Scheduling Activities in Wireless Sensor Networks

Winter School on
Hot Topics in Distributed Computing

ENS Lyon — A4RES/INRIA
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Many thanks to…

- Large collection of authors
  - D. Culler (UCB)
  - D. Estrin (UCLA)
  - R. Wattenhofer (ETHZ)
  - …

Literature

- Y. Chen & E. Fleury, “Scheduling Activities in Wireless Sensor Networks” in Handbook of Wireless Ad Hoc and Sensor Networks, Springer
- Dorothea Wagner & Roger Watthenhofer – Algorithms for Sensor and Ad Hoc networks, LNCS 4621
- Holger Karl & Andreas Willig, Protocols and Architectures for Wireless Sensor Networks, Wiley
- Bhaskar Krishnamachari – Networking Wireless Sensors
- Paolo Santi – Topology Control in Wireless Ad Hoc and Sensor Networks
- F. Zhao & L. Guibas – Wireless Sensor Networks: An Information Processing Approach
- Ivan Stojmenovic – Handbook of Wireless Networks and Mobile Computing
- C. Siva Murthy & B. S. Manoj – Ad Hoc Wireless Networks

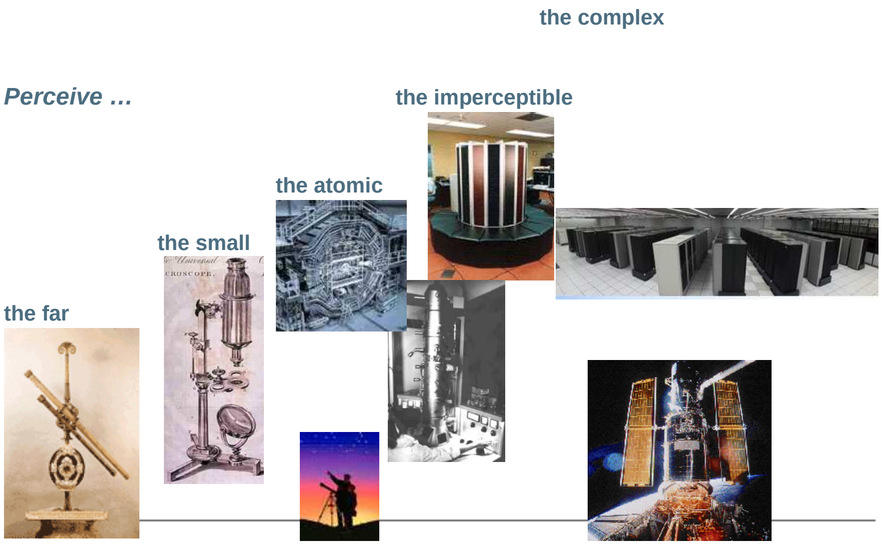
- And tons of papers...

Overview

- Introduction
- Applications
- Challenges
  - Technologies
  - System
  - Networking
  - Energy / Life time

- Back to our first subject
  - scheduling activities !

Enabling Technology for Science



The (A) Promise of Sensor Networks

- Dense monitoring & analysis of complex phenomena over large regions of space for long periods
  - Many, small, inexpensive sensing devices
  - Frequent sampling over long durations
  - Non-perturbing
  - Close to the physical phenomena of interest
  - Compute, communicate, and coordinate
  - Many sensory modes and vantage points
- Observe complex interactions

Embedded Networked Sensing: Motivation

• Many critical issues facing science, government, and the public call for high fidelity and real time observations of the physical world

• Networks of smart, wireless sensors can reveal the previously unobservable

• Designing physically-coupled, robust, scalable, distributed-systems is challenging

• The technology will also transform the business enterprise (from inventory to manufacturing), and human interactions (from medical to social)

Sensing the world

- Miniaturization and Moore's law has enabled us to combine:
  - sensing, computation and wireless communication
  - integrated, low-power devices
  - **embed networks of these devices in the physical world**.
- By placing sensing devices up close to the physical phenomena we are now able to study details in space and time that were previously unobservable.
- Across a wide array of applications, the ability to observe physical processes with such high fidelity will allow us to create models, make predictions, and thereby manage our increasingly stressed physical world

Embedded Networked Sensing

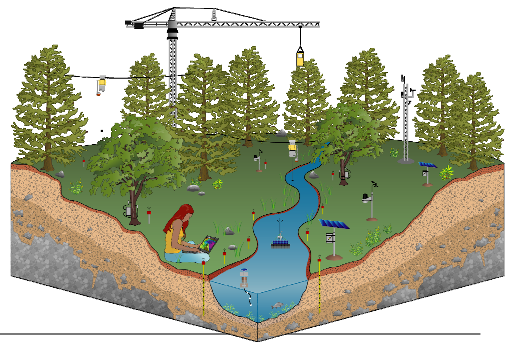
Embed numerous devices to monitor the physical world

Network to monitor, coordinate and perform higher-level identification

Sense and actuate adaptively to maximize information return

In-network and multi-scale processing algorithms to achieve:

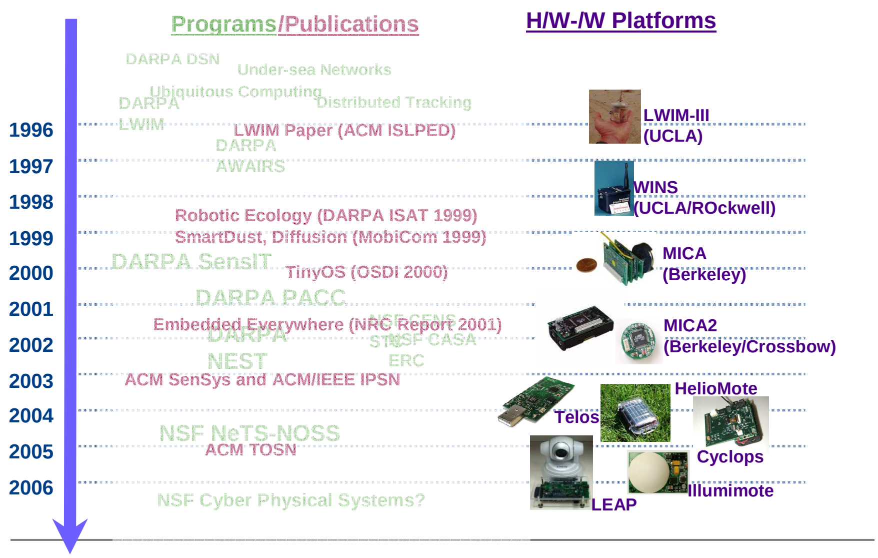
- *Scalability* for densely deployed sensors
- *Low-latency* for interactivity, triggering, adaptation
- *Integrity* for challenging system deployments



Advantages of Embeded-WSN

- The essential power of this technology derives from **EMBEDDING** measurement devices in the physical world and **NETWORKing** them to achieve intelligent coordinated SENSING Systems
- ENS has the perfect ingredients for multidisciplinary research because it offers transforming capabilities to the applications and challenging problems for the technologists.
- Most generally stated our objective is to
  - **maximize information** return from these adaptive sensing and actuation systems, across design, deployment, and run time
  - the design of multiscale and in network processing algorithms.

