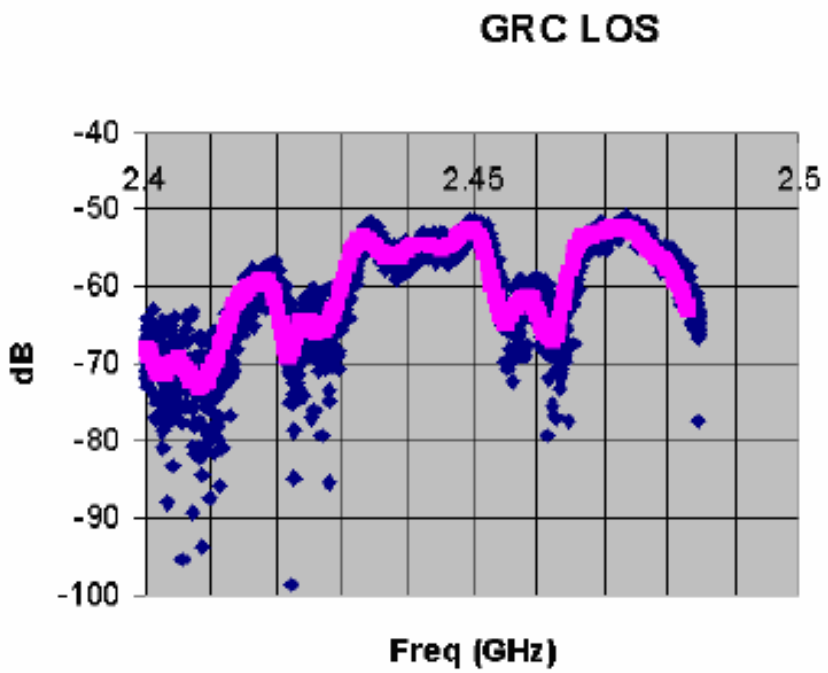
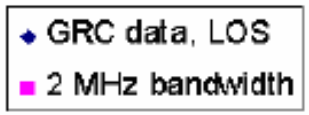
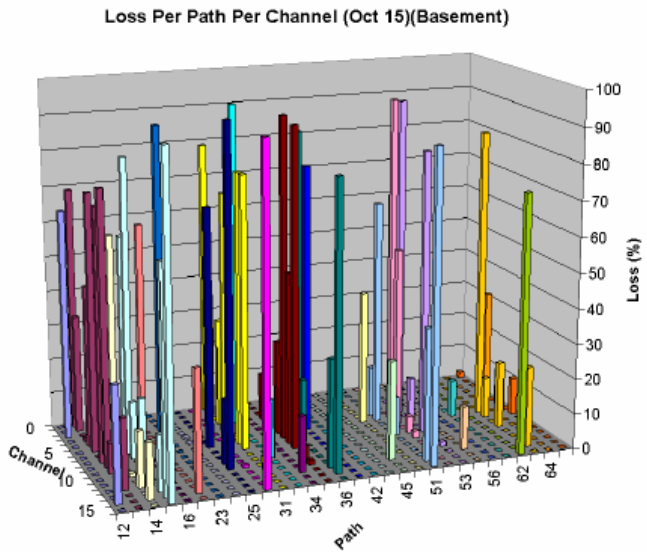
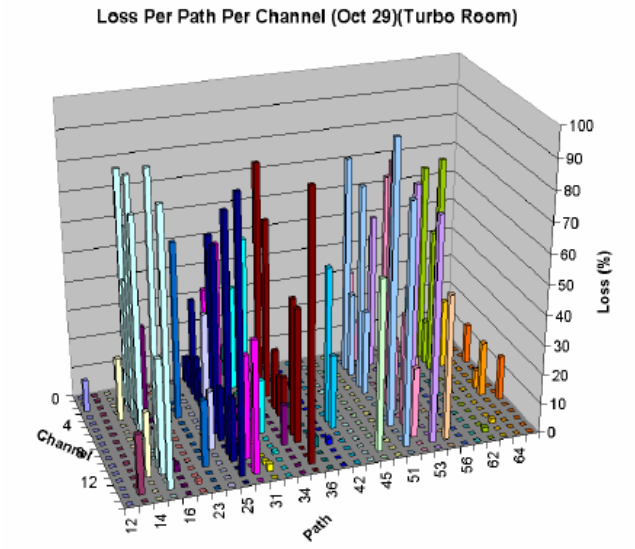
Frequency dependent fading and interference









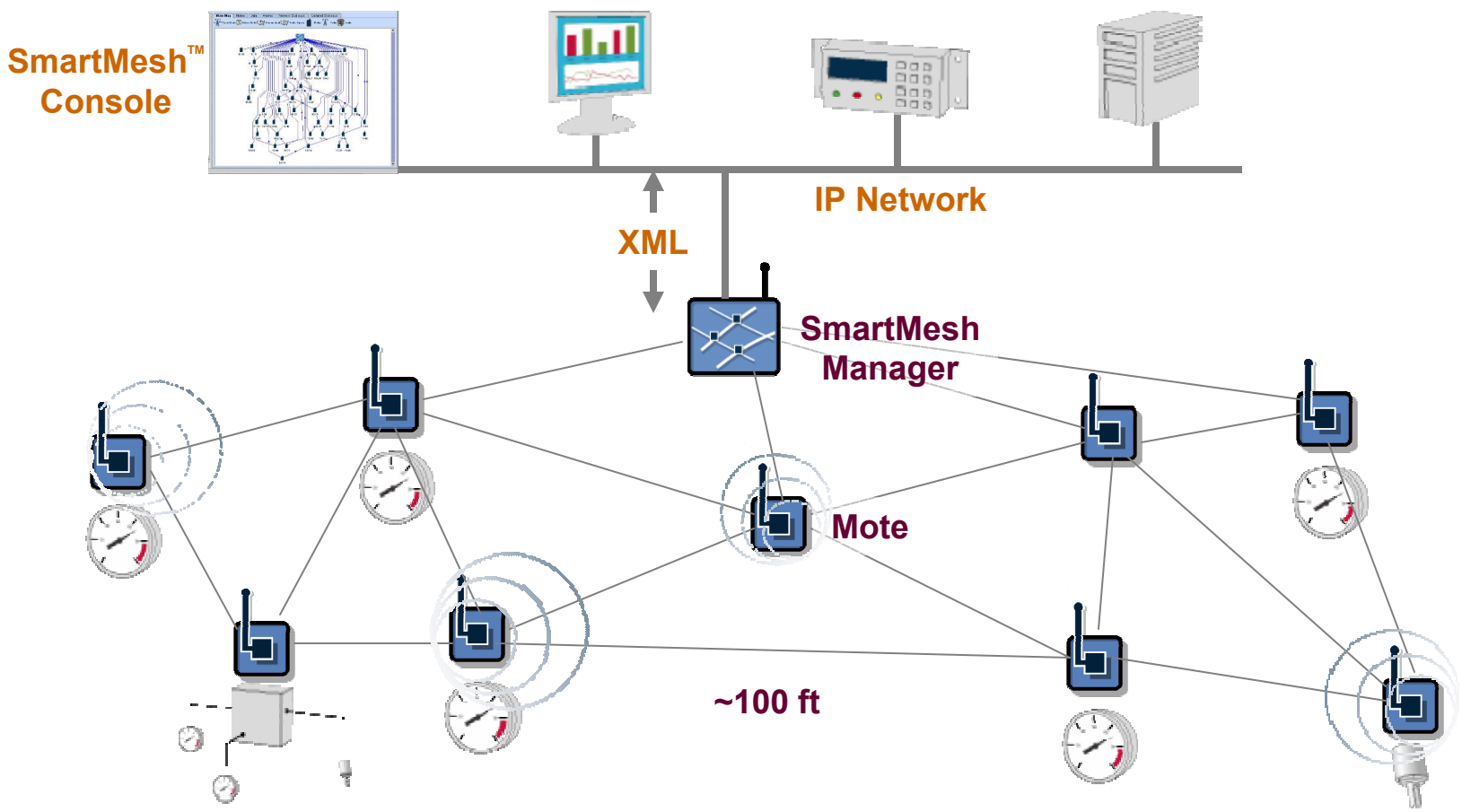
From: Werb et al., “Improved Quality of Service in IEEE 802.15.4 Networks”, Intl. Wkshp. On Wireless and Industrial Automation, San Francisco, March 7, 2005.

