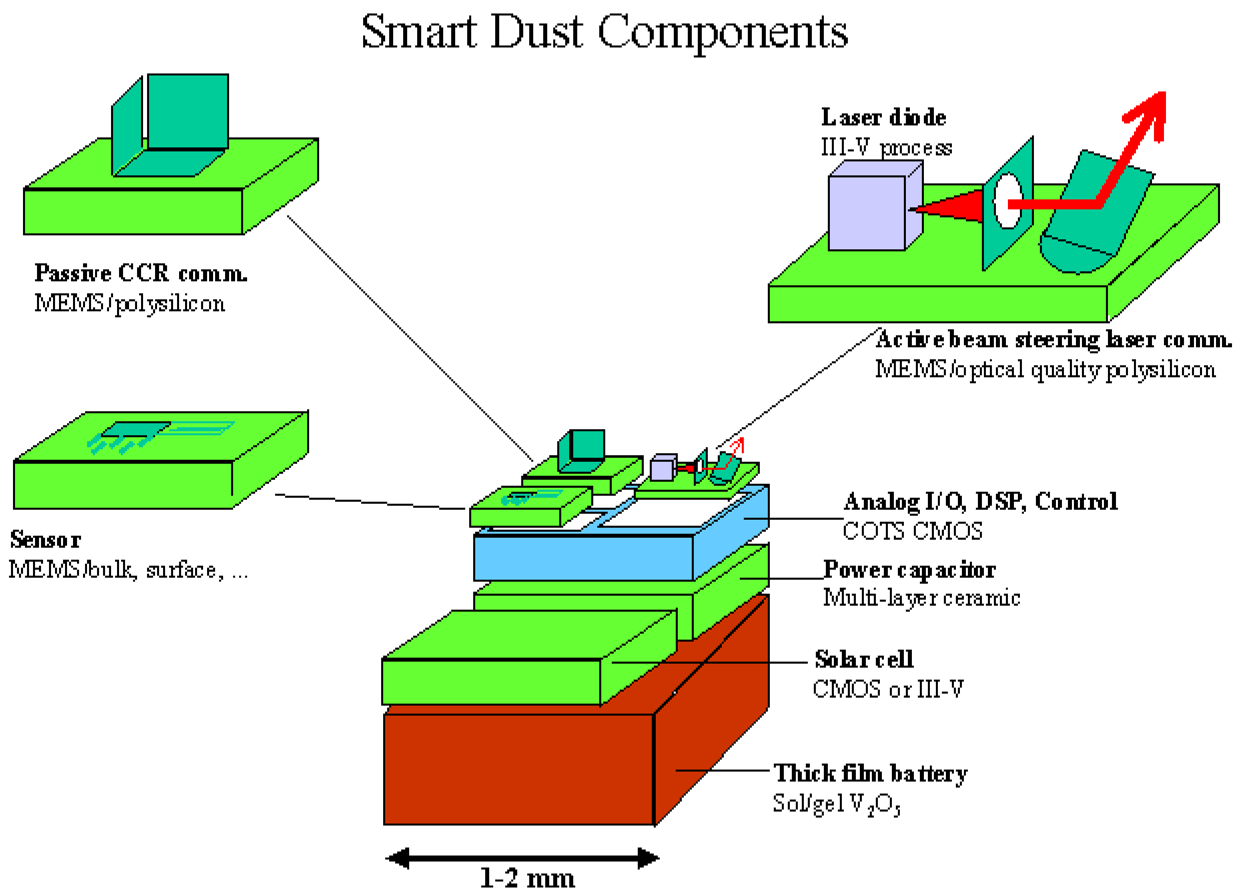
From Smart Dust to Reliable Networks

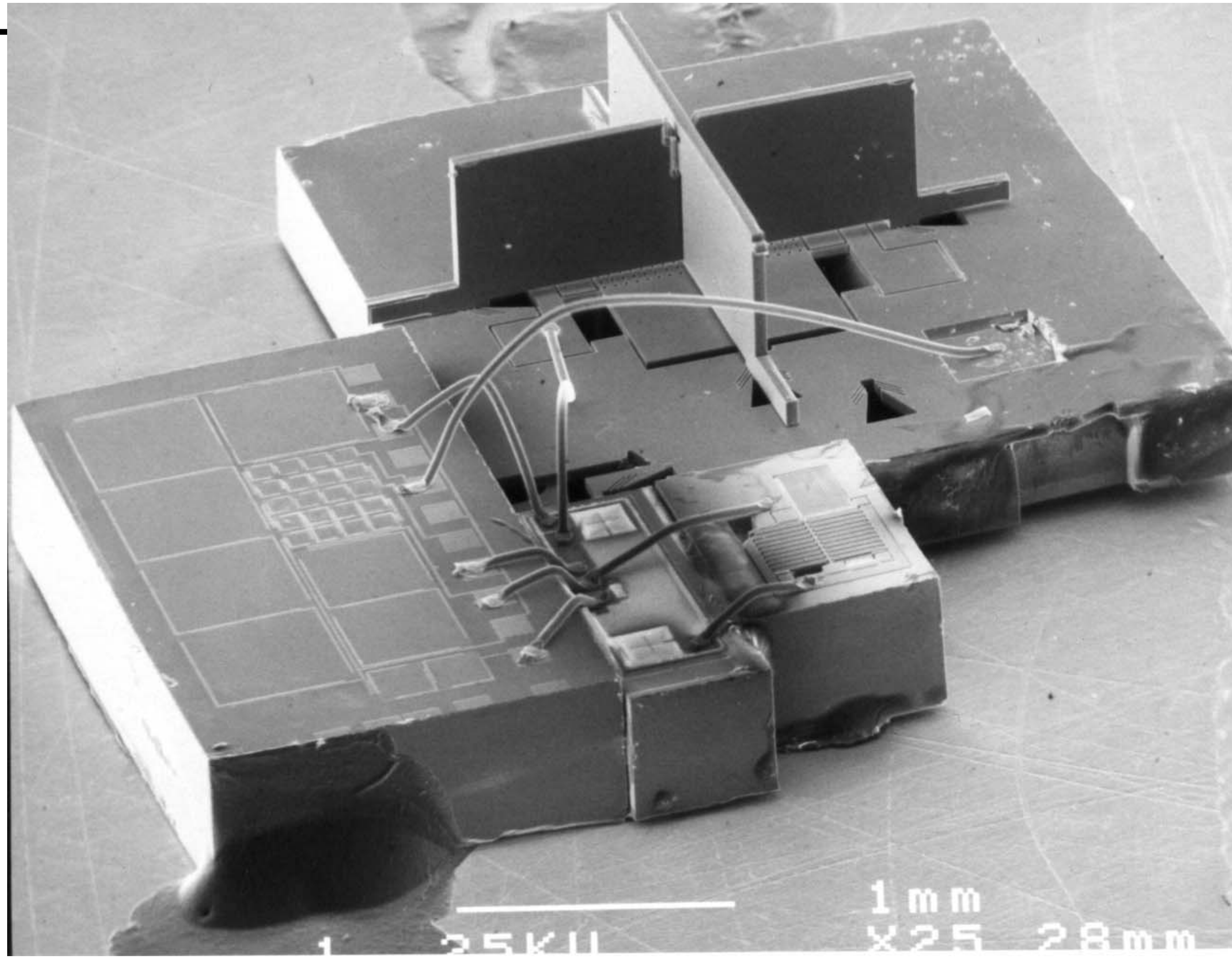
Kris Pister
Prof. EECS, UC Berkeley
Founder & CTO, Dust Networks

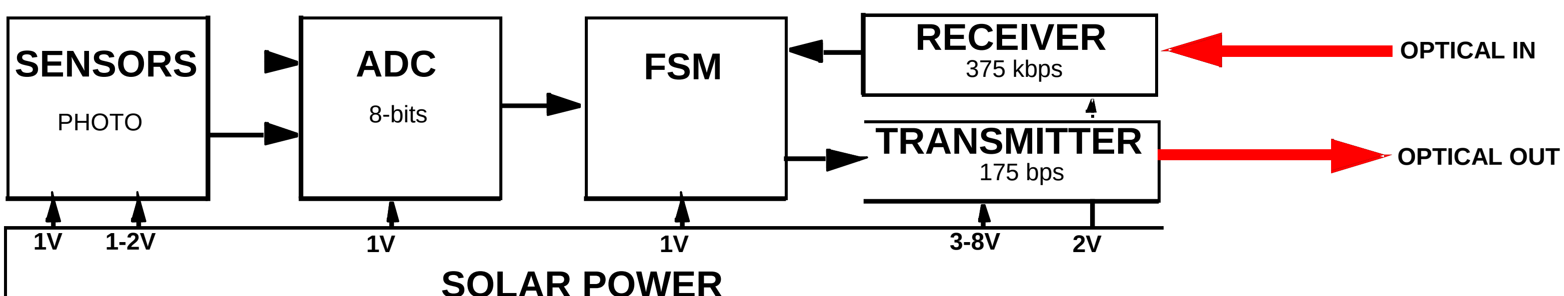
Smart Dust Goal

c. 1997



Smart Dust, 2002





UCB "COTS Dust" Macro Motes

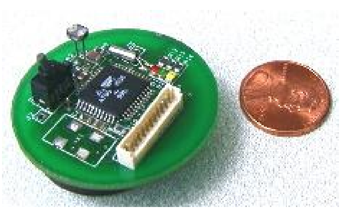
Services

David Culler, UCB

Networking

TinyOS

WeC 99
James McLurkin MS



Small microcontroller

- **8 kb code, 512 B data**

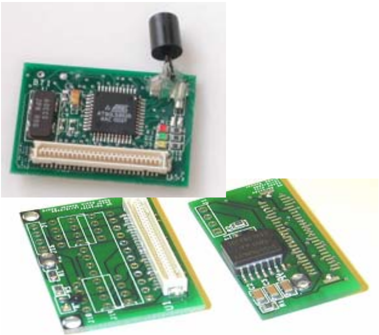
Simple, low-power radio

- **10 kbps**

EEPROM storage (32 KB)

Simple sensors

Rene 00



Designed for experimentation

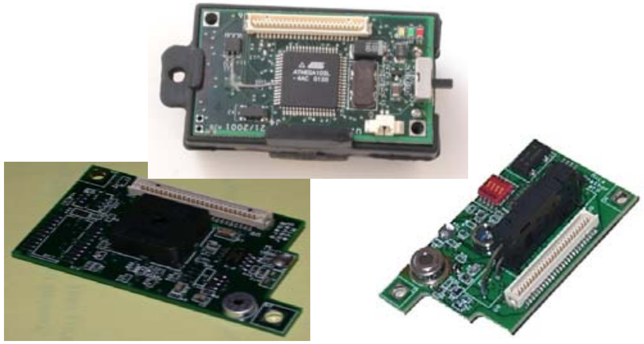
-**sensor boards**

-**power boards**

Dot 01

Demonstrate scale

Mica 02



NEST open exp. platform

128 KB code, 4 KB data

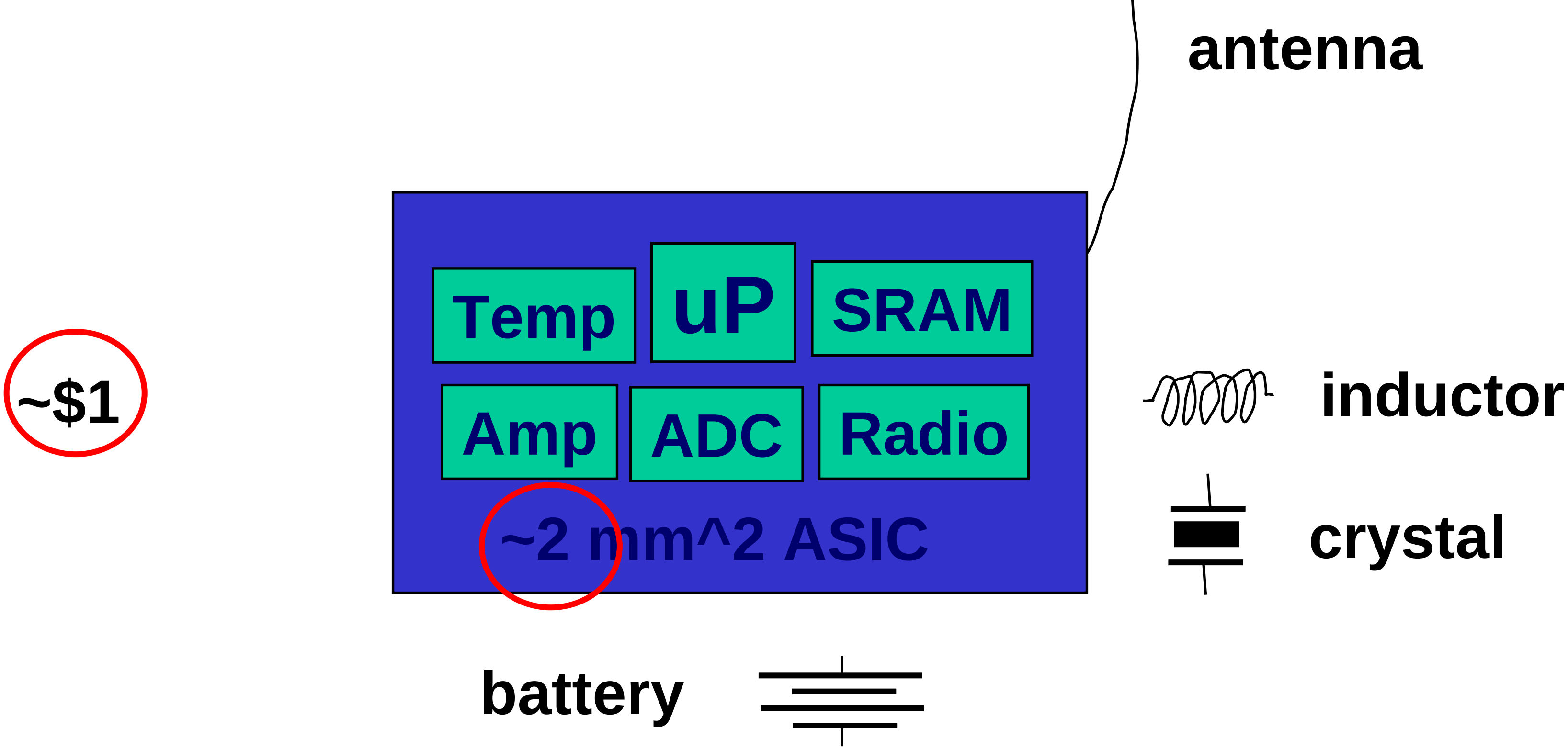
50 KB radio

512 KB Flash

comm accelerators

Mote on a Chip? (circa 2001)