A Walk Through History



Srivastava, et al

Future: Expanding Sensor Suite

present → *future*

abiotic ↓ *biotic*

Physical Sensors: Microclimate above and below ground

Chemical Sensors: gross concentrations

Chemical Sensors: trace concentrations

Acoustic and Image data samples

Acoustic, Image sensors with on board analysis

DNA analysis onboard embedded device

Organism tagging, tracking

Sensor triggered sample collection

- Commercially available devices available for many physical and chemical measures
- Advancements in sensor technologies will further transform wireless sensing systems as new capabilities broaden physical, chemical, and biological *in situ, autonomous,* observations

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Application scenarii

-- state of the art --

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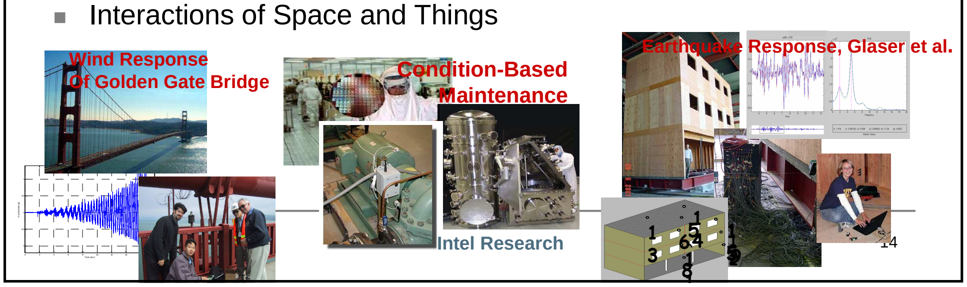
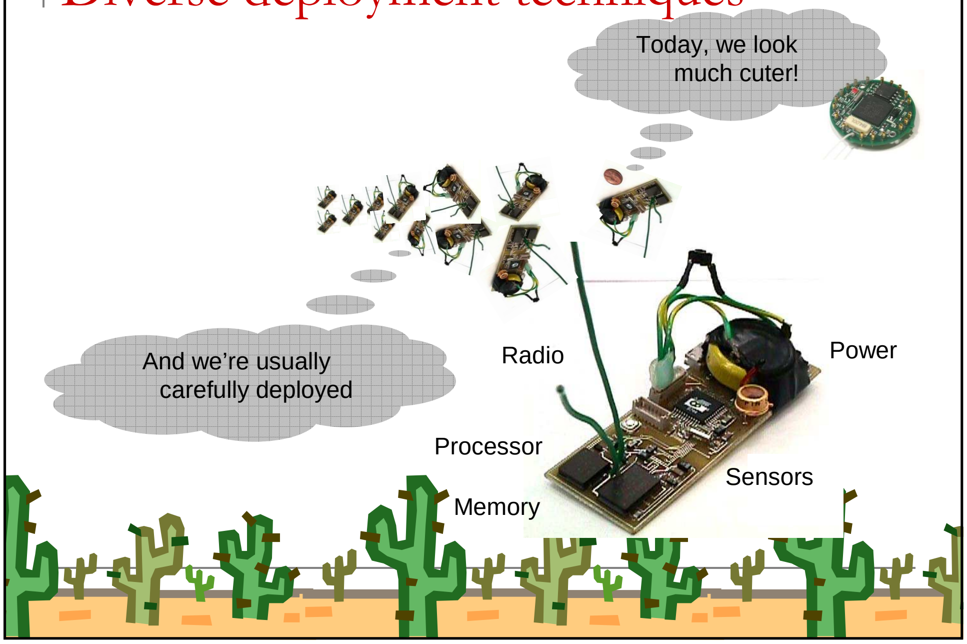
Diverse Applications

- Monitoring Spaces
  - Env. Monitoring, Conservation biology, ...
  - Precision agriculture,
  - built environment comfort & efficiency ...
  - alarms, security, surveillance, treaty verification ...
- Monitoring Things
  - condition-based maintenance
  - disaster management
  - Civil infrastructure
- Interactions of Space and Things



Diverse deployment techniques



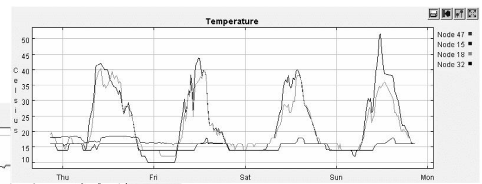
Ad Hoc Networks vs. Sensor Networks

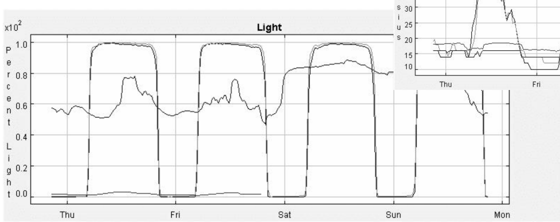
There is no strict separation; more variants such as mesh or sensor/actor networks exist

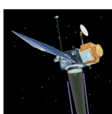
Ad Hoc Networks	Sensor Networks
Laptops, PDA's, cars, soldiers	Tiny nodes: 4 MHz, 32 kB, …
All-to-all routing	Broadcast/Echo from/to sink
Often with mobility (MANET's)	Usually no mobility ❑ but link failures
Trust/Security an issue ❑ No central coordinator	One administrative control
Maybe high bandwidth	Long lifetime → Energy
Network oriented	Application oriented

Animal Monitoring (Great Duck

1. Biologists put sensors in underground nests of storm petrel
2. And on 10cm stilts
3. Devices record data about birds
4. Transmit to research station
5. And from there via satellite to lab

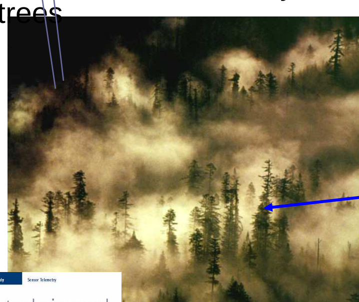






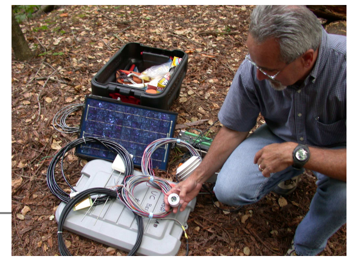
Environmental Monitoring : Redwood Ecophysiology