Commercialization

- DARPA
  - Over $100M 1995--2005
- Venture Capital
  - Over $200M since 2002
- Acquisitions
  - TI pays $200M for Chipcon, 2006

Mesh Systems

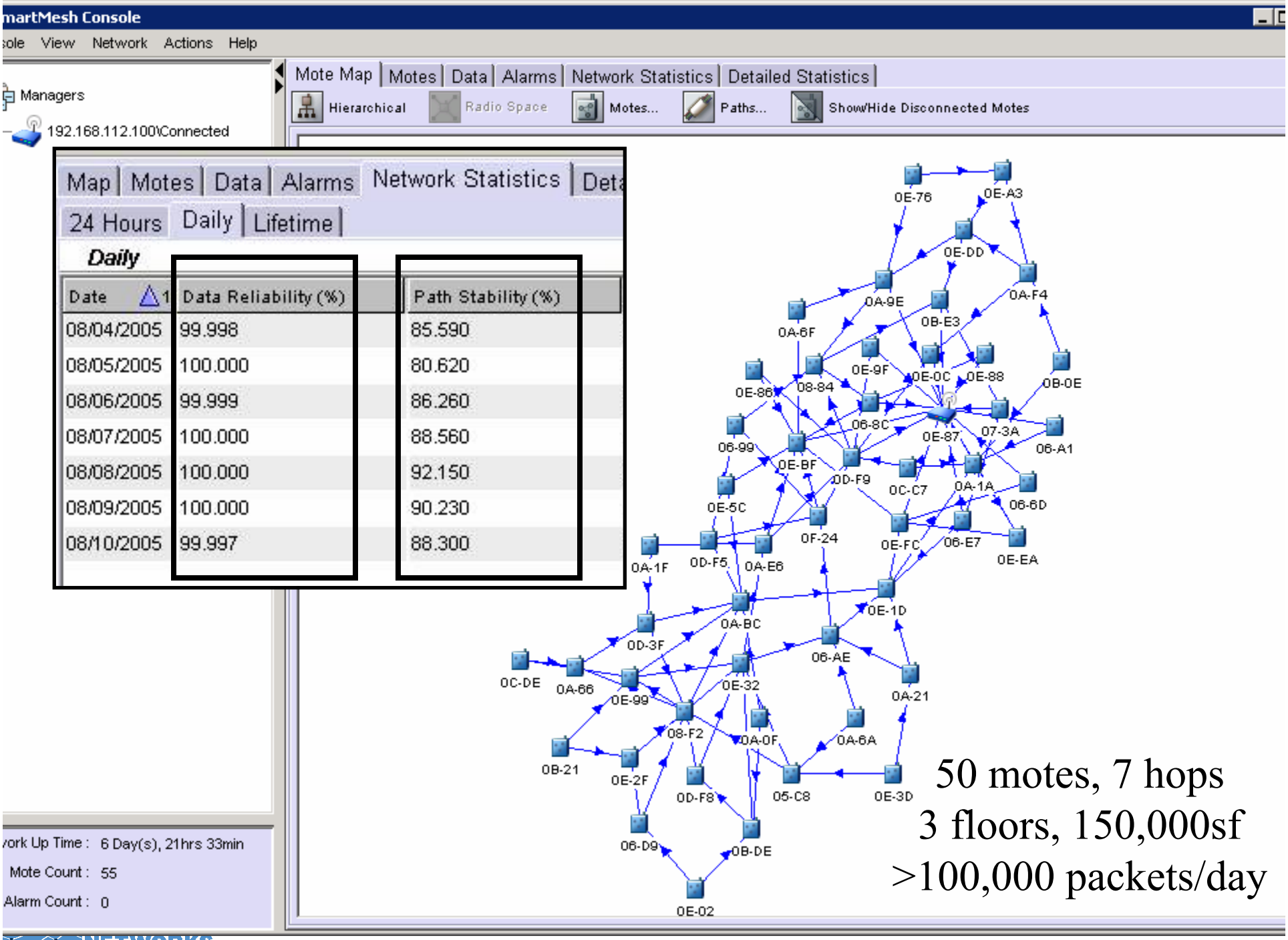
Configure, don't compile

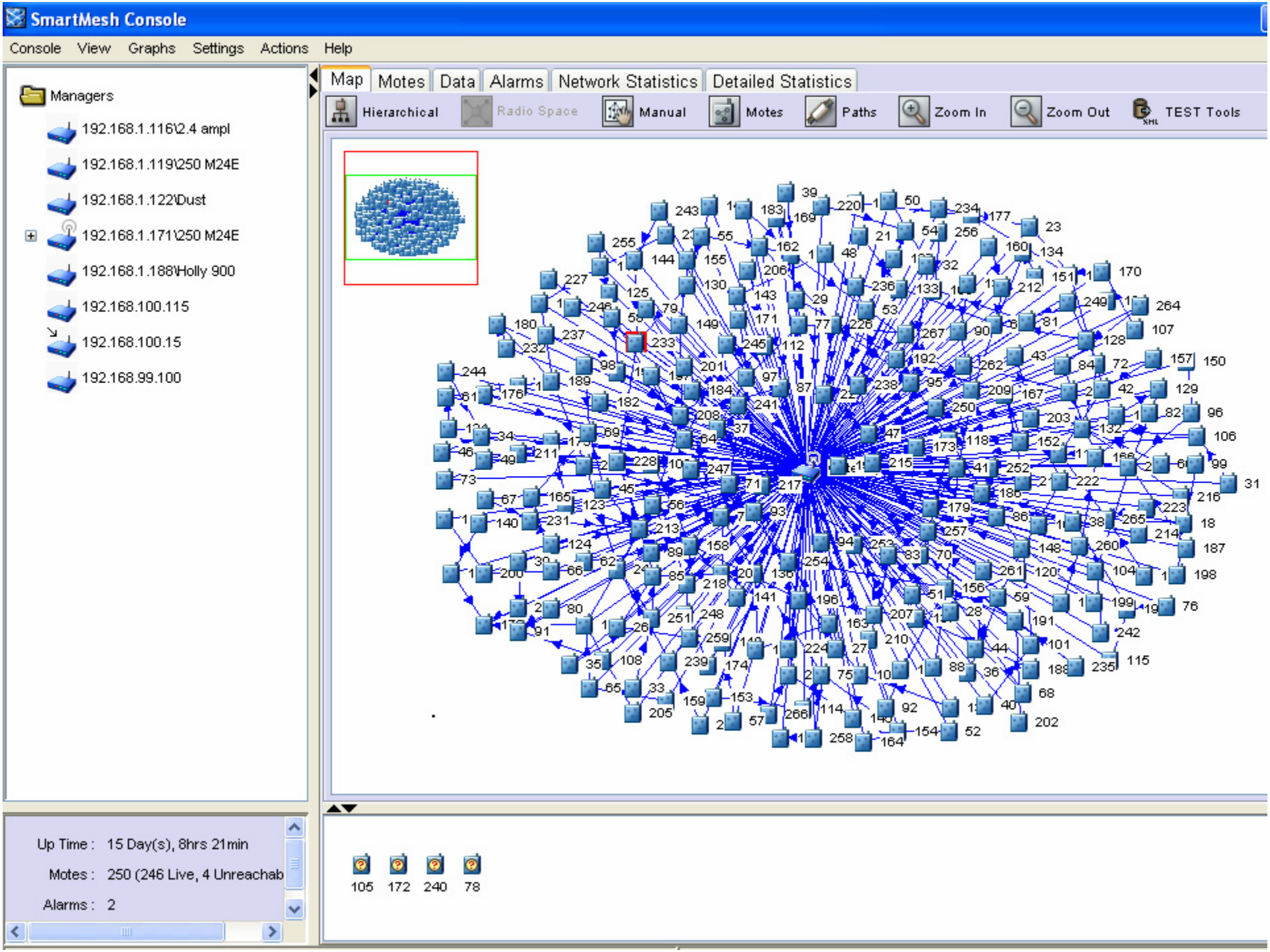


Reliability: 99.99%+

Power consumption: < 100uA average

DUST™ NETWORKS

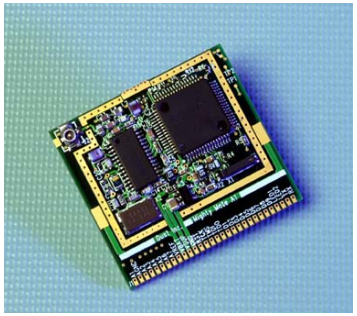

martMesh Console
ole View Network Actions Help
Managers
192.168.112.100\Connected
Mote Map Motes Data Alarms Network Statistics Detailed Statistics
Hierarchical
Radio Space
Motes...
Paths...
Show/Hide Disconnected Motes
Map Motes Data Alarms Network Statistics Deta
24 Hours Daily Lifetime
Daily
Date 1
Data Reliability (%)
Path Stability (%)
08/04/2005 99.998 85.590
08/05/2005 100.000 80.620
08/06/2005 99.999 86.260
08/07/2005 100.000 88.560
08/08/2005 100.000 92.150
08/09/2005 100.000 90.230
08/10/2005 99.997 88.300
ork Up Time : 6 Day(s), 21hrs 33min
Mote Count : 55
Alarm Count : 0
0E-76
0E-A3
0E-DD
0A-F4
0A-9E
0B-E3
0A-6F
0E-9F
0E-0C
0E-88
0B-0E
0E-86
08-84