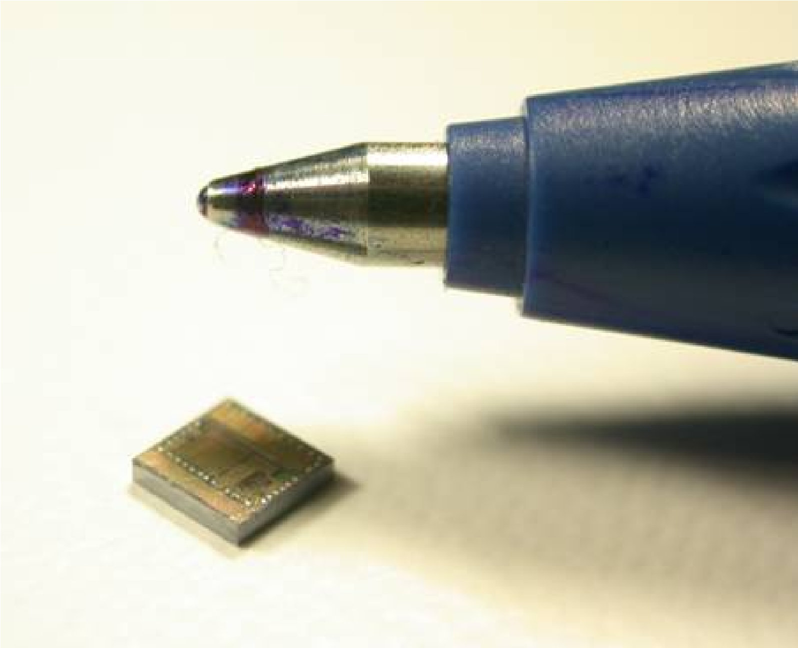
- Goals:
  - Standard CMOS
  - Low power
  - Minimal external components

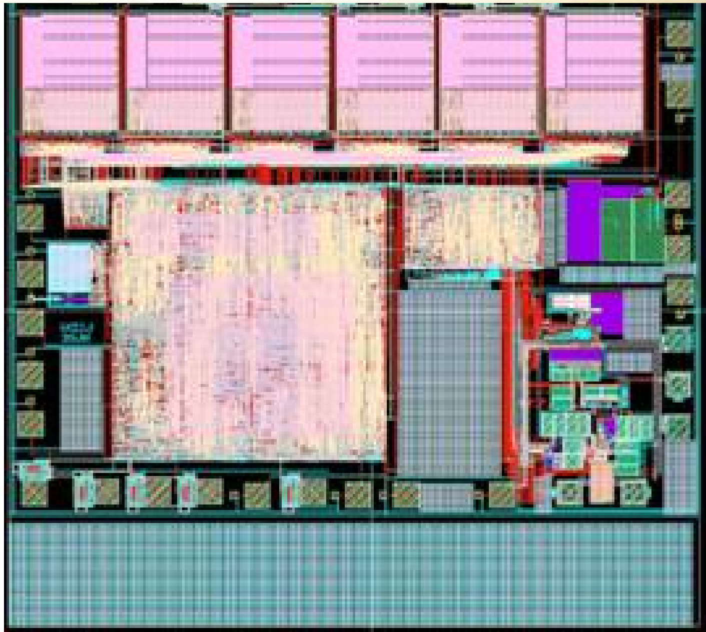


UCB Hardware Results ~2003

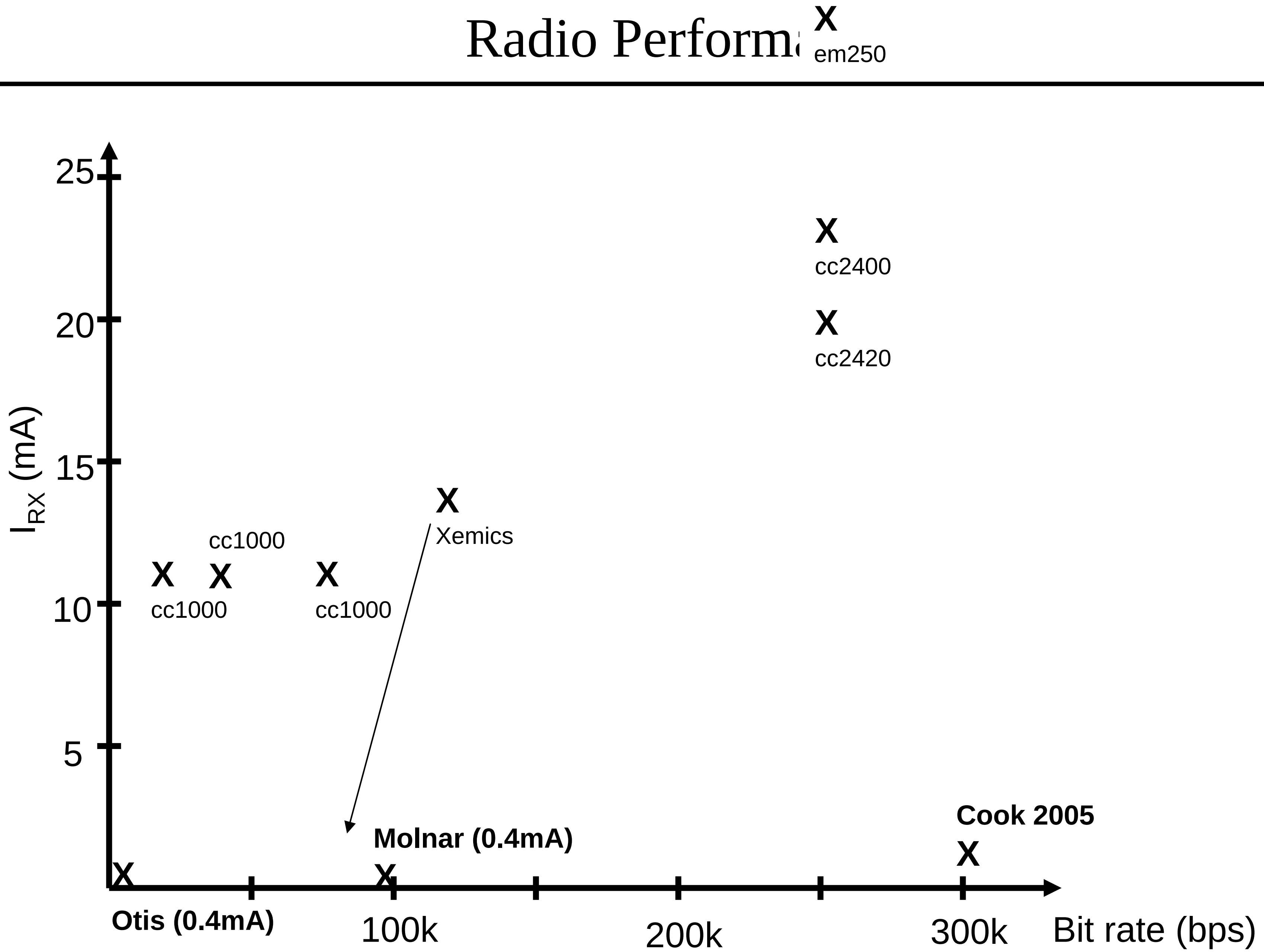
- 2 chips fabbed in 0.25um CMOS
  - "Mote on a chip" worked, missing radio RX
  - 900 MHz transceiver worked

- 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

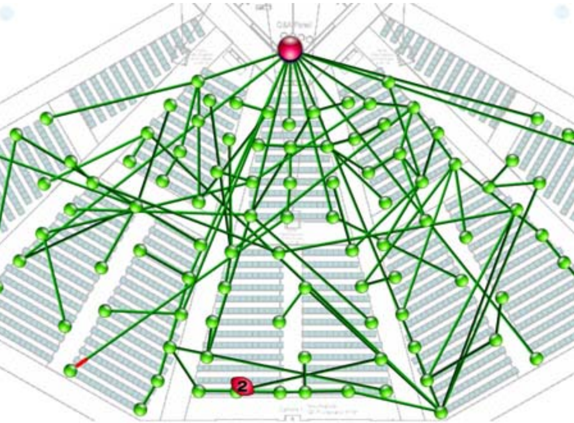
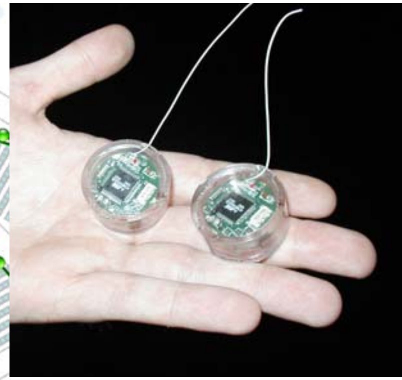




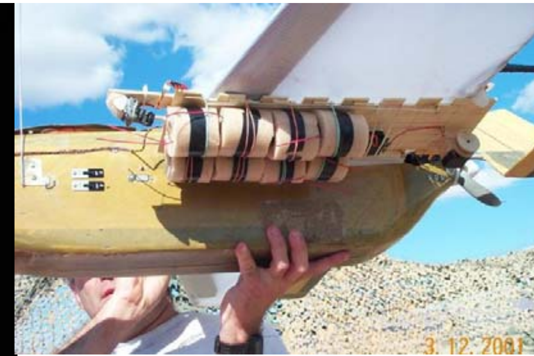
Radio Performa



University Demos – Results of 100 man-years of research

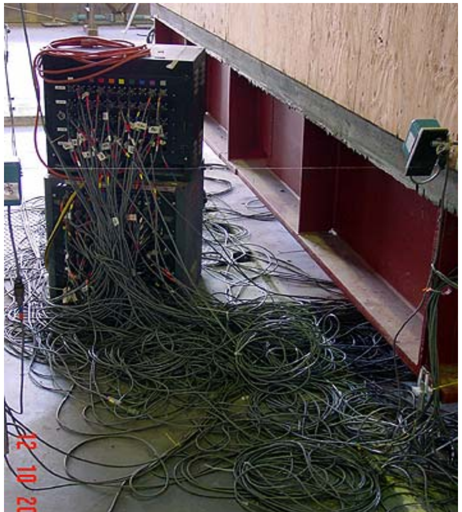
Intel Developers Forum, live demo 800 motes, 8 level dynamic network,



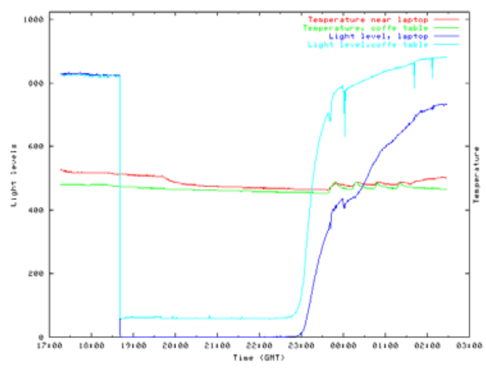
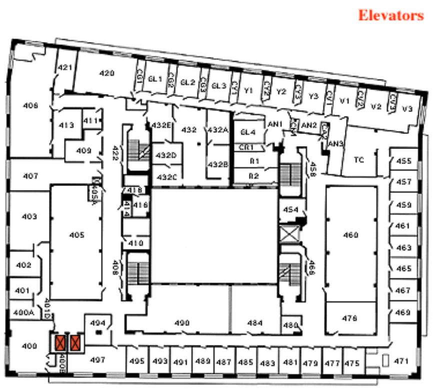

Motes dropped from UAV, detect vehicles, log and report direction and velocity

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.

What do OEMs and SIs want?