- 70% of H2O cycle is through trees, not ground
- Complex interactions of tree growth and environment
  - Effected by and effect the microclimate
- Need to understand dynamic processes *within* the trees

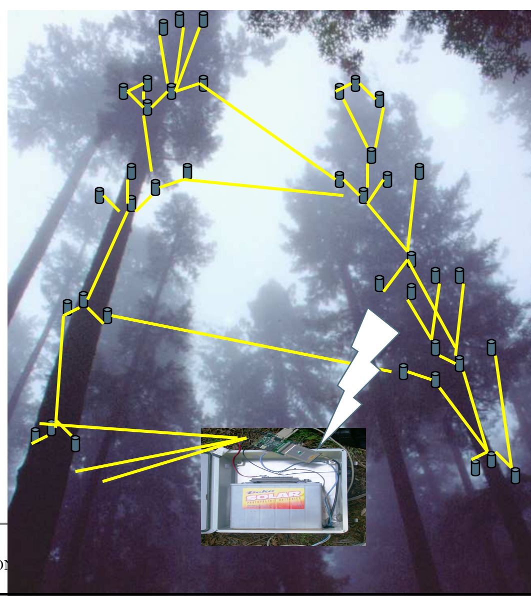


State of the Art

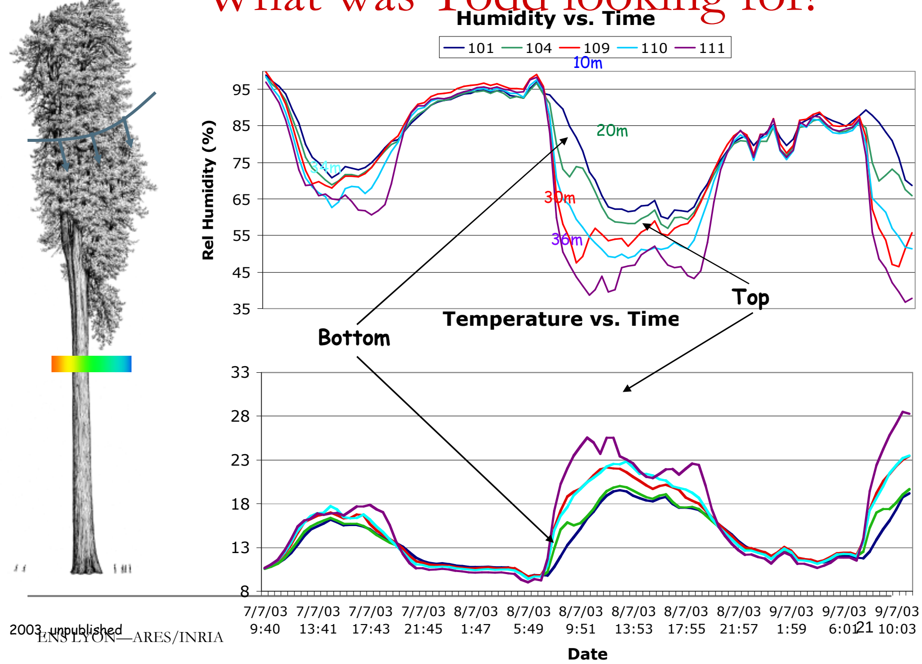
- Solid understanding of leaf physiology
  - Good models, good empirical data, good fit
- Extension to the entire tree canopy is open problem
  - Various models focused on particular aspects
    - Nutrient transport, transpiration, …
  - Extremely limited empirical basis
- Data Dirth
  - Satellite observations: wide coverage, low resolution, canopy surface
  - Spot weather stations: single point in space
  - Instrument elevator: haul data logger along vertical transect
  - Wide range of sensors: climate, sap-flow, dew, …
- Goal: dense monitoring throughout canopy of sampling of trees throughout forest



The alternative…



What was Todd looking for?

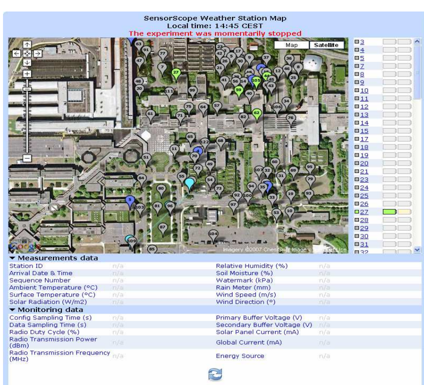


2003, unpublished

Environmental Monitoring (SensorScope)

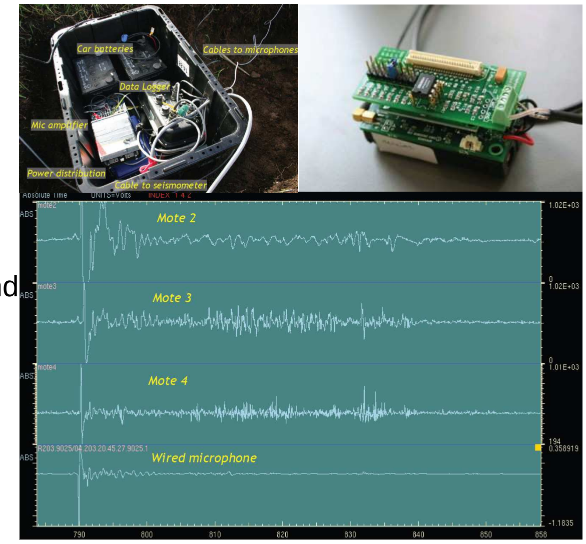
Comfortable access with web interface

- Swiss made (EPFL)
- Japan made (e-sense)
- Various deployments (campus, glacier, etc.)



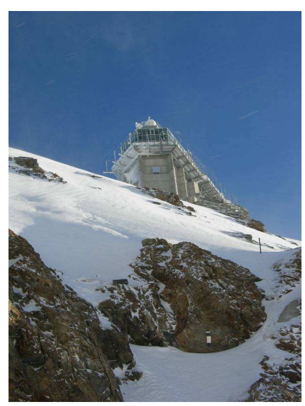
Environmental Monitoring (Volcanic monitoring)

- Old hardware vs. new hardware
- Sensors: infrasonic mic (for pressure trace) and seismometer (for seismic velocity)
- Equivalent: Earthquake, Tsunami, etc.