06-8C
0E-87
07-3A
06-A1
06-99
0E-BF
0D-F9
0C-C7
0A-1A
06-6D
0E-5C
0F-24
0E-FC
06-E7
0E-EA
0A-1F
0D-F5
0A-E6
0E-1D
0A-BC
0D-3F
06-AE
0C-DE
0A-66
0E-99
0E-32
0A-21
08-F2
0A-0F
0A-6A
0B-21
0E-2F
0D-F8
05-C8
0E-3D
06-D9
0B-DE
0E-02
50 motes, 7 hops
3 floors, 150,000sf
>100,000 packets/day

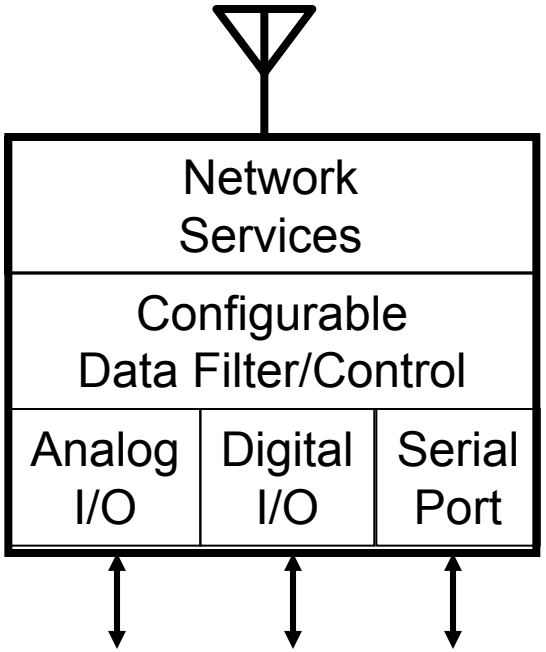

SmartMesh Console
Console View Graphs Settings Actions Help
Managers
192.168.1.116\2.4 ampl
192.168.1.119\250 M24E
192.168.1.122\Dust
192.168.1.171\250 M24E
192.168.1.188\Holly 900
192.168.100.115
192.168.100.15
192.168.99.100
Map Motes Data Alarms Network Statistics Detailed Statistics
Hierarchical
Radio Space
Manual
Motes
Paths
Zoom In
Zoom Out
TEST Tools
Up Time : 15 Day(s), 8hrs 21min
Motes : 250 (246 Live, 4 Unreachab
Alarms : 2
105 172 240 78

Micro Network Interface Card

μNIC

- No mote software development
- Variety of configurable data processing modules
- Integrators develop applications, not mesh networking protocols
- For compute-intensive applications, use an external processor/OS of your choice.