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

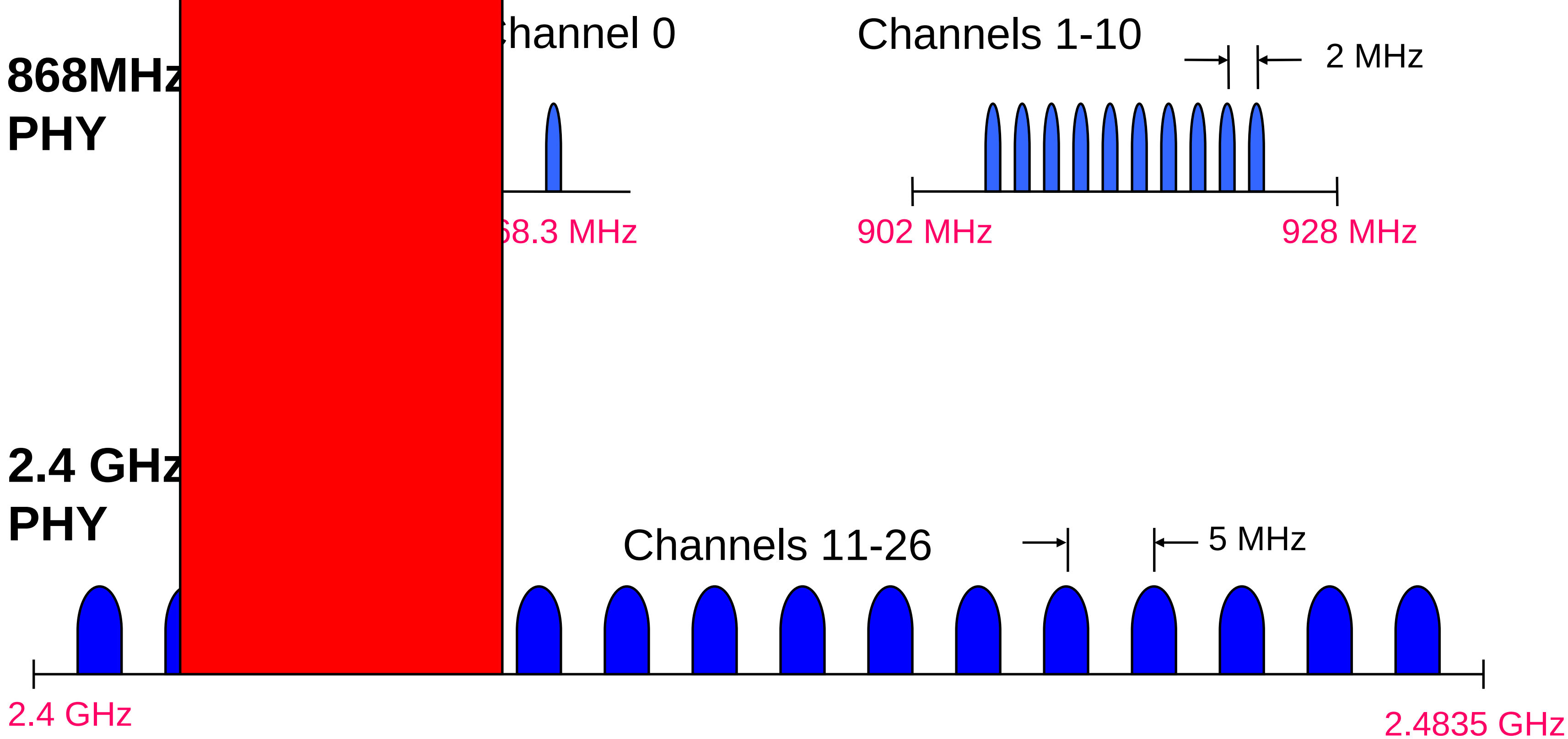
- Reliability
- Reliability
- Reliability
- Low installation and ownership costs
  - No wires; >5 year battery life
  - No network configuration
  - No network management
- Typically "trivial" data flow
  - Regular data collection
    - 1 sample/minute…1 sample/day?
  - Event detection
    - Threshold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

Reliability

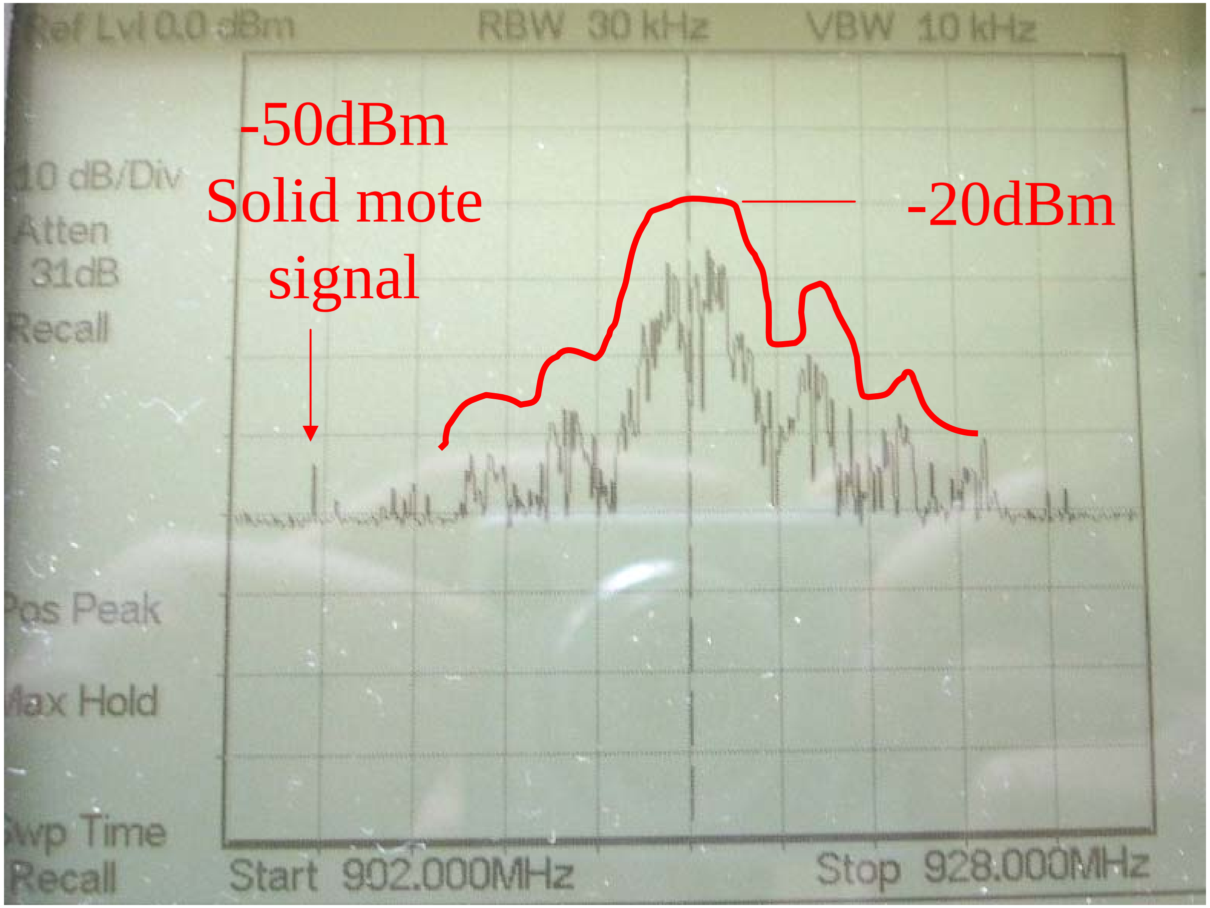
- Hardware
  - Temperature, humidity, shock
  - Aging
  - MTBF = 5 centuries
- Software
  - Linux yes (manager/gateway)
  - TinyOS no (motes)
- Networking
  - RF interference
  - RF variability