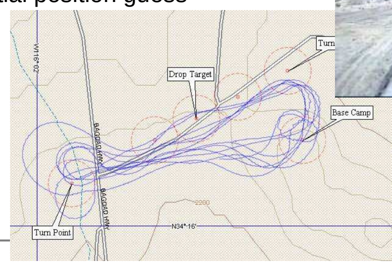
Environmental Monitoring (PermaSense)

- Understand global warming in alpine environment
- Harsh environmental conditions
- Swiss made (Basel, Zurich)



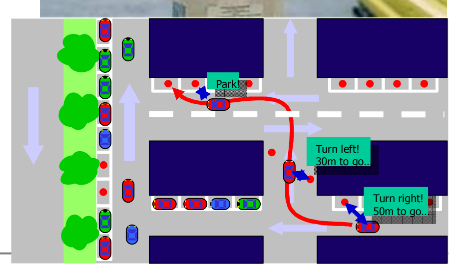
Vehicle Tracking

- Sensor nodes (equipped with magnetometers) are packaged, and dropped from fully autonomous GPS controlled "toy" air plane
- Nodes know dropping order, and use that for initial position guess
- Nodes then track vehicles (trucks mostly)



Smart Spaces (Car Parking)

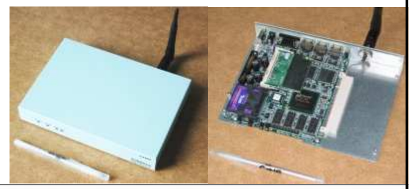
- The good: Guide cars towards empty spots
- The bad: Check which cars do not have any time remaining
- The ugly: Meter running out: take picture and send fine



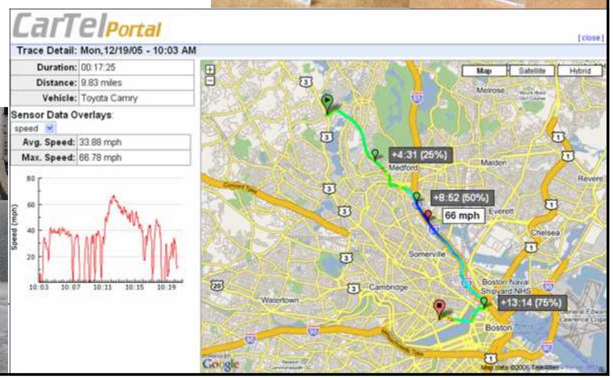
[Matthias Grossglauser, EPFL & Nokia Research]

Traffic Monitoring and Routing Planning (CarTel)

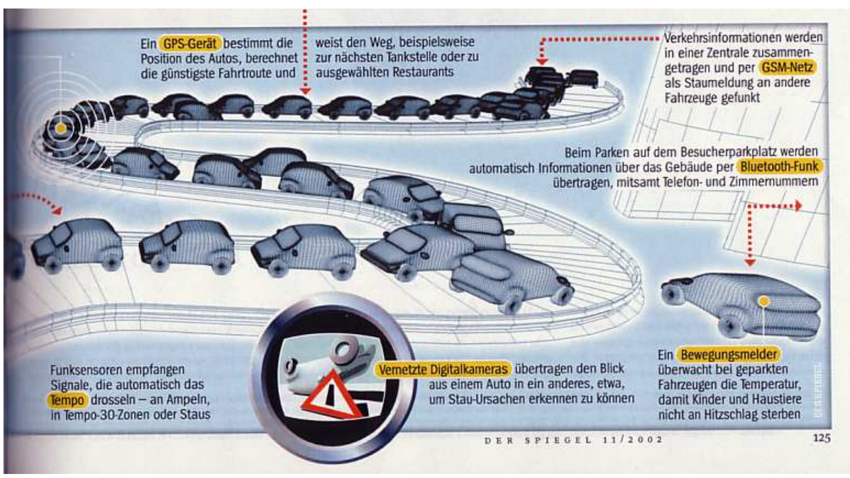
- GPS equipped cars for optimal route predictions, not necessarily “shortest” or “fastest” but also “most likely to get me to target by 9am”



- Various other applications e.g. Pothole Patrol

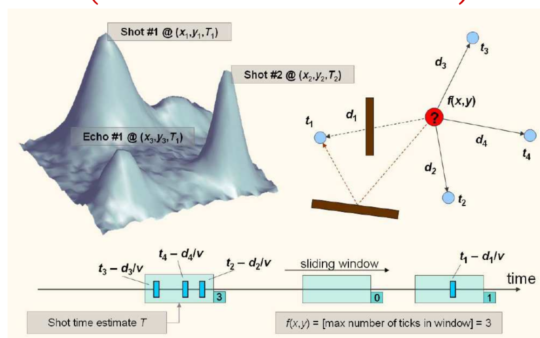


More Car Network Ideas

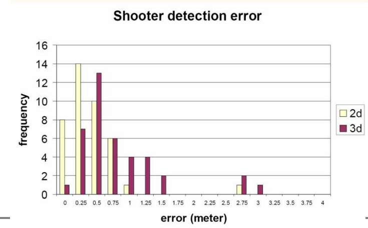


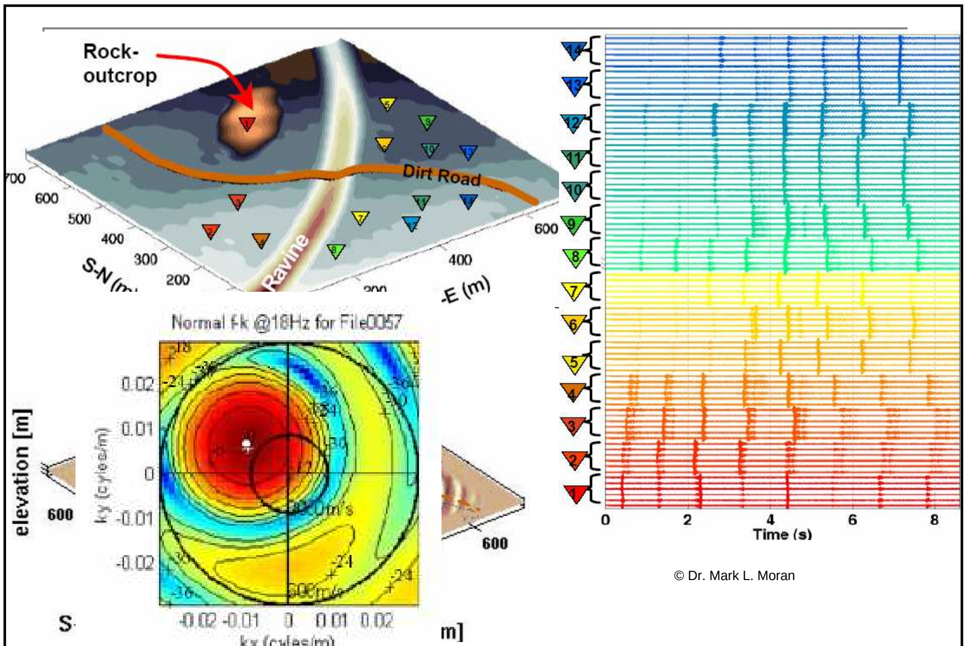
- CAR2CAR Consortium: Audi, BMW, Daimler, Fiat, GM, Honda, Renault, VW