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Energy Monitoring Pilot

Honeywell

- Honeywell Service: monitor, analyze and reduce power consumption
- Problem: >> $100/sensor wiring cost
- Solution:
  - Entire network installed in 3 hours (vs. 3-4 days)
  - 9 min/sensor
  - Software developed in 2 weeks (XML interface to existing data system)
  - 15 months, 99.99%

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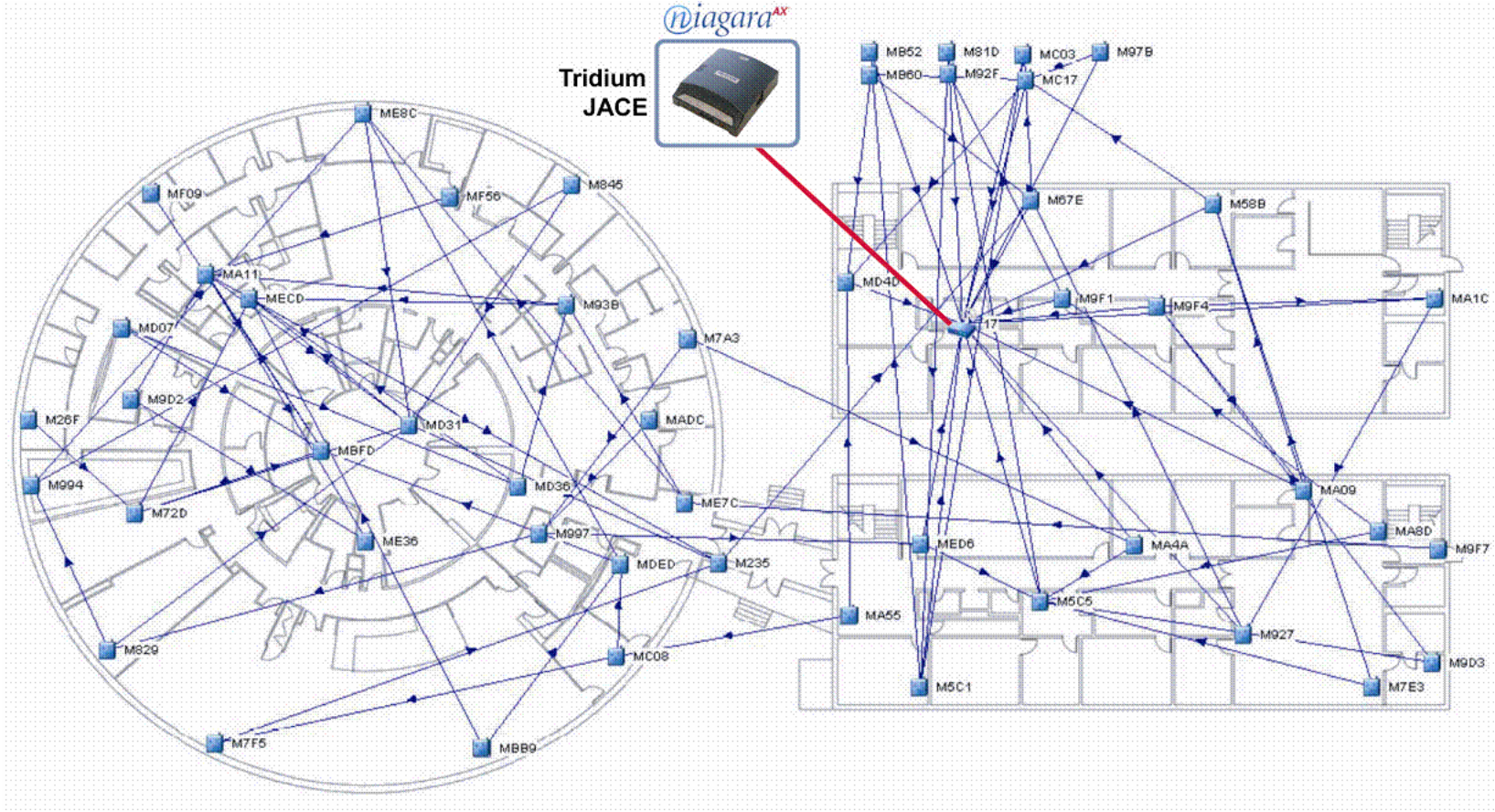
Chicago Public Health – Dust, Tridium, Teng



Temperature and power monitoring

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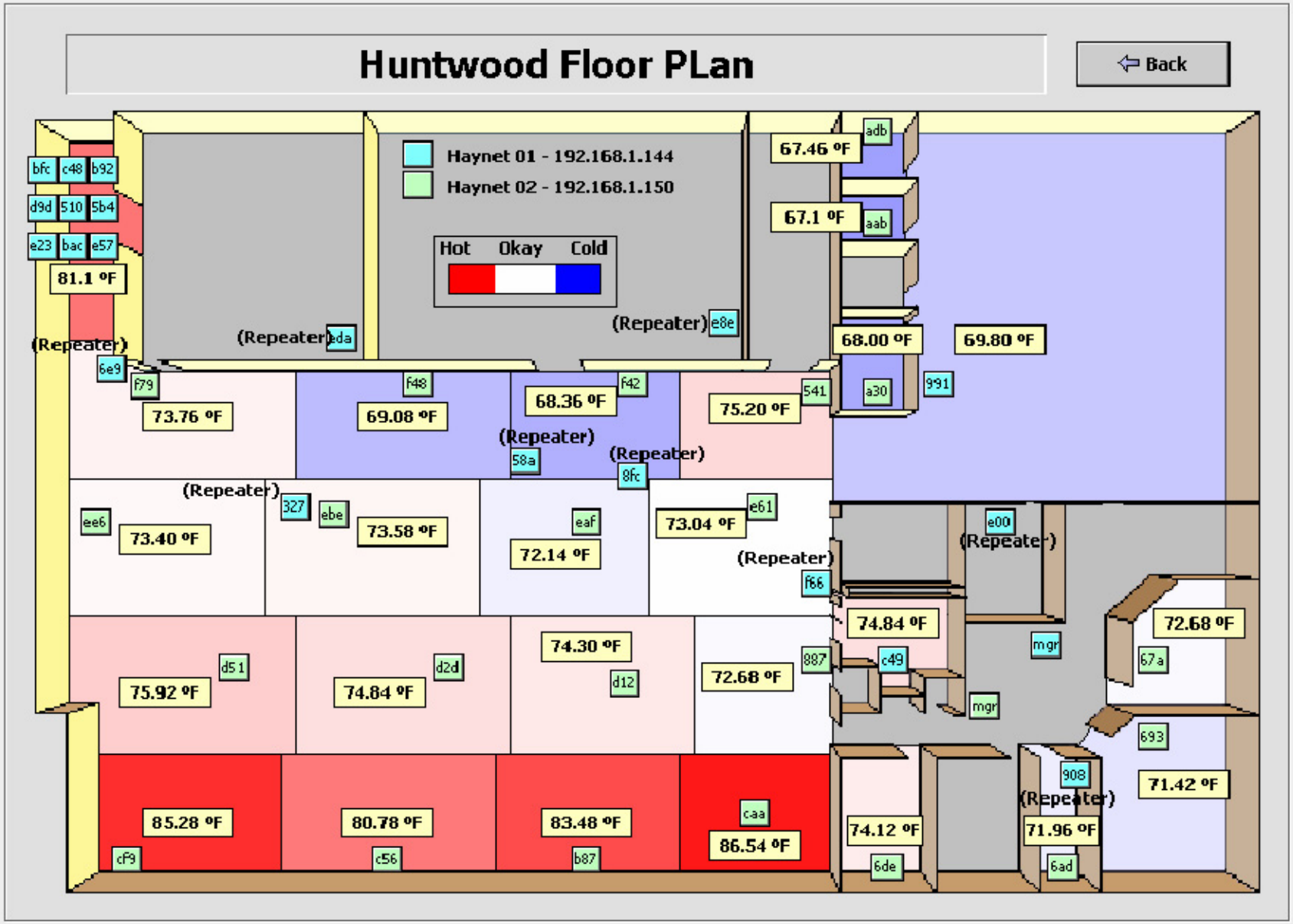
Tridium Niagra^{AX}