EE 802.15.4 & WiFi

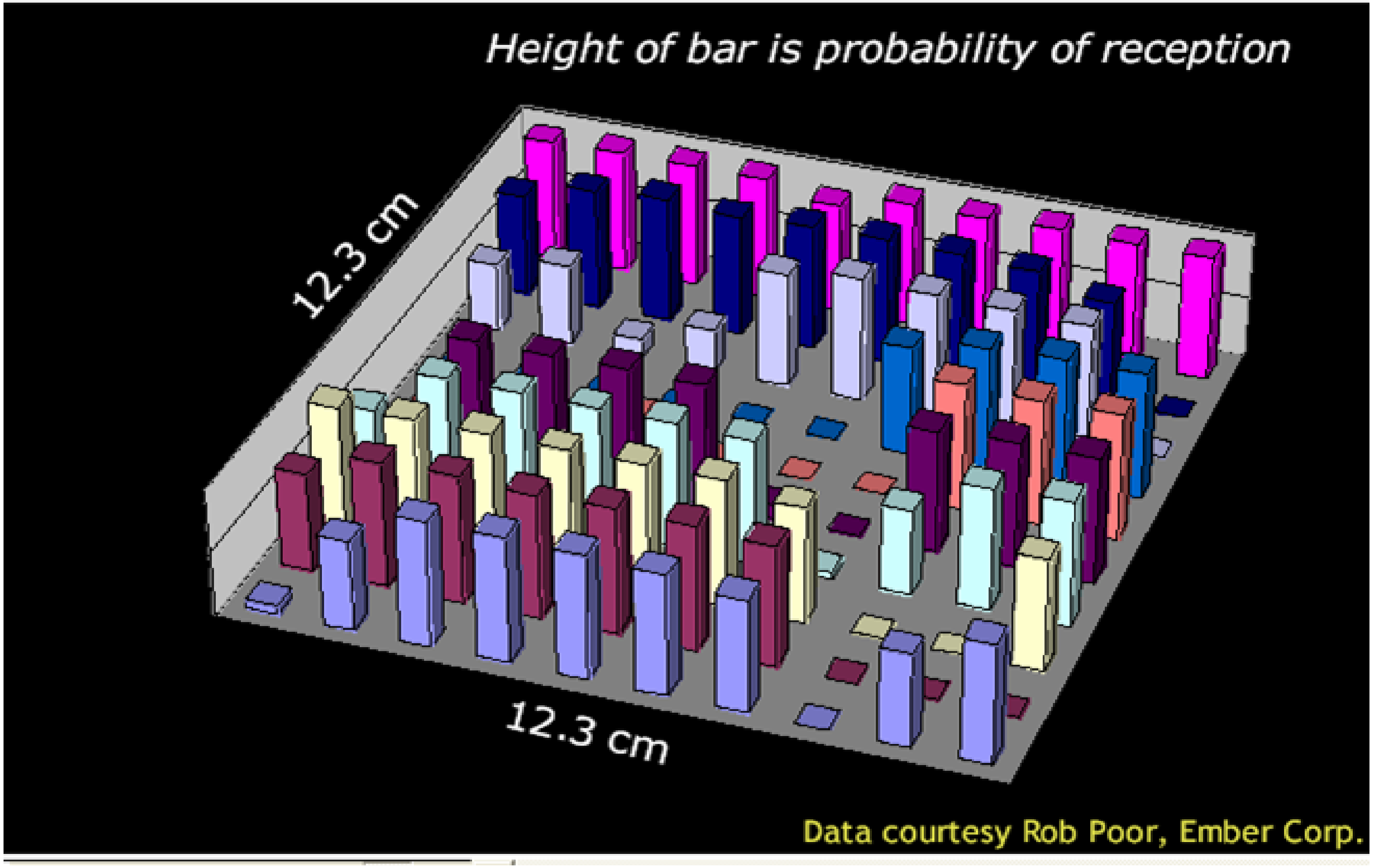
erating Frequency Bands



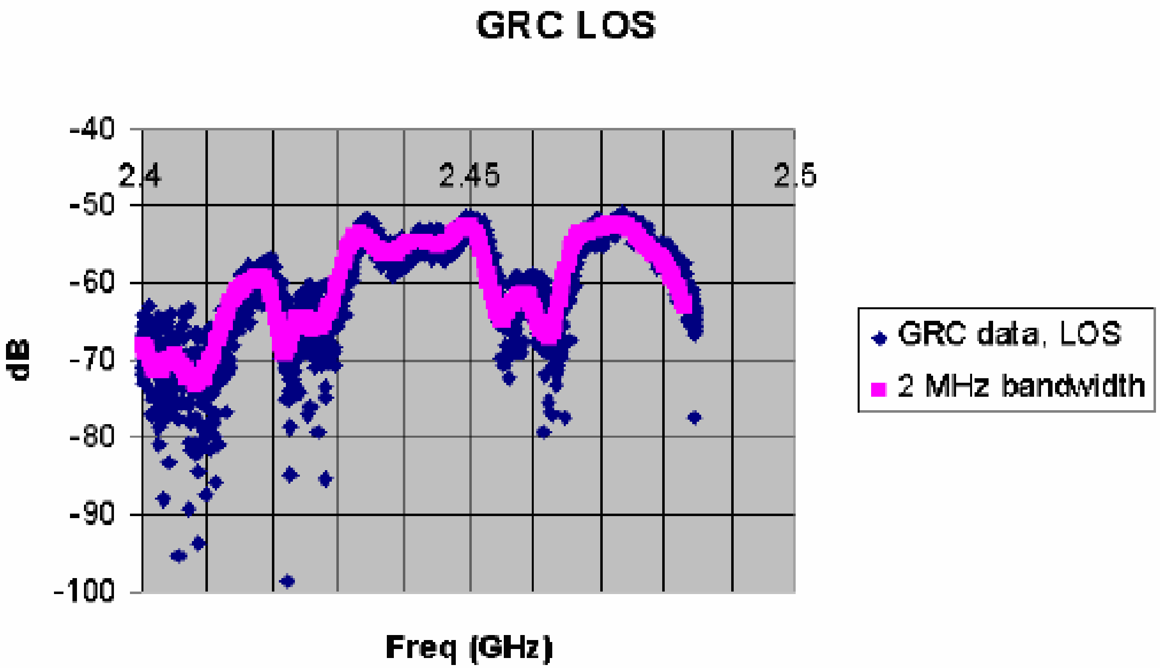
900 MHz cordless phone

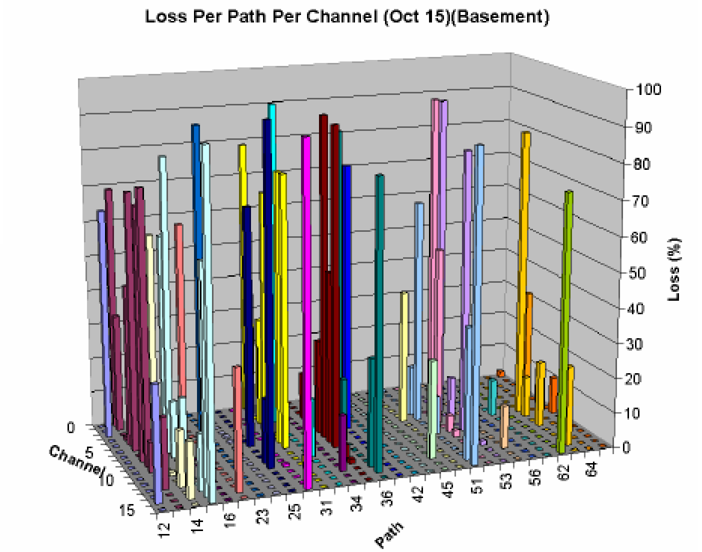


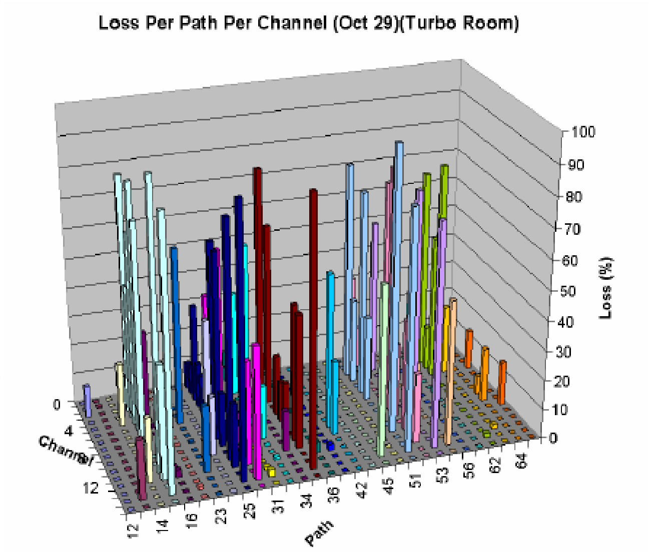
Spatial effect of multipath



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.

Network Architecture

- Goals
  - High reliability
  - Low power consumption
  - No customer development of embedded software
  - Minimal/zero customer RF/networking expertise necessary

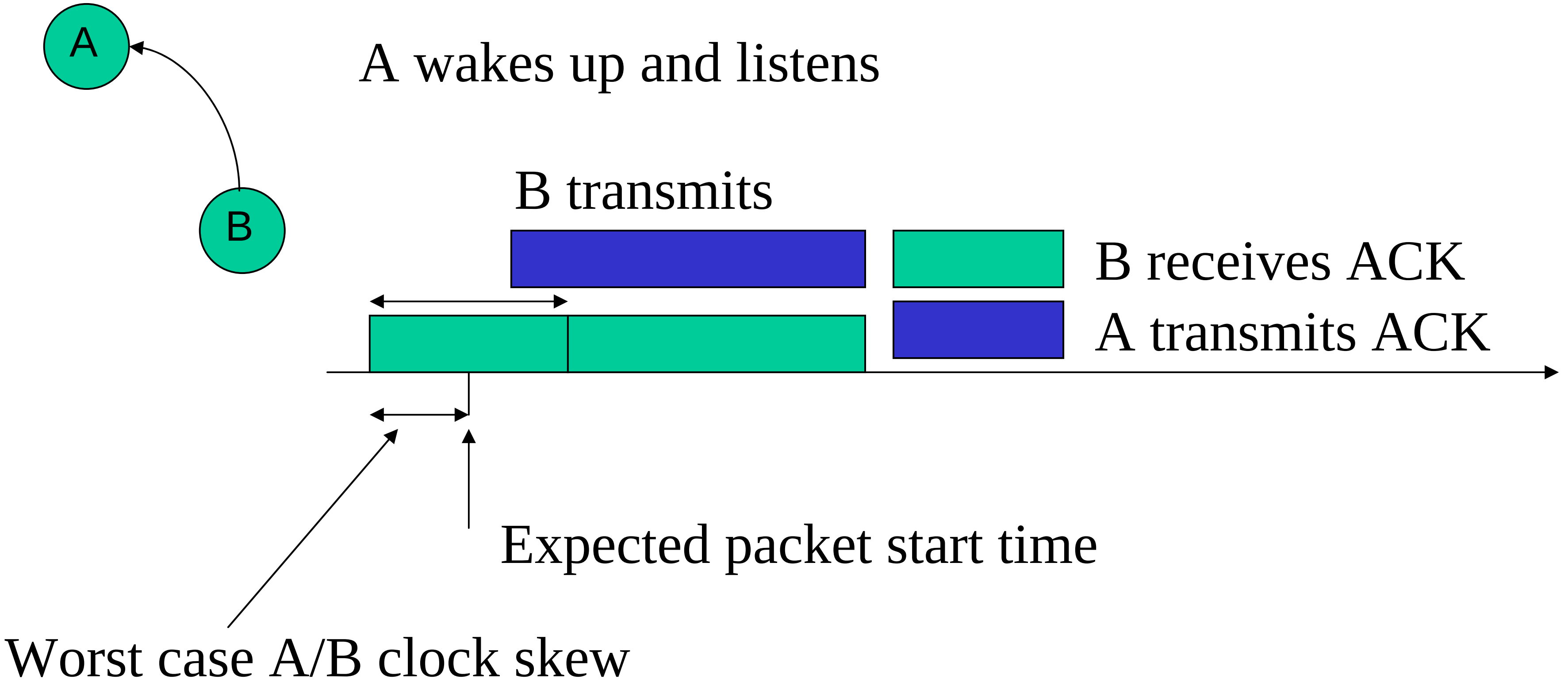
Time Synchronization

- Required for frequency hopping
- Required for low power

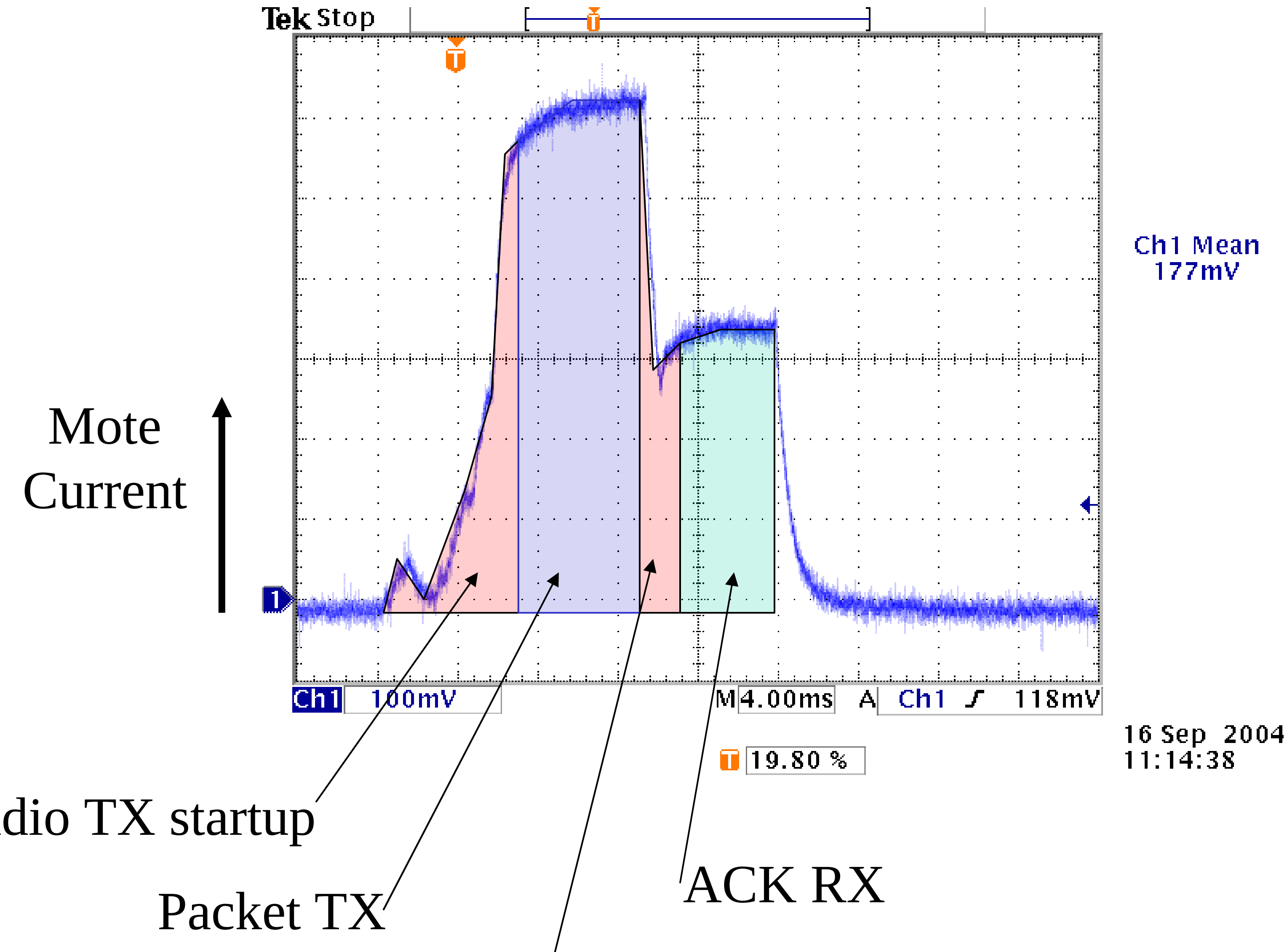
- Lots of good academic work…
- …but you still see this too often
  - "synchronization is hard"
  - "here's something that doesn't work well"
  - "it gets a lot better if we keep track of our neightbors listening/talking/… schedule"

Power-optimal communication

- Assume all motes share a network-wide synchronized sense of time, accurate to ~1ms
- For an optimally efficient network, mote A will only be awake when mote B needs to talk