Acoustic Detection (Shooter Detection)

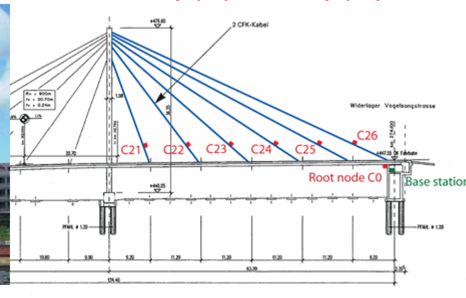


- Sound travels much slower than radio signal (331 m/s)
- This allows for quite accurate distance estimation (cm)
- Main challenge is to deal with reflections and multiple events



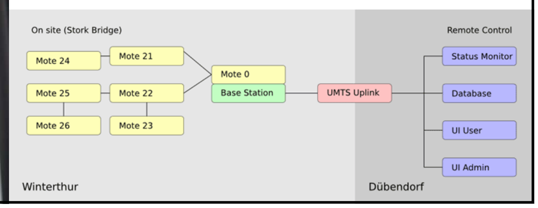


Structural Health Monitoring (Bridge)



Swiss Made
[EMPA]

Detect structural defects, measuring temperature, humidity, vibration, etc.



Home Automation

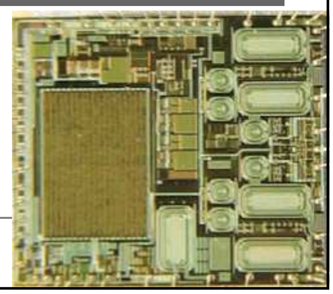
- Light
- Temperature
- Sun-Blinds
- Fans

- Energy Monitoring
- Audio/Video
- Security
  - Intrusion Detection
  - Fire Alarm

Standby Energy [digitalSTROM.org]

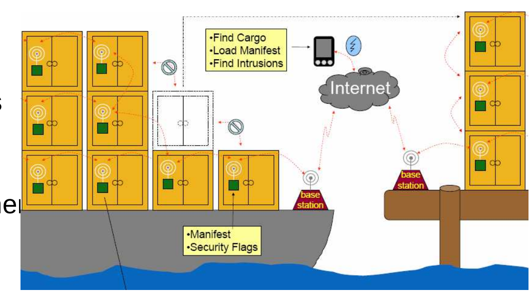
- 10 billion electrical devices in Europe
- 9.5 billion are not networked
- 6 billion euro per year energy lost

- Make electricity smart
  - cheap networking (over power)
  - true standby
  - remote control
  - electricity rates
  - universal serial number
  - …



Inventory Tracking (Cargo Tracking)

- ANR SVP project
- Current tracking systems require line-of-sight to satellite.
- Count and locate containers
- Search containers for specific item
- Monitor accelerometer for sudden motion
- Monitor light sensor for unauthorized entry into container

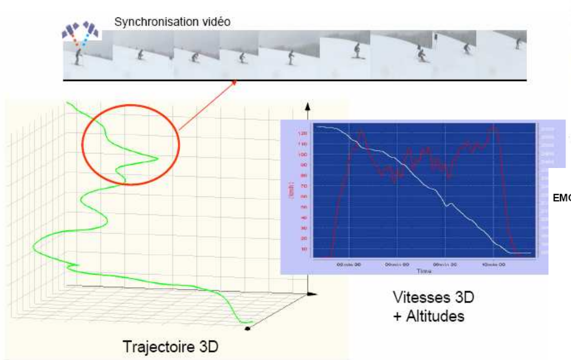


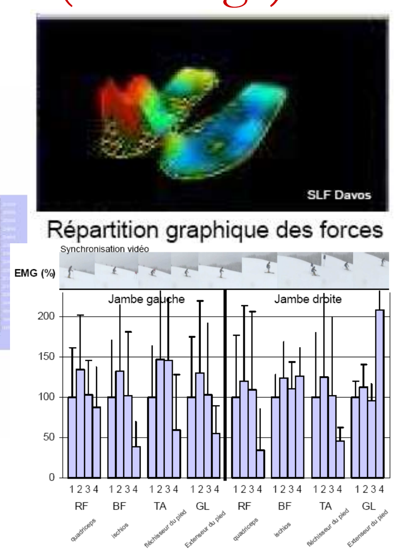
Virtual Fence (CSIRO Australia)

- Download the fence to the cows. Today stay here, tomorrow go somewhere else.
- When a cow strays towards the co-ordinates, software running on the collar triggers a stimulus chosen to scare the cow away, a sound followed by an electric shock; this is the “virtual” fence. The software also "herds" the cows when the position of the virtual fence is moved.
- If you just want to make sure that cows stay together, GPS is not really needed…

Cows learn and need not to be shocked later… Moo!

High performance sport (Tracedge)

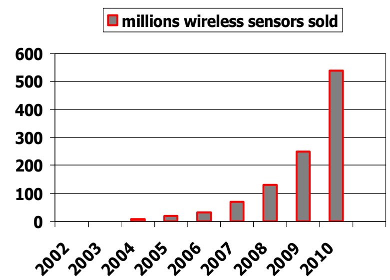




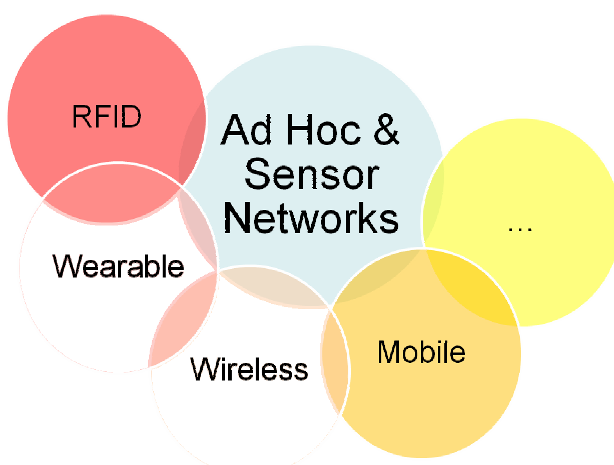
Economic Forecast

[Jean-Pierre Hubaux, EPFL]

- Industrial Monitoring (35% – 45%)
  - Monitor and control production chain
  - Storage management
  - Monitor and control distribution
- Building Monitoring and Control (20 – 30%)
  - Alarms (fire, intrusion etc.)
  - Access control
- Home Automation (15 – 25%)
  - Energy management (light, heating, AC etc.)
  - Remote control of appliances
- Automated Meter Reading (10-20%)
  - Water meter, electricity meter, etc.
- Environmental Monitoring (5%)
  - Agriculture
  - Wildlife monitoring