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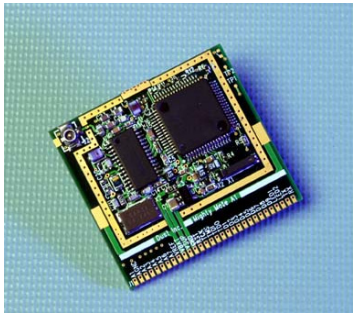

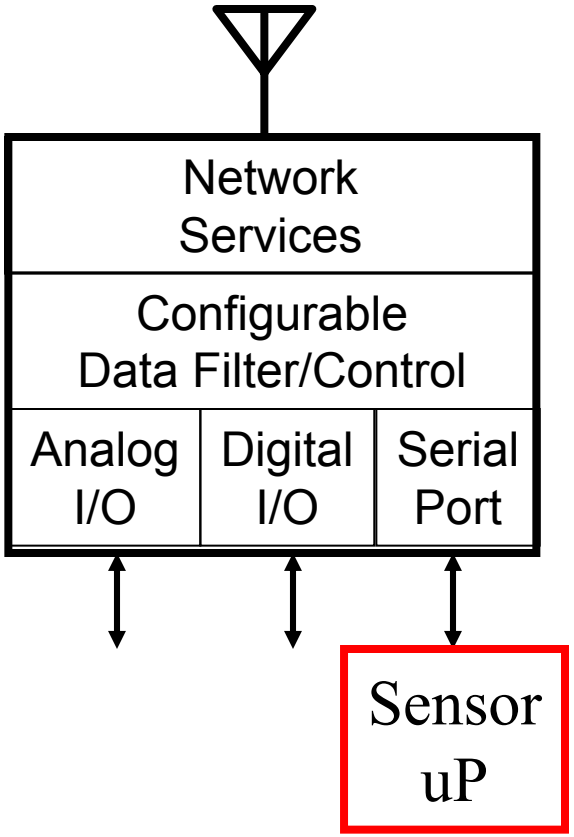

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Perimeter Security

Passive IR and Camera

Passive IR

MEMS and GPS

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Standards

- IEEE 802.15.4
- Zigbee
- Wireless HART
- ISA/SP100

Conclusion

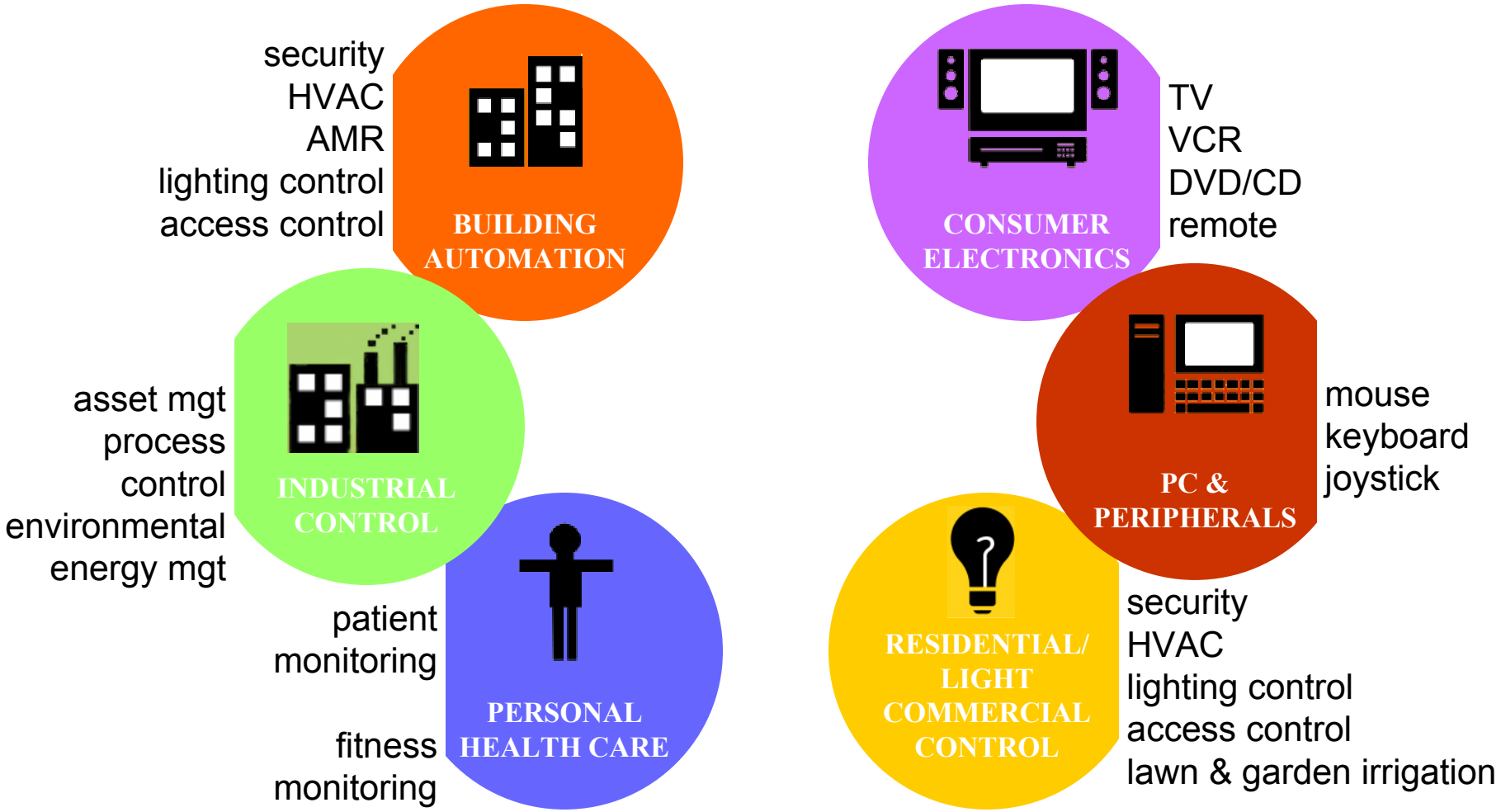
- The market is real
  - Industrial Automation, Building Automation
  - $100M? in 2006, $500M by 2010
- Adoption is gated by reliability and power
- Existing commercial solutions meet those requirements