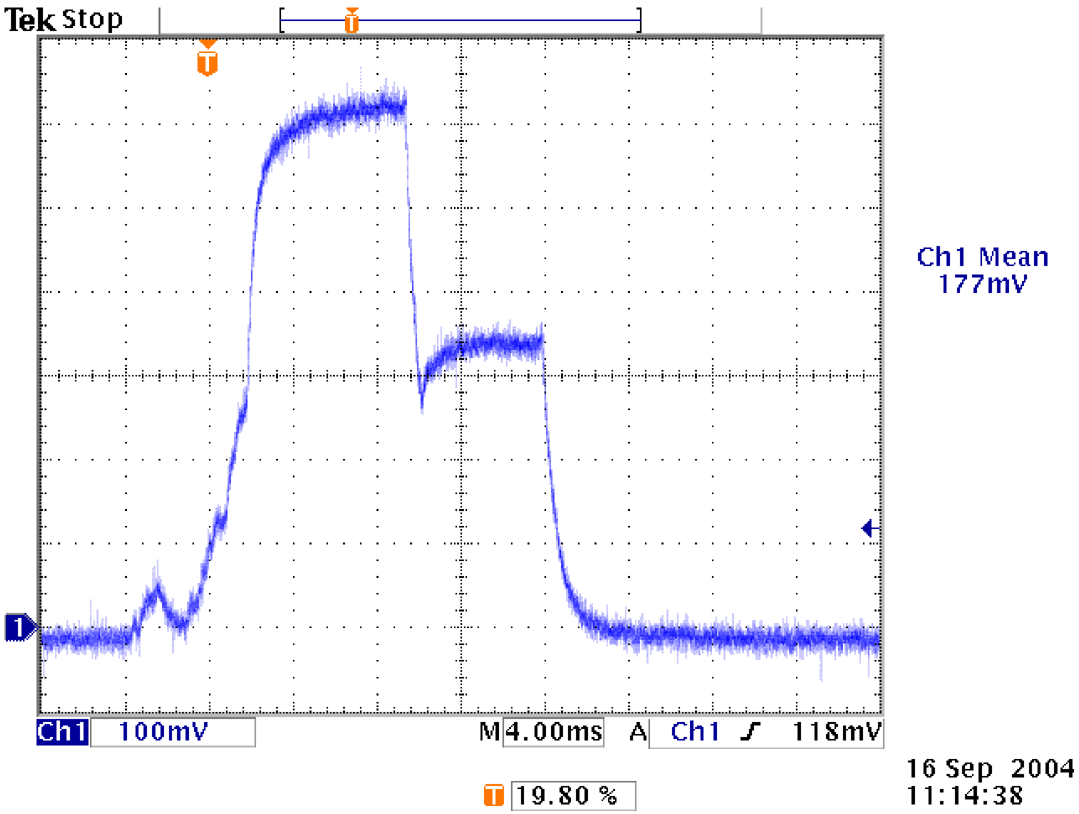
Packet transmission and acknowledgement



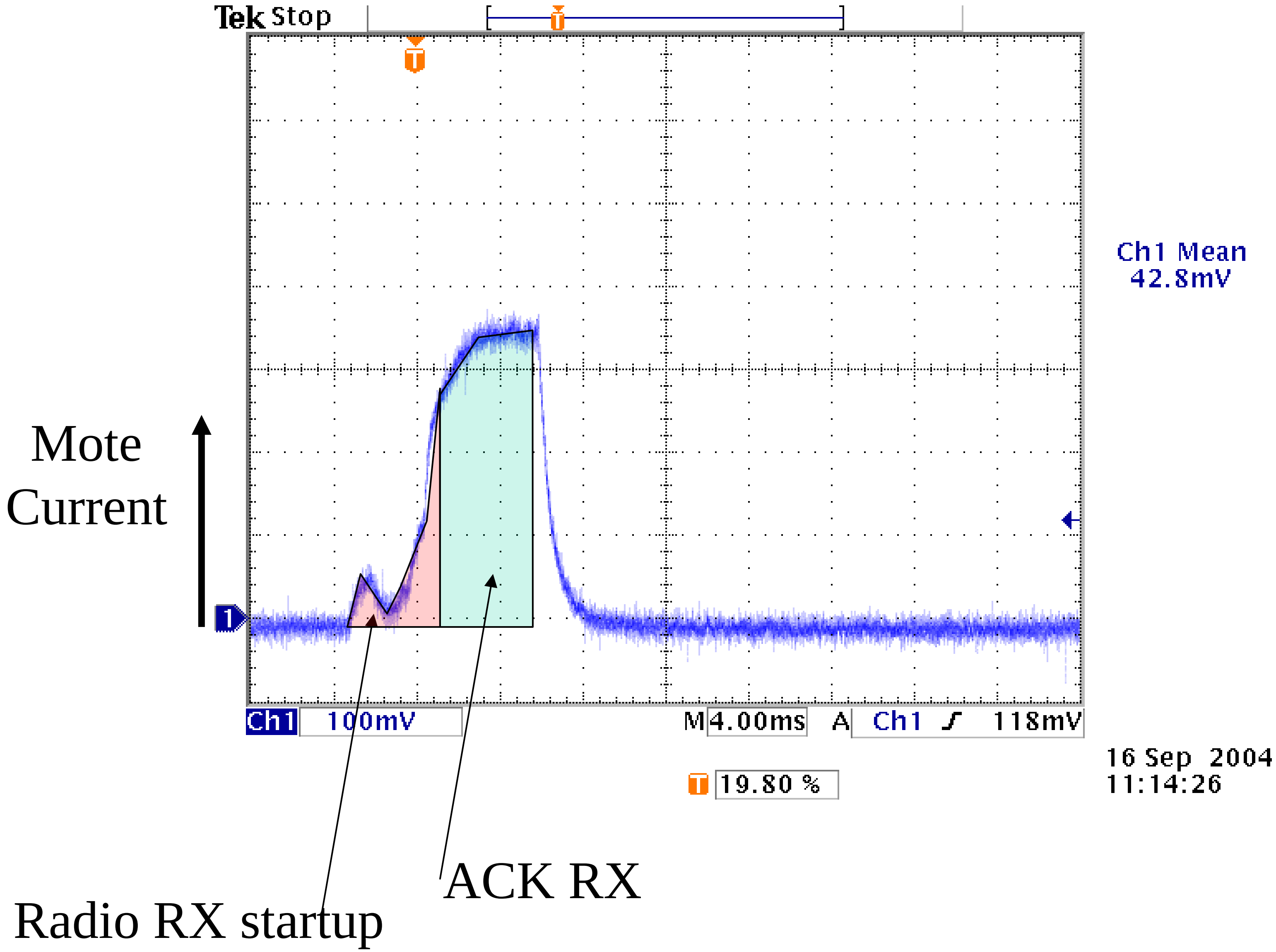
Energy cost: 295 uC

Fundamental platform-specific energy requirements

- Packet energy & packet rate determine power
  - $(Q_{TX} + Q_{RX})/T_{listen}$
  - E.g. (300 uC + 200 uC) /10s = 50 uA



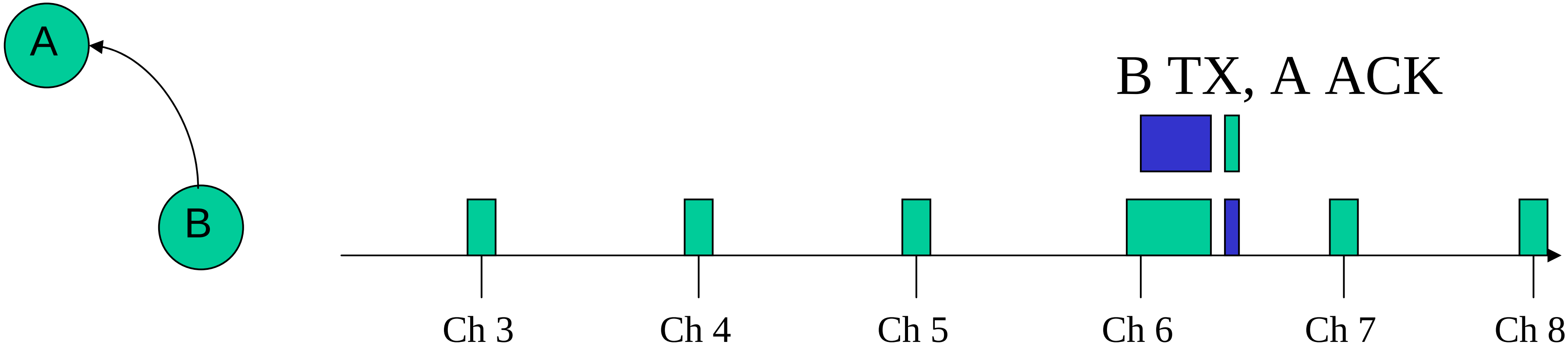
Idle listen (no packet exchanged)



Energy cost: 70 uC

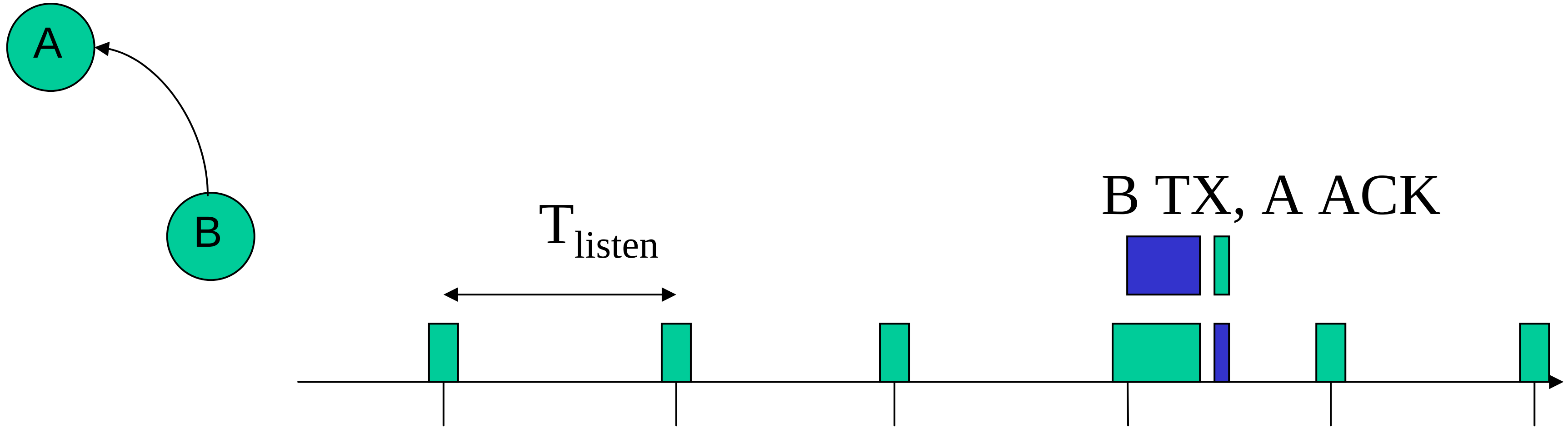
Scheduled Communication Slots

- Mote A can listen more often than mote B transmits
- Since both are time synchronized, a different radio frequency can be used at each wakeup
- Time sync information transmitted in both directions with every packet



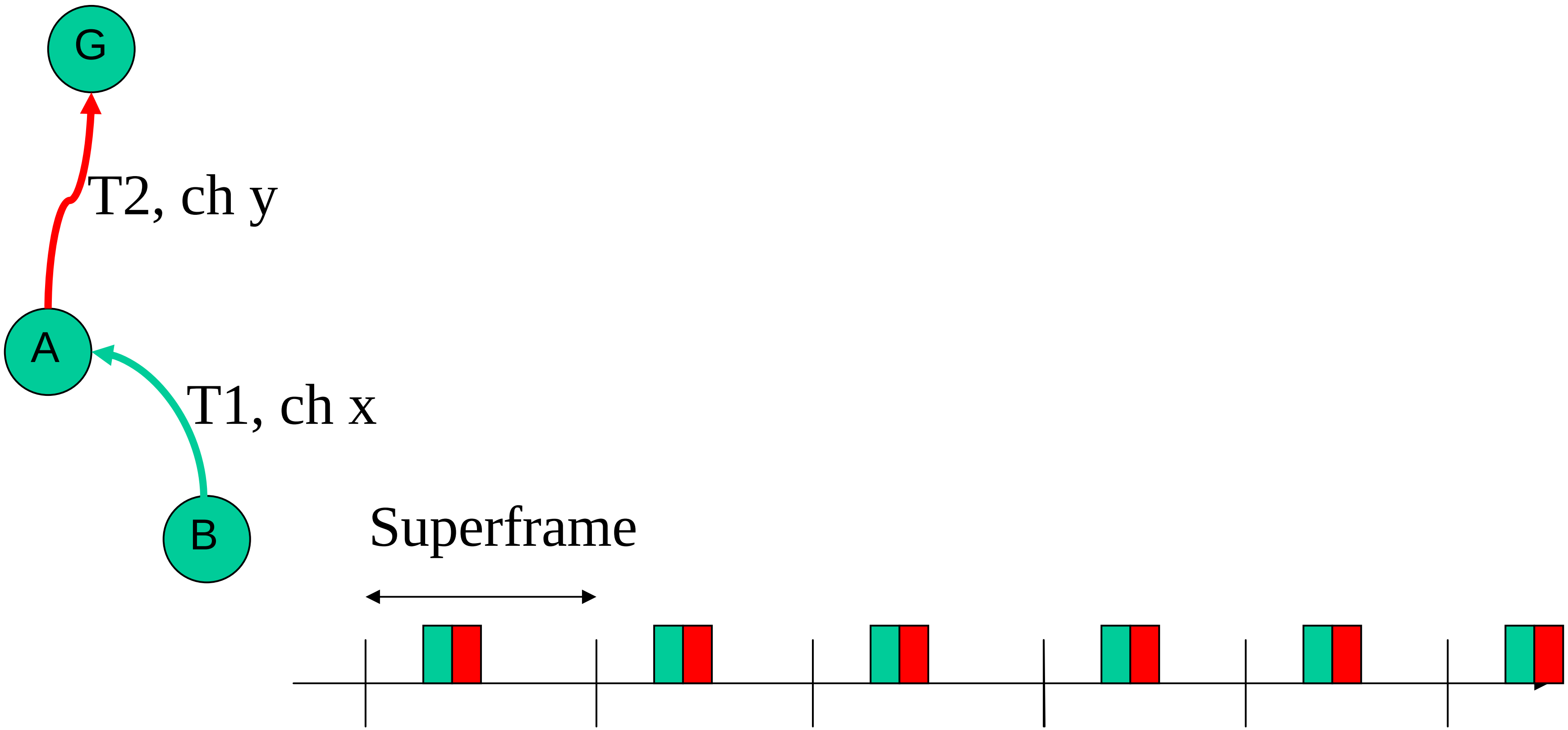
Latency reduction

- Energy cost of latency reduction is easy to calculate:
  - Q_{listen} / T_{listen}
  - E.g. 70uC/10s = 7uA
- Low-cost "virtual on" capability
- Latency vs. power tradeoff can vary by mote, time of day, recent traffic, etc.