Related Areas



Some challenges

-- state of the art --

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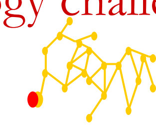
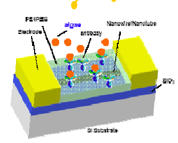
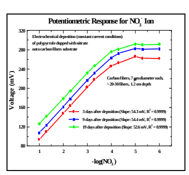
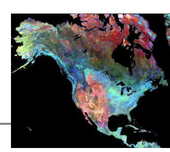
Technology challenges

Objectives	Constraints
Embeddable, low-cost sensor devices	Sensing channel uncertainties
Robust, portable, interactive systems	Environmentally compatible deployment
Data integrity, system dependability	Limited resources: node, infrastructure
Programmable, transparent systems	Complexity of distributed systems
Multiscale sensing and actuation	No ground truth









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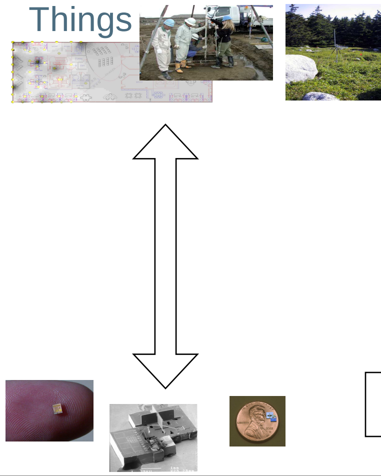
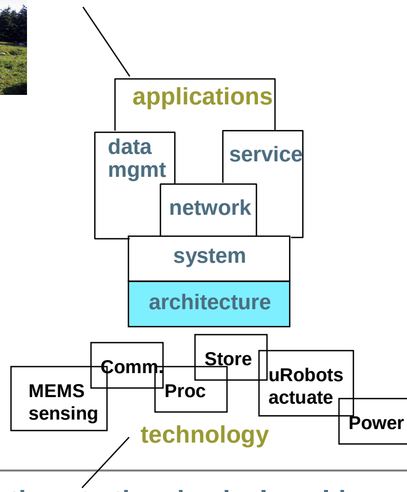
Node Design

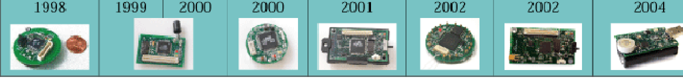
Monitoring & Managing Spaces and Things





Miniature, low-power connections to the physical world

Mote Platform Evolution



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 (μW)	45		45		75		75	2
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	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

http://www.worldsens.net

First Apple II

$1298 $ for

-4 Ko

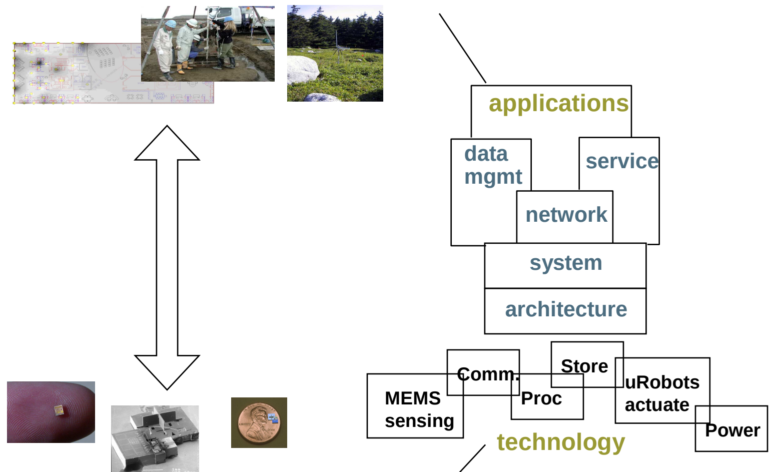
-MOS 6502 1 MHz

Node design lessons

- Components of a sensor net node
  - Processor / Radio / Storage / Interface
  - Sensor suite
  - Power subsystem
  - Mechanical design
- Which are specific to the application?
- Let the expert pick the sensors
  - Previous experience
  - Reference design
  - Lab tools for calibration
  - Trust

The Systems Challenge

Monitoring & Managing Spaces and Things



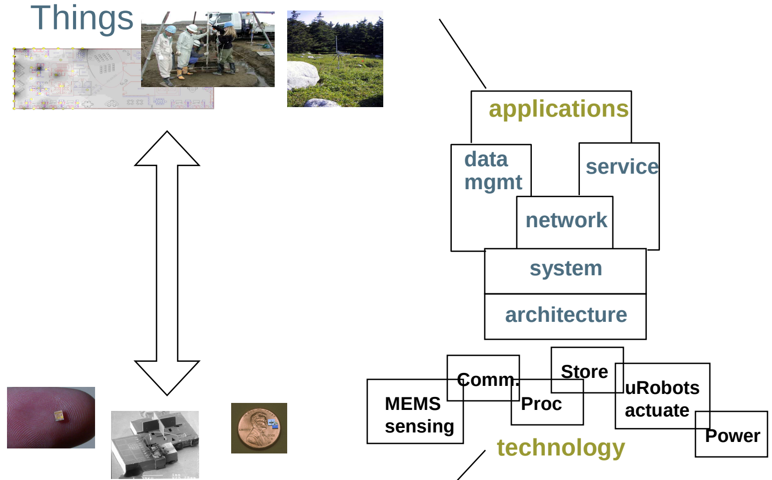
Miniature, low-power connections to the physical world

How does a bunch of wireless devices become a (programmable) network?

- Localized algorithms: Distributed computation where each node performs local operations and communicates within *some neighborhood* to accomplish a desired global behavior
  - D. Estrin, "21st Century Challenges…"

Networking

Monitoring & Managing Spaces and Things



Miniature, low-power connections to the physical world

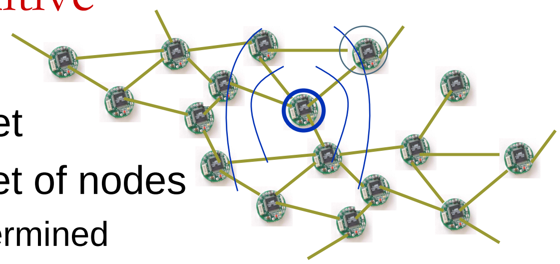
Common Communication Patterns

- Internet
  - Many independent pt-pt stream
- Parallel Computing
  - Shared objects
  - Message patterns (any, grid, n-cube, tree)
  - Collective communications
    - Broadcast, Grid, Permute, Reduces
- Sensor Networks
  - Dissemination (broadcast & epidemic)
  - Collection
  - Aggregation
  - Tree-routing
  - Neighborhood
  - Point-point