UC Monitoring Ideas

- 10,000 points per campus
- Campus-wide submetering at 10kW level
- Every steam trap, every chiller, …

Additional Slides

Low Data Rate WPAN Applications (Zigbee)



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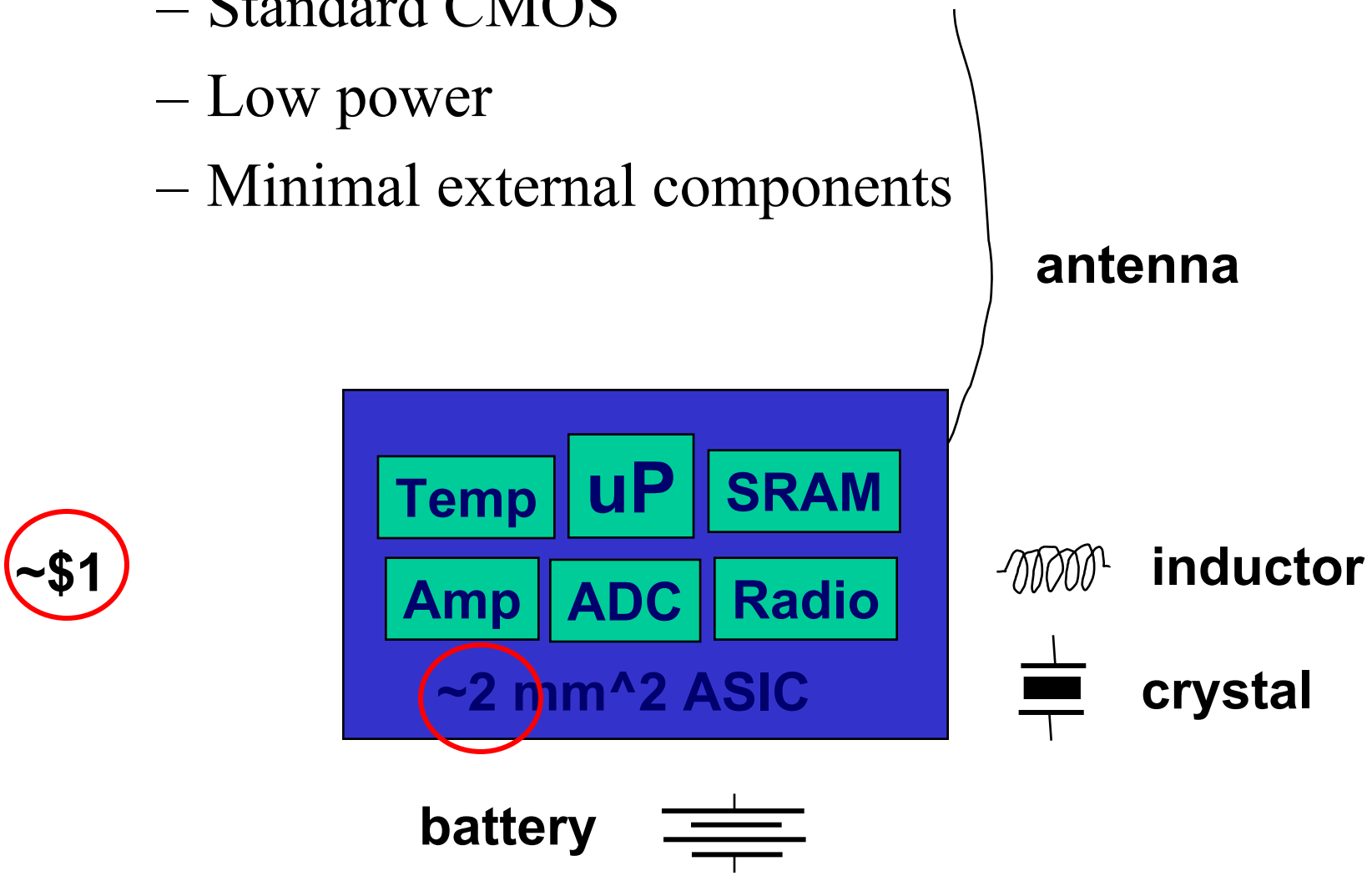
Mote on a Chip? (circa 2001)

- Goals:
  - Standard CMOS
  - Low power
  - Minimal external components



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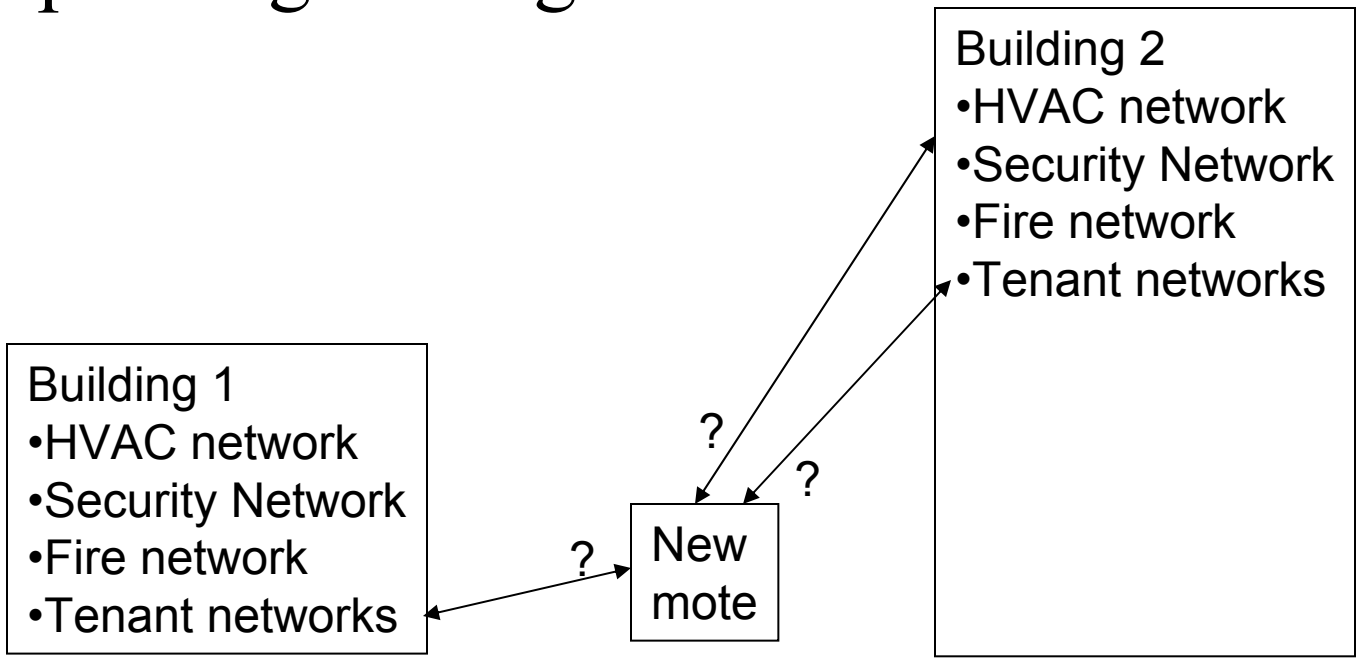
Use cases