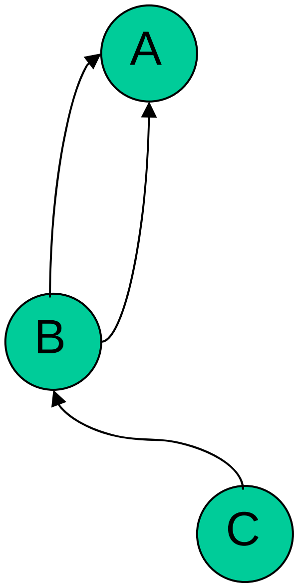


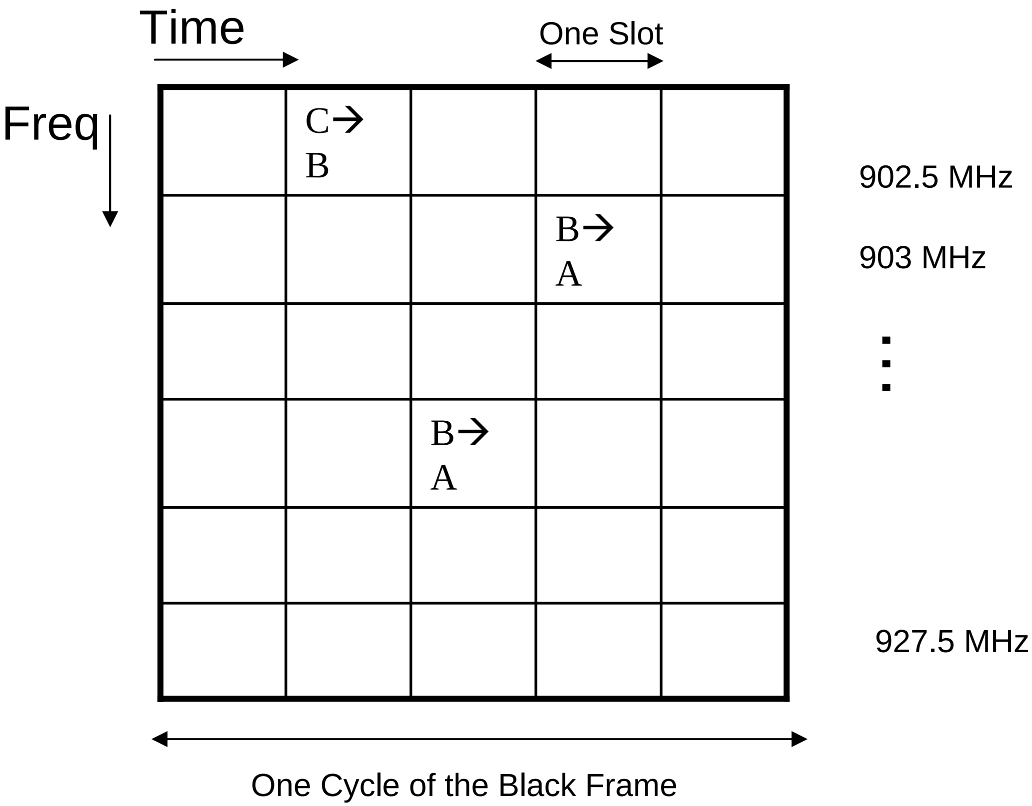
Latency reduction

- Global time synchronization allows sequential ordering of links in a “superframe”
- Measured average latency over many hops is $T_{frame}/2$



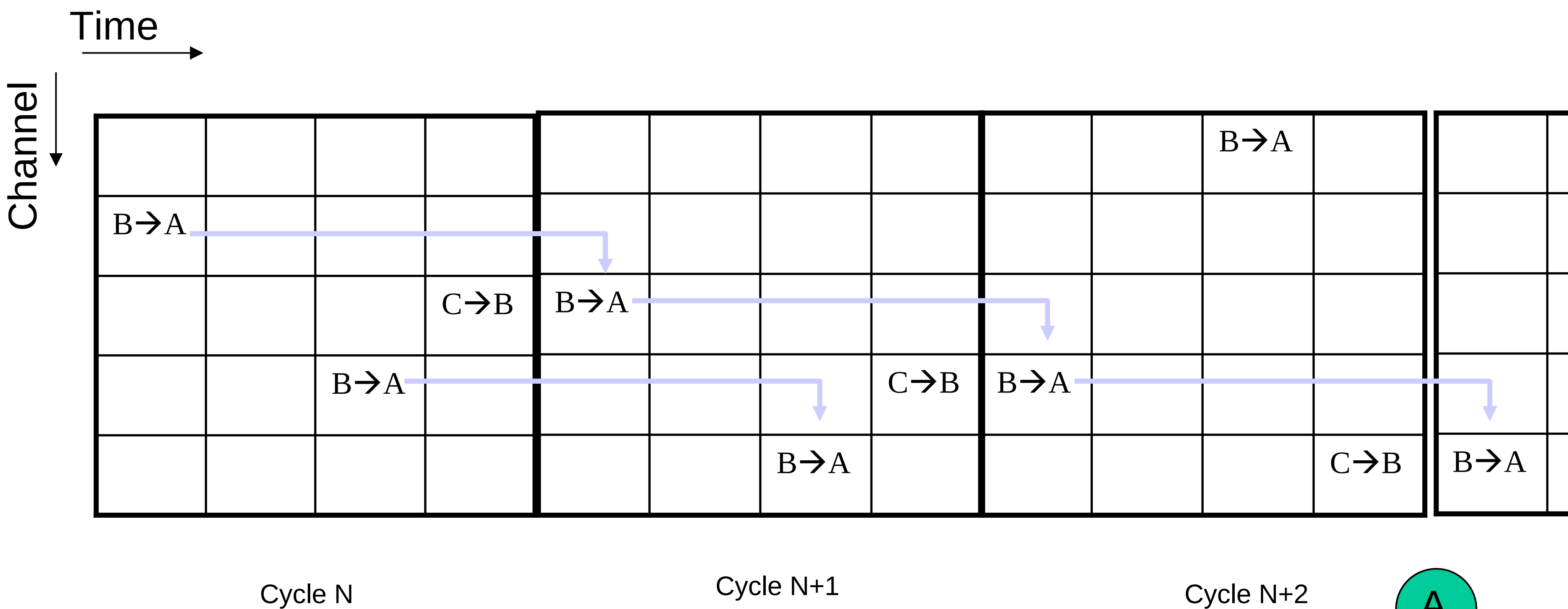
Time and Frequency

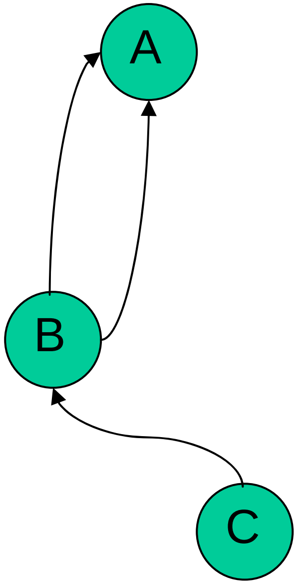




- Graphs & Links are abstract, with no explicit time or frequency information.
- Frames and slots are more concrete
- Time synchronization is required
- Latency, power, characteristic data rate are all related to frame length
- Relative bandwidth is determined by multiplicity of links

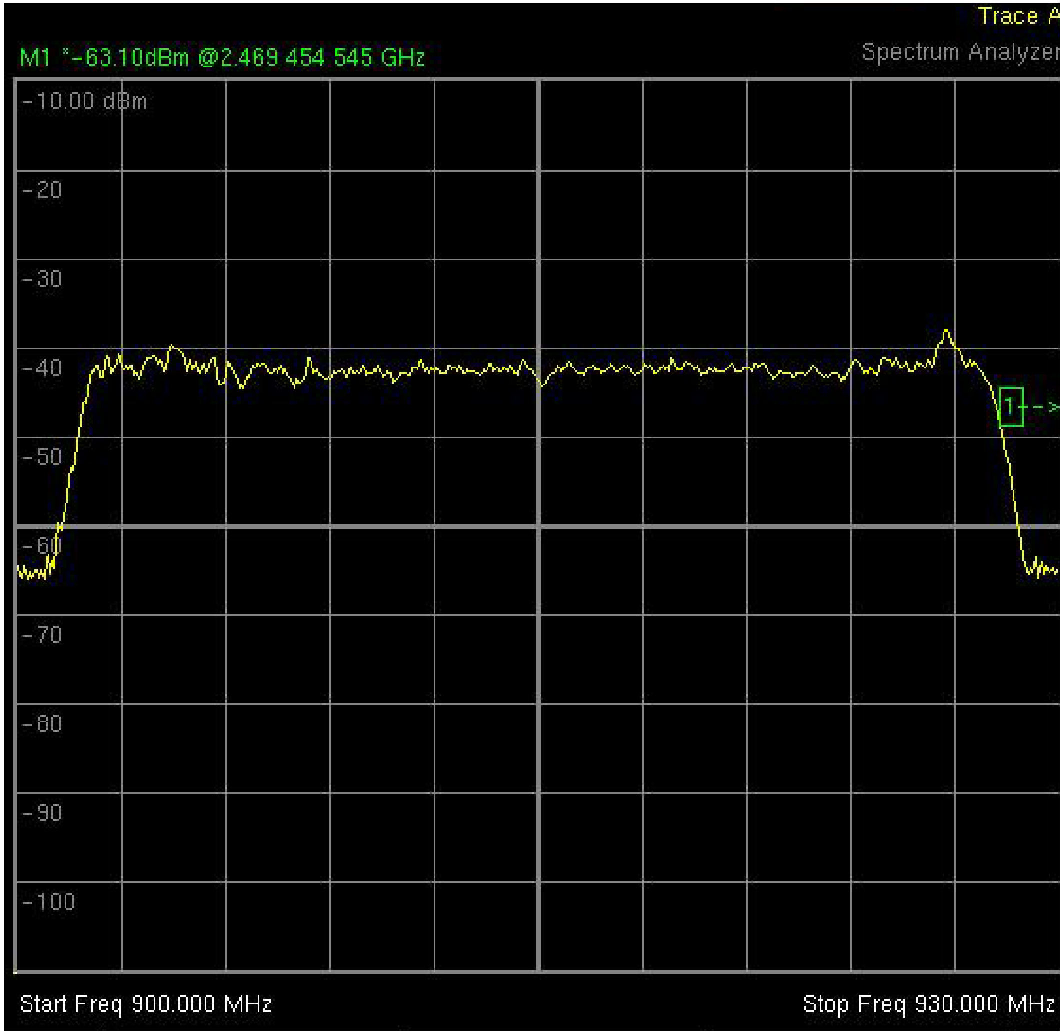
Time and Frequency





- Every link rotates through all RF channels over a sequence of N_{CH} cycles
- 32 slots/sec * 16 ch = 512 cells/sec
- Sequence is pseudo-random