Disseminate the Query
- eventual consistency
Collect (aggregate) results

The Emergence of Networking Abstractions and Techniques in TinyOS
Philip Levis, Sam Madden, David Gay, Joseph Polastre, Robert Szewczyk, Alec Woo, Eric Brewer, and David Culler, NSDI'04

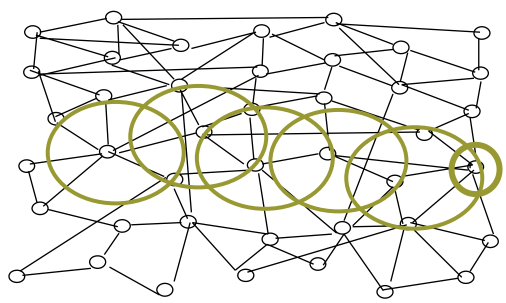
The Basic Primitive



- Transmit a packet
- Received by a set of nodes
  - Dynamically determined
  - Depends on physical environment at the time
  - What other communication is on-going
- Each selects whether to retransmit
  - Potentially after modification
- And if so, when

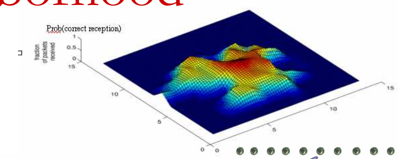
Routing Mechanism

- Upon each transmission, one of the recipients retransmit
  - determined by source, by receiver, by …
  - on the 'edge of the cell'

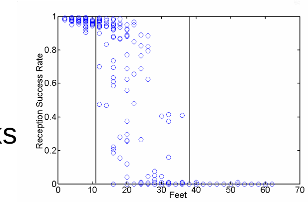


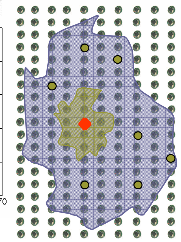
The Most Basic Neighborhood

- Direct Reception

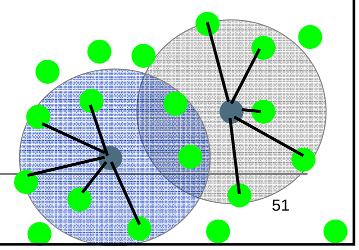


- Non-isotropic
- Large variation in affinity
  - Asymmetric links
  - Long, stable high quality links
  - Short bad ones





- Varies with traffic load
  - Collisions
  - Distant nodes raise noise floor
  - Reduce SNR for nearer ones
- Many poor “neighbors”
- Good ones mostly near, some far



Flooding vs Gossip / epidemic

- In gossip protocols, at each step pick a random neighbor
- Assumes an underlying connectivity graph
- Typically used when graph is full connected
  - E.g., ip
- Much slower propagation

How Should We Think About Routing?

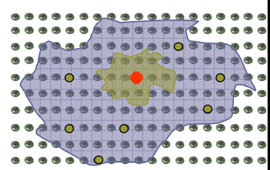
Classical View

- Discover the connectivity graph
- Determine the routing subgraph
  - relative to traffic pattern
- Compute a path and Route data hop-by-hop
  - Destination selection
  - Queuing, multiplexing, scheduling, retransmission, coding, …

Here?

- What does it mean to be connected?
- What does it mean to route?

Local Operations => Global Behavior



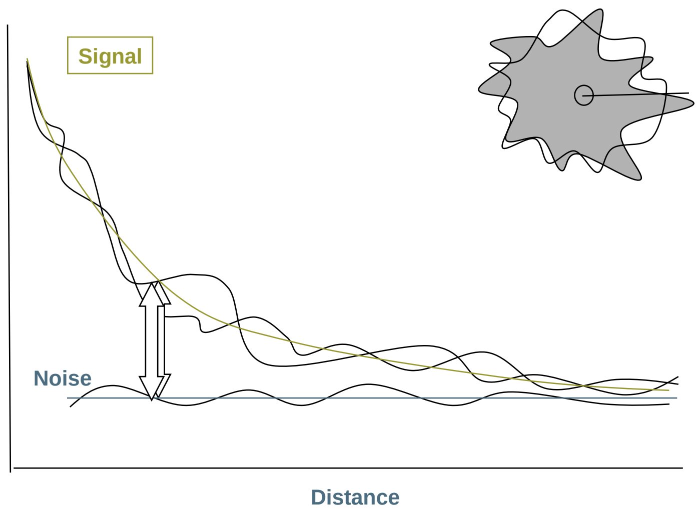
- Nodes continually ‘sense’ network environment
  - uncertain, partial information
- Packets directed to a “parent” neighbor
  - all other neighbors “hear” too
  - carry additional organizational information
- Each nodes builds estimate of neighborhood
  - adjusted with every packet and with time
- Interactively selects parent
  - # trans := 1/ParentRate + #trans(Parent->root)
- Routes traffic upward

⇒ Collectively they build and maintain a stable spanning tree
  - ⇒ takes energy to maintain structure

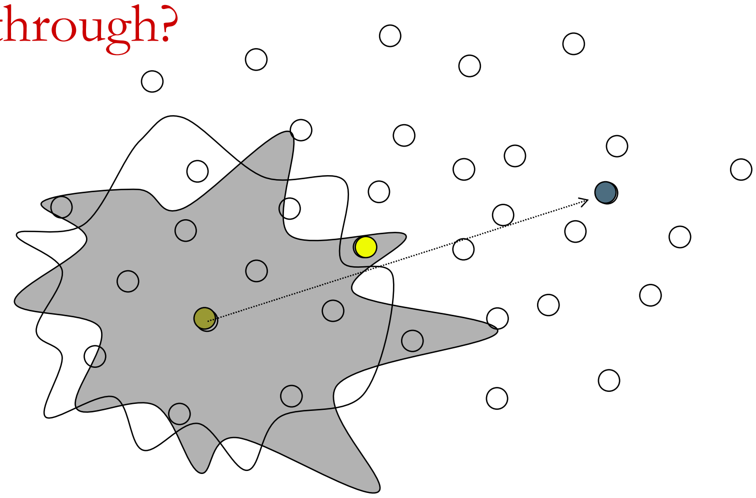
Predictable global behavior built from local operations on uncertain data

node #	depth	child ?	parent ?	% link	goodness
17	1		yes	90	.7
6	3	yes		75	.6
…					

The Amoeboed "cell"



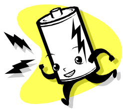
Which node do you route through?



What does this mean?