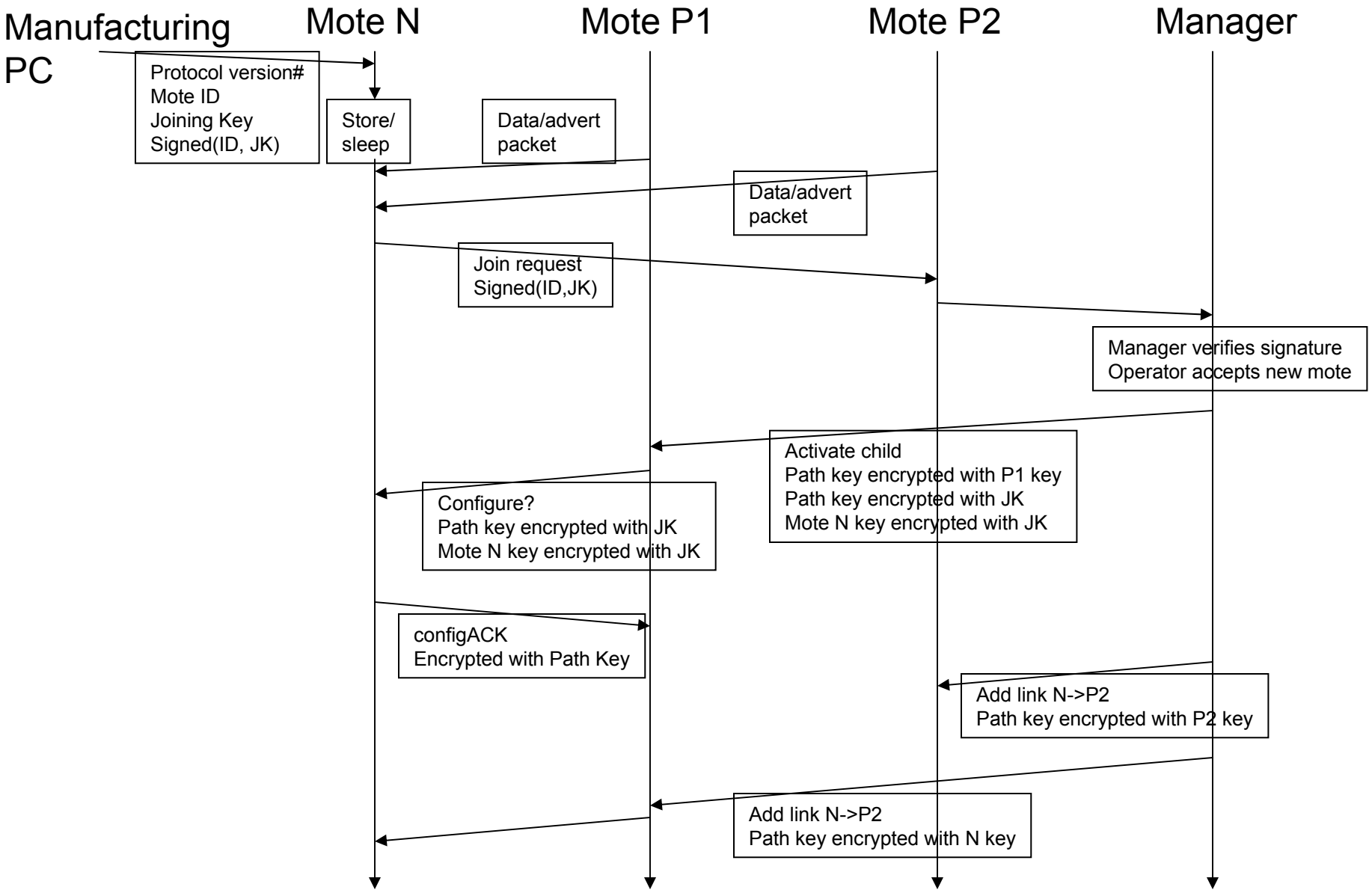
- One supplier/integrator
- One supplier, separate integrator
- Multiple suppliers, one integrator
- Multiple suppliers, multiple integrators, multiple neighboring customers



Security Goals

- Encryption
  - Make sure that no one can see the data
- Integrity
  - Make sure that no one can fake the data, fake control packets, screw up the network with replay of old packets, screw up the network with random packets
  - Make sure that random bit errors don't screw up the network
- Certification
  - Networks only accept trusted motes
  - Motes only join trusted networks
- Binding
  - Motes only join the right network

From manufacture to 3AM join



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Radio Reliability in a Crowded Spectrum

- UWB?
  - Unclear potential for duty cycling
- DSSS doesn't cut it
  - Helpful, but only about 10dB
- +20 dBm doesn't cut it
  - Helpful, but expensive in batteries
  - 802.11 & cordless phones
- Must frequency hop
  - Time synchronization required…