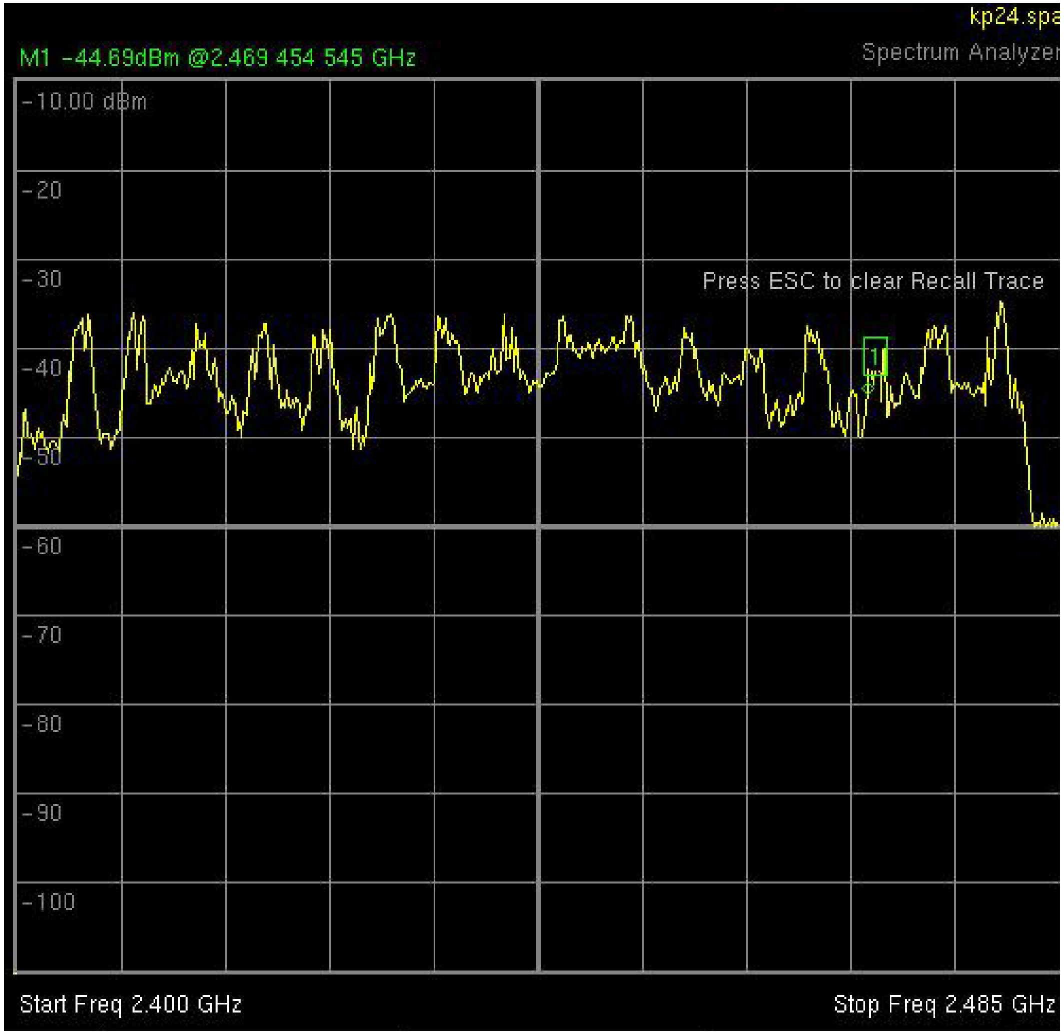
50 channels, 900 MHz



900MHz

930MHz

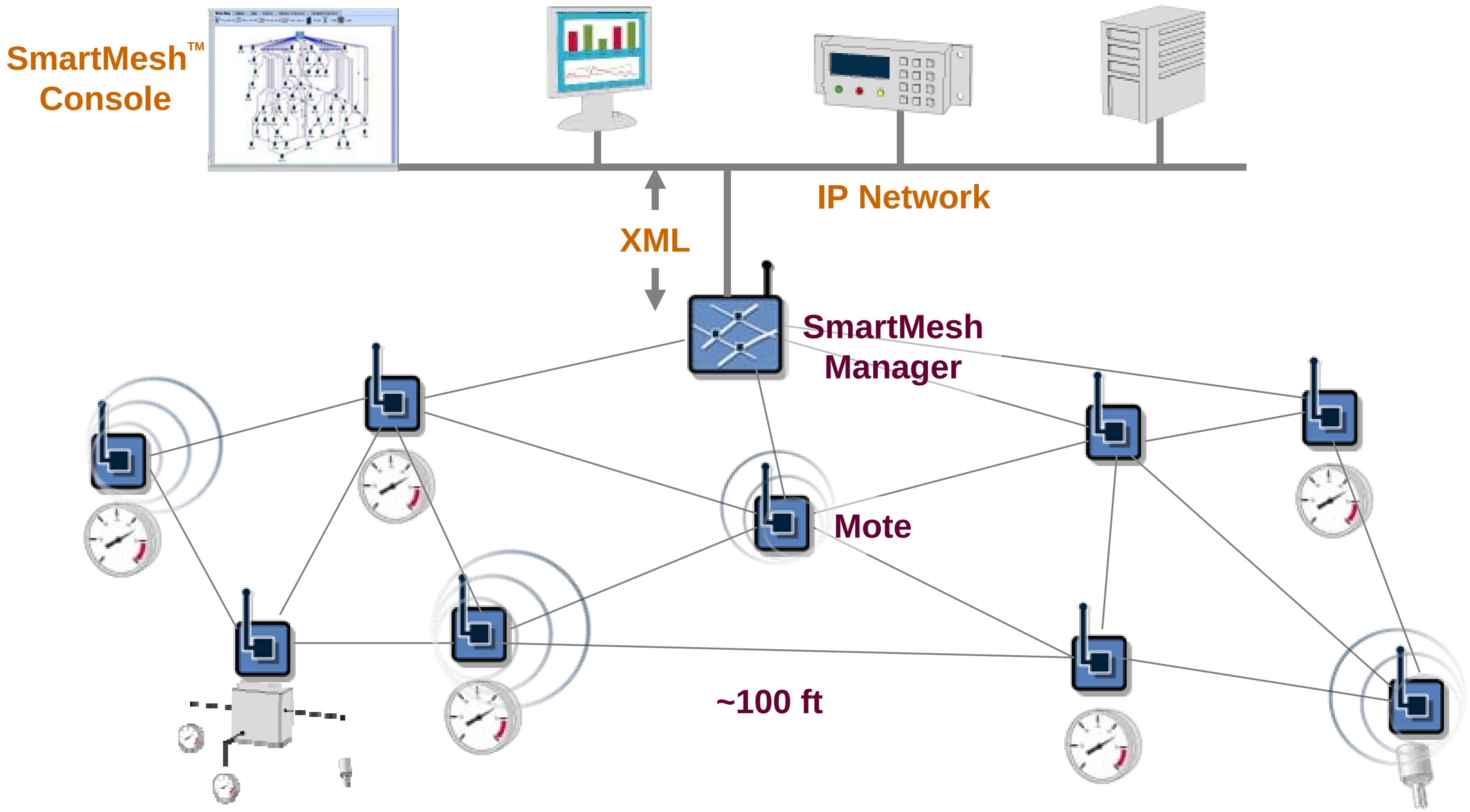
16 channels, 2.4 GHz



2.4GHz

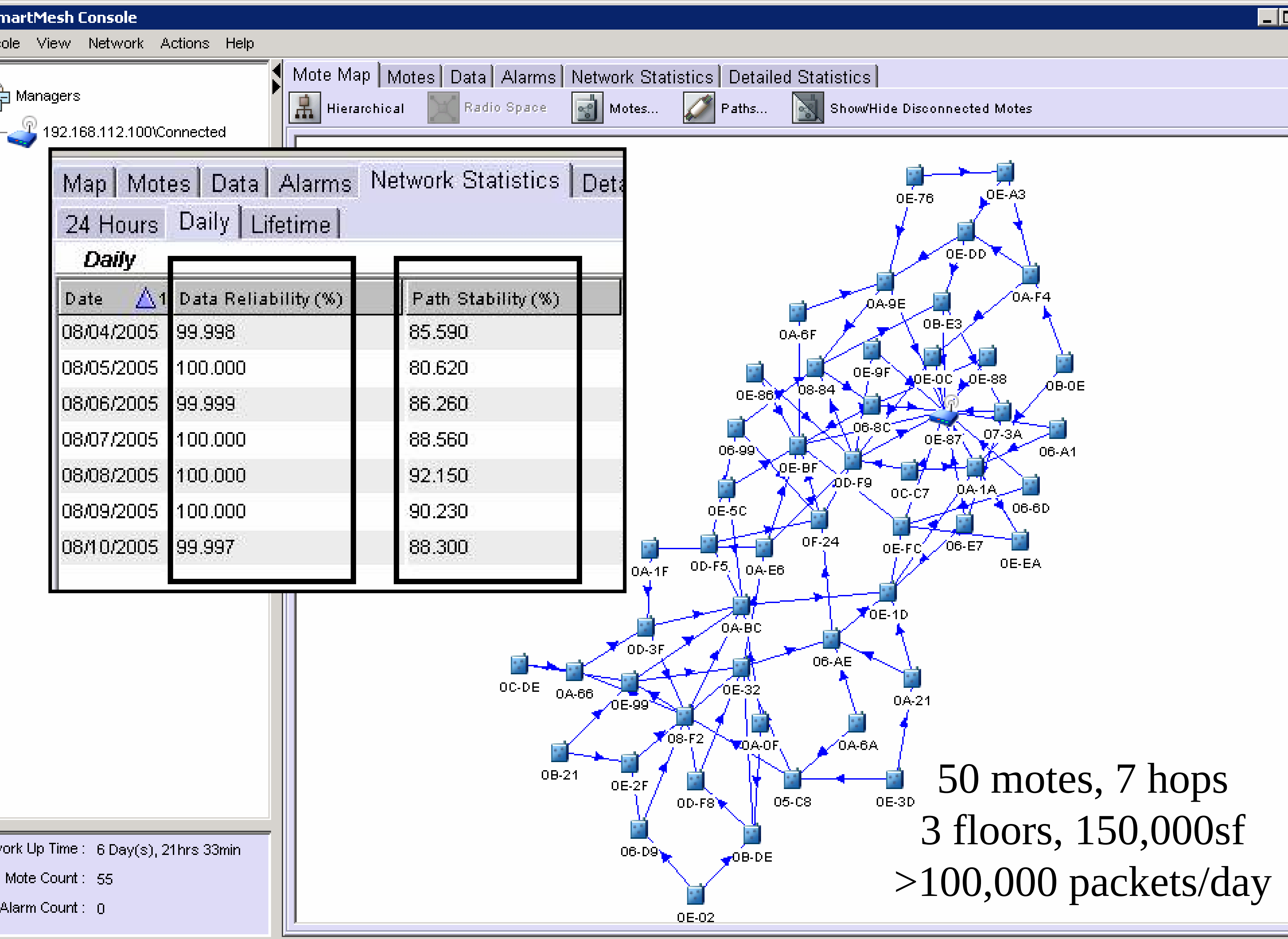
2.485 GHz

Configure, don't compile



Reliability: 99.99%+

Power consumption: < 100uA average

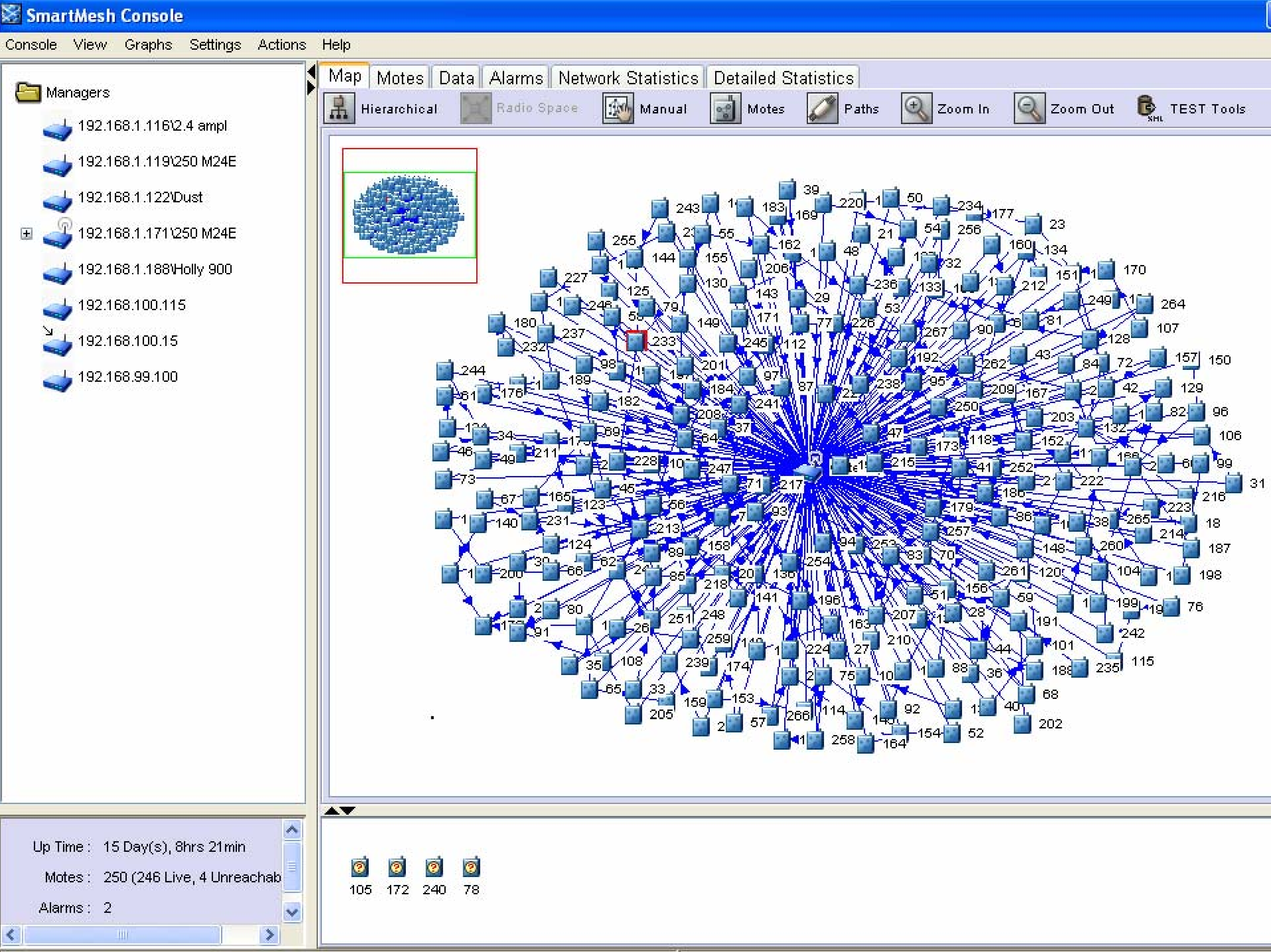


Date	Data Reliability (%)	Path Stability (%)
08/04/2005	99.998	85.590
08/05/2005	100.000	80.620
08/06/2005	99.999	86.260
08/07/2005	100.000	88.560
08/08/2005	100.000	92.150
08/09/2005	100.000	90.230
08/10/2005	99.997	88.300

50 motes, 7 hops

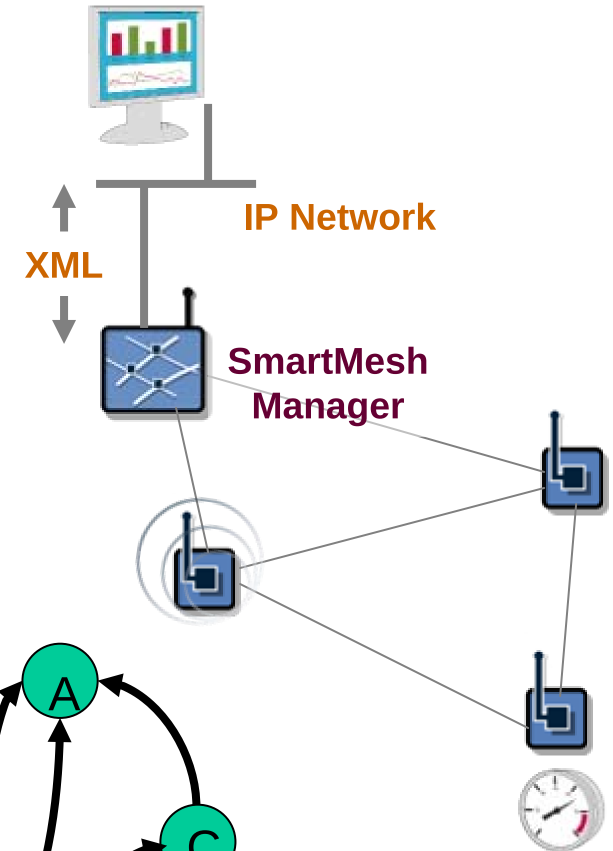
3 floors, 150,000sf

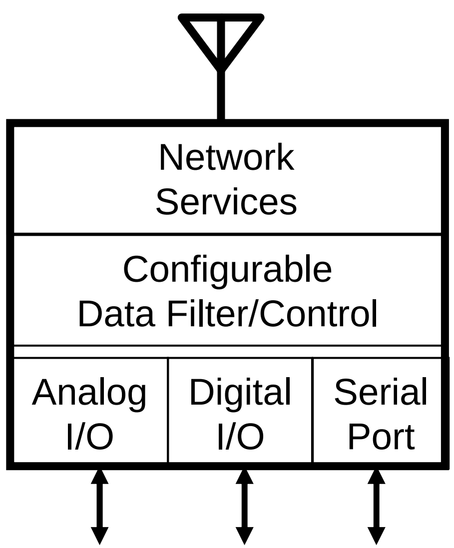
>100,000 packets/day

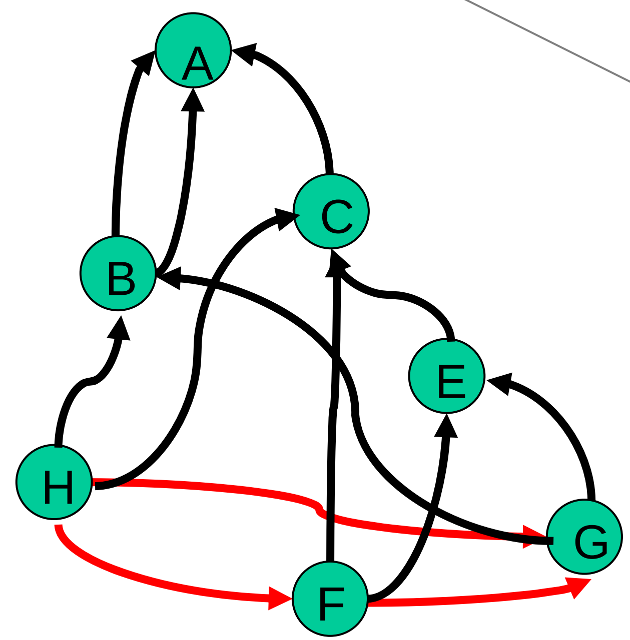

SmartMesh Console
Console View Graphs Settings Actions Help
Map Motes Data Alarms Network Statistics Detailed Statistics
Hierarchical Radio Space Manual Motes Paths Zoom In Zoom Out TEST Tools
Managers
192.168.1.116\2.4 ampl
192.168.1.119\250 M24E
192.168.1.122\Dust
192.168.1.171\250 M24E
192.168.1.188\Holly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

Communication Abstraction

- Packets flow along independent digraphs
- Digraphs/frames have independent periods
- Energy of atomic operations is known, (and can be predicted for future hardware)
  - Packet TX, packet RX, idle listen, sample, …
- Capacity, latency, noise sensitivity, power consumption models match measured data
- Build connectivity & applications via xml interface

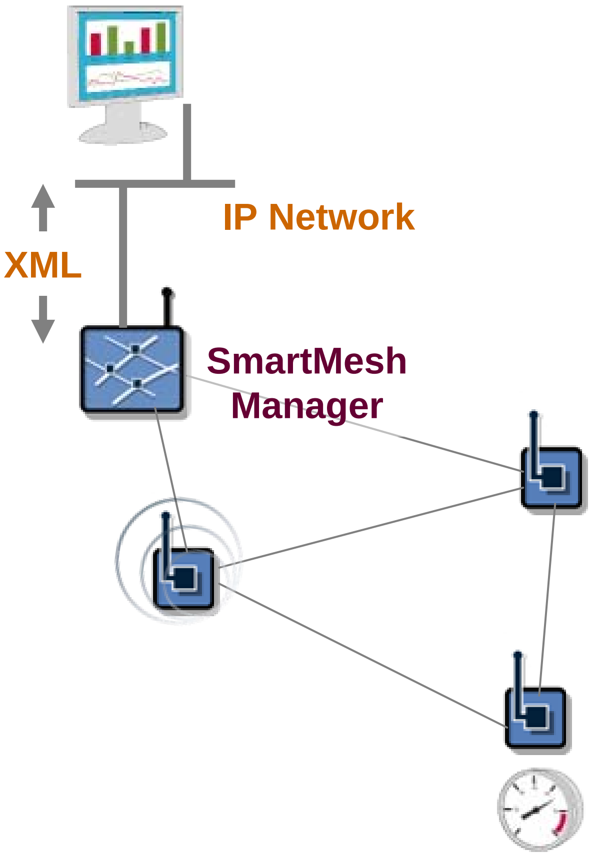






Available data

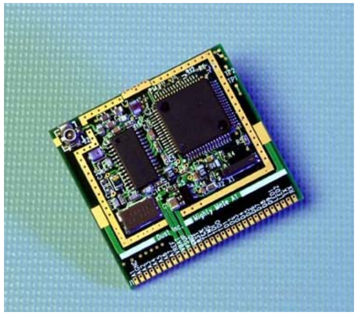
- Connectivity
  - Min/mean/max RSSI
- Path-by-path info:
  - TX: attempts, successes
  - RX: idle, success, bad CRC
- Latency (generation to final arrival)
- Data maintained
  - Every 15 min for last 24 hours
  - Every day for last week
  - Lifetime
- Available in linux log files or via XML

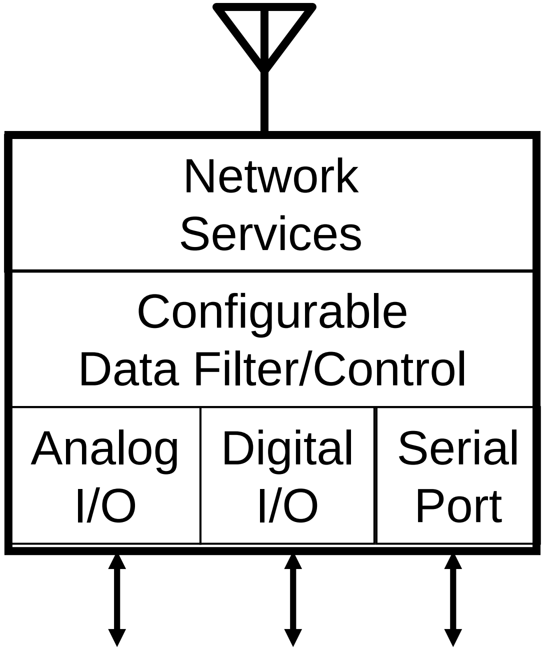


Micro Network Interface Card

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.



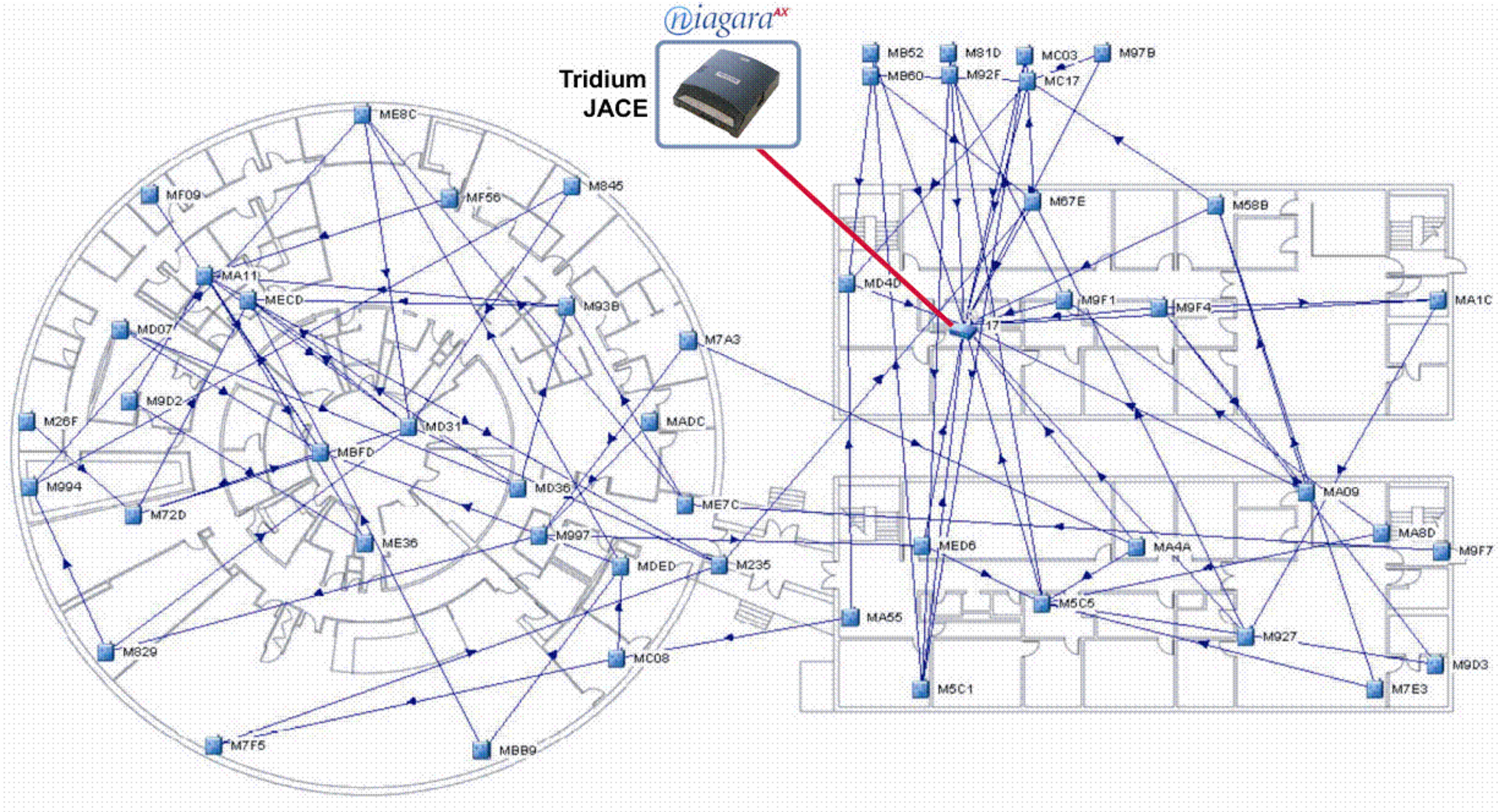


Energy Monitoring Pilot

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)
  - 12 months, 99.99%

Chicago Public Health – Dust, Tridium, Teng



Temperature and power monitoring

Micro Network Interface Card

μNIC

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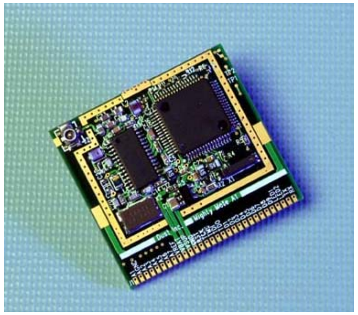
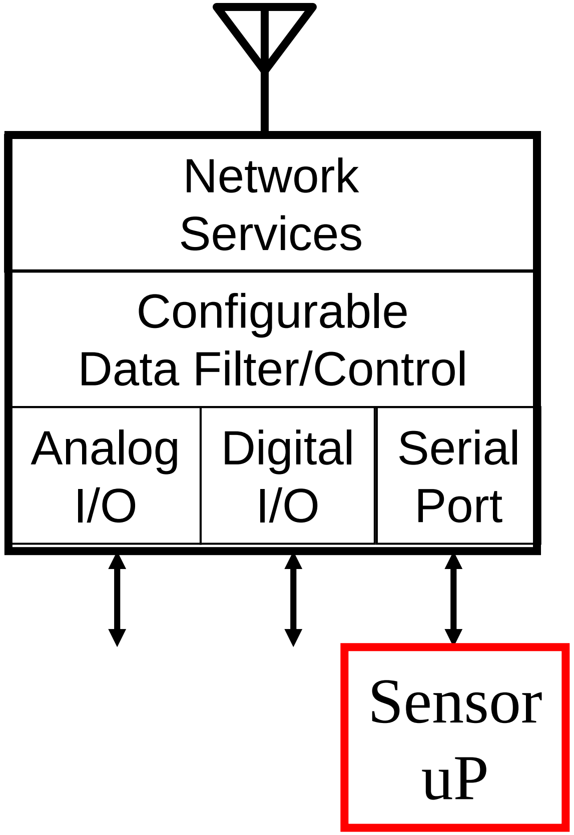




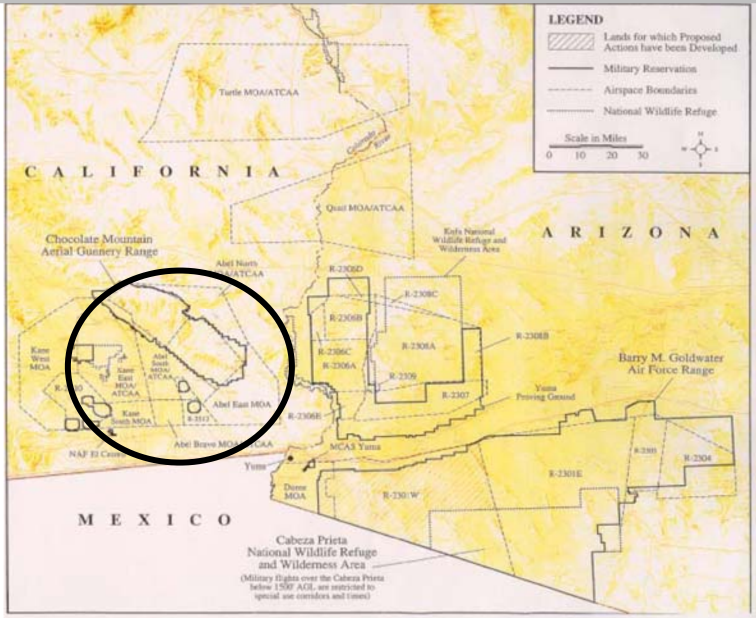
Perimeter Security

Passive IR and Camera

Passive IR

MEMS and GPS

Perimeter Security - MARFORPAC



Key Participants:

MARFORPAC, MCWL, MCAS, SAIC, and Dust Networks

Objectives:

Develop and demonstrate an ultra-low-power, low-cost, reliable wireless sensor network for widespread and persistent surveillance of borders and perimeters in support of OEF and OIF

Deploy and demonstrate at the Chocolate Mountains Aerial Gunnery Range (CMGAR) at the Marine Corps Air Station (MCAS) near Yuma, Arizona

- Addresses a need to detect intruders, smugglers and scrappers at the CMAGR
- Provides a proving ground and relevant data collections for production and deployment in OEF and OIF

SAIC®
From Science to Solutions™

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