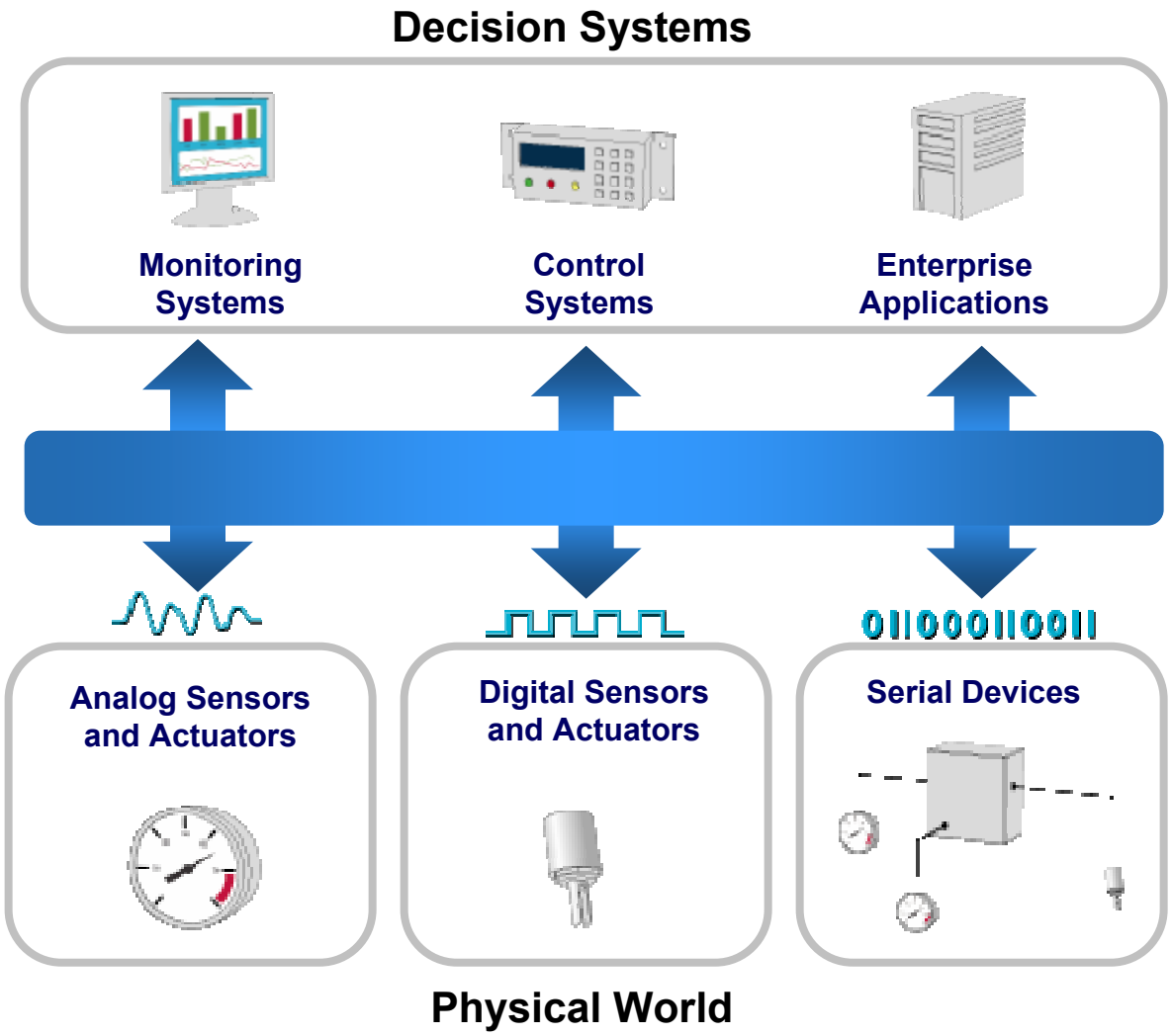
    …but you probably needed that anyway.
  - Lots of channels, lots of bandwidth, better scaling, …

Zigbee 1.0

- Single channel networks are built into standard. This will be fatal for reliability.
- Tree-based routing recommended by standard will likely not be adopted, especially given the single-channel radio.
- No definition of duty cycling routers
  - Assumes powered routers, battery powered leaf nodes
  - No explicit prevention of router duty cycling – Zigbee 2.0?

JW1

Wireless Sensor Networking



- Significant reduction in the cost of installing sensor networks
- Enables new class of services
- Increases sensor deployment

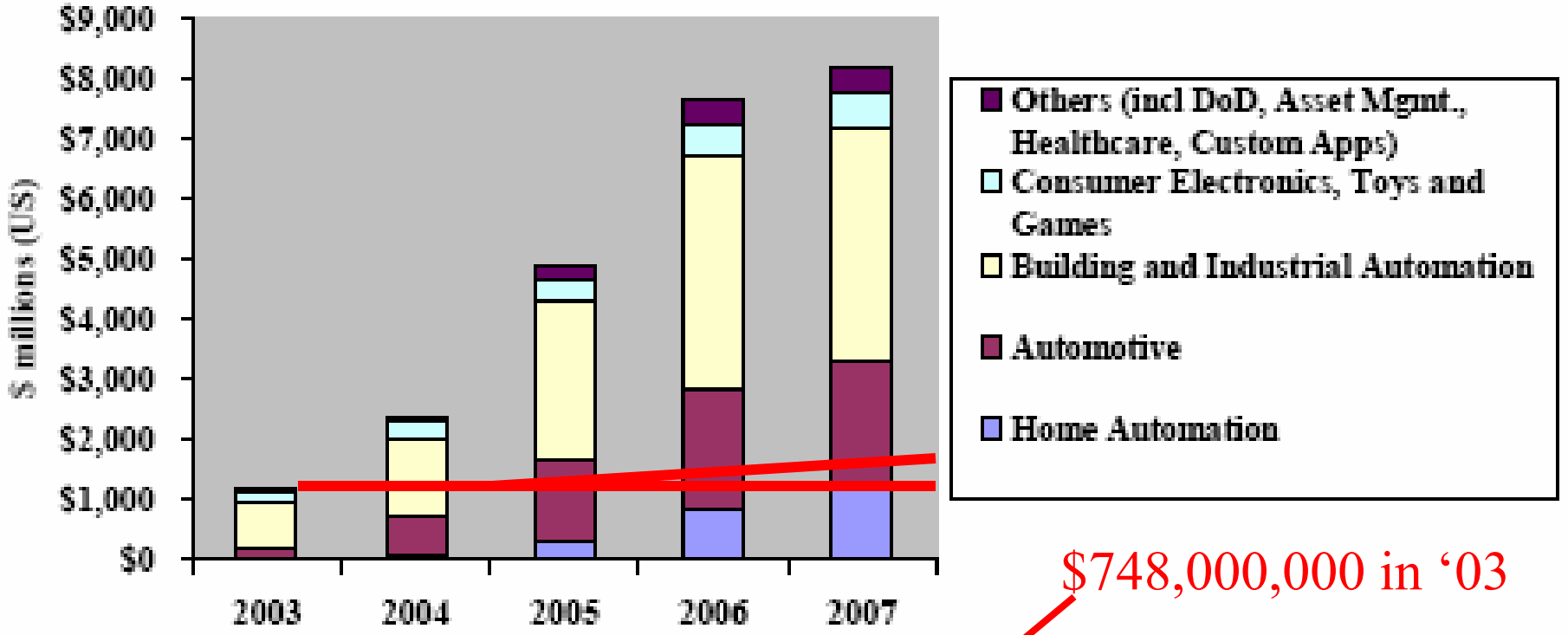
DUST NETWORKS

Slide 40

JW1 conversation on their perception of value to sensor company: do they see it increasing the deployment of sensors ?
Joy Weiss, 10/4/2004

WW LR-WPAN Component Revenues by Industry

WDRG, 2003



$748,000,000 in '03

($ US millions)

Industry	2003	2004	2005	2006	2007	CAGR
Home Automation	$ 39	$ 79	$ 321	$ 821	$ 1,273	101.0%
Automotive	$ 192	$ 615	$ 1,345	$ 2,022	$ 2,033	60.4%
Building and Industrial Automation	$ 748	$ 1,333	$ 2,648	$ 3,910	$ 3,873	38.9%
Consumer Electronics, Toys and Games	$ 164	$ 275	$ 384	$ 528	$ 585	29.0%
Others (incl DoD, Asset Mgmt., Healthcare, Custom Apps)	$ 33	$ 74	$ 216	$ 377	$ 419	65.8%
Total	$ 1,176	$ 2,377	$ 4,914	$ 7,659	$ 8,183	47.4%

Dust Networks

- Founded July 2002
  - Angels, In-Q-Tel, ~$1.5M
  - 28 employees in Jan 04
- Series A Feb 2004
  - Foundation
  - IVP
- Series B Feb 2005
  - Crescendo
  - Cargill