- Always routing through nodes "at the hairy edge"
  - Wherever you set the threshold, the most useful node will be close to it
- The underlying connectivity graph changes when you use it
  - More connectivity when less communication
  - Discovery must be performed under load

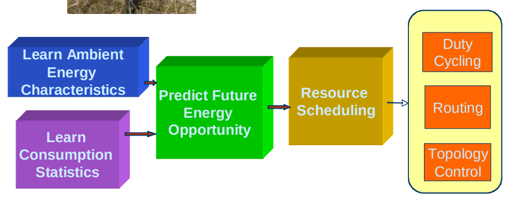
Energy challenge



INRIA

Sustaining Long-term Deployments

- The chimera of longevity
  - Batteries require replacement!
- Current state:
  - about one year using mote class devices with simple sensors periodically sampling at low rates and duty cycles (< 1%)
  - about a week using microserver class devices with sophisticated high rate sensing modalities
- Harvesting-aware nodes promise 20+ years at 20-60% duty cycle



- Architecture implications: **energy neutral** operation
  - HelioMote
  - Harvesting-aware duty cycling, routing.

Notion of life time

- Time when
  - The first node die
  - A given fraction die
  - Loss of connectivity
  - Loss of coverage

Resource and Energy Constraints as Drivers

- Dominance of communication over storage and processing
- Dominance of Rx over Tx
- The power vs. {energy efficiency, performance} choice
- Achieving sustained operation
- High cost of sensor sampling

Communication vs. Storage vs. Processing

Mote-class 802.15.4 Node	Transmit	2950 nJ/bit	Processor	4 nJ/op
	Receive	2600 nJ/bit	~ 1400 ops/bit	

Microserver-class Node	Transmit	6600 nJ/bit	Processor	1.6 nJ/op
	Receive	3300 nJ/bit	~ 6000 ops/bit	

Atmel AVR Flash (256b/page)	Write	470 nJ/bit to 120750 nJ/bit
	Read	30 nJ/bit to 7600 nJ/bit

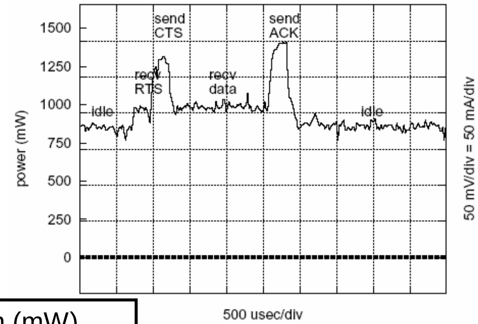
1GB NAND Flash Chip (512b/page)	Write	1 nJ/bit to 550 nJ/bit
	Read	0.4 nJ/bit to 220 nJ/bit

Energy/bit sent >> Energy/bit stored > Energy/op

- Architecture implications: **in-network processing & storage**

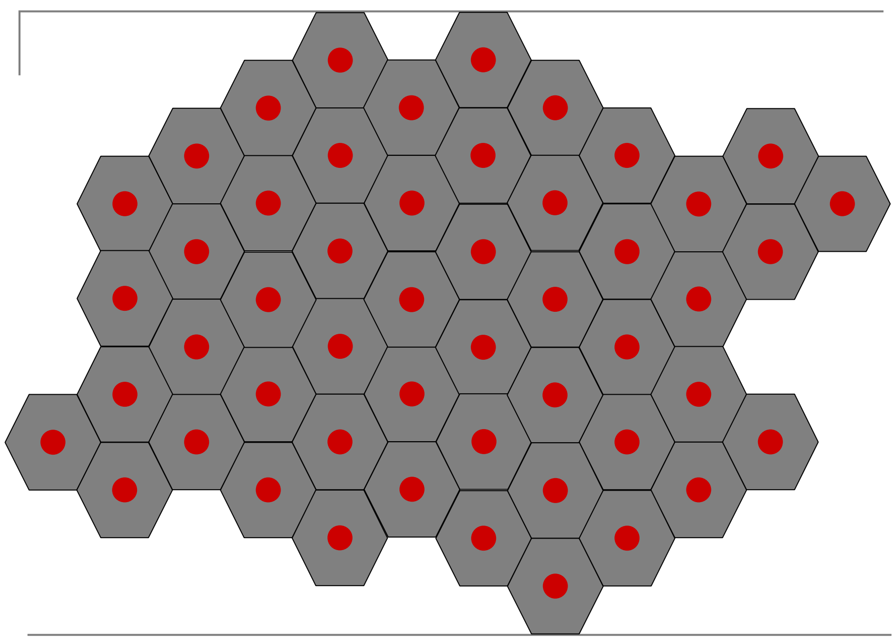
Energy consumption in communication

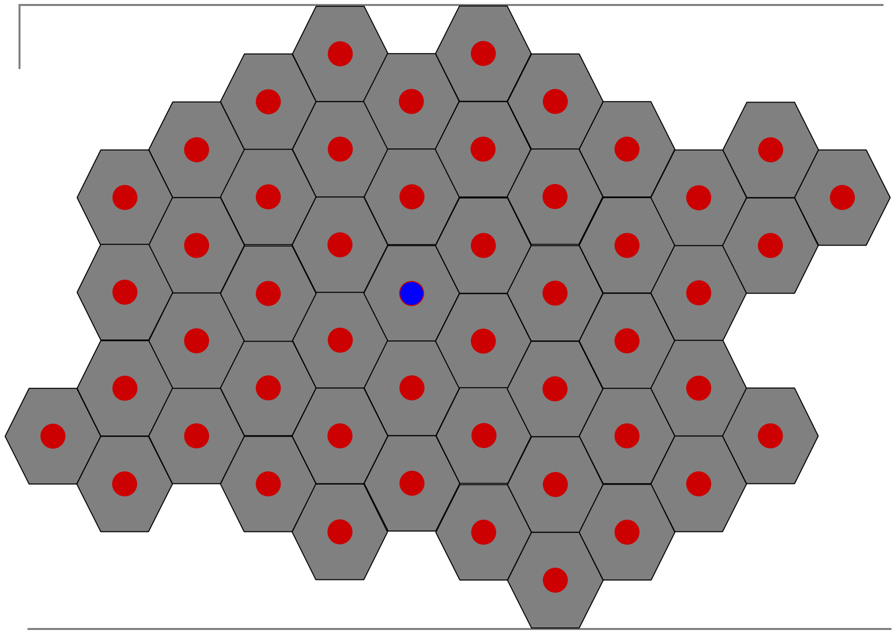
- Listening == waste of energy
- Trade off between energy and latency



Radio Mode	Consumption (mW)
Tx	14.88
Rx	12.50
Idle	12.36
Off	0.016

Radio Power Characterization, Schurgers et. al.: Optimizing Sensor Networks in the Energy-Latency-Density Design Space. IEEE Transactions on Mobile Computing, Vol. 1, No. 1, January-March 2002.





ENS LYON—ARES/INRIA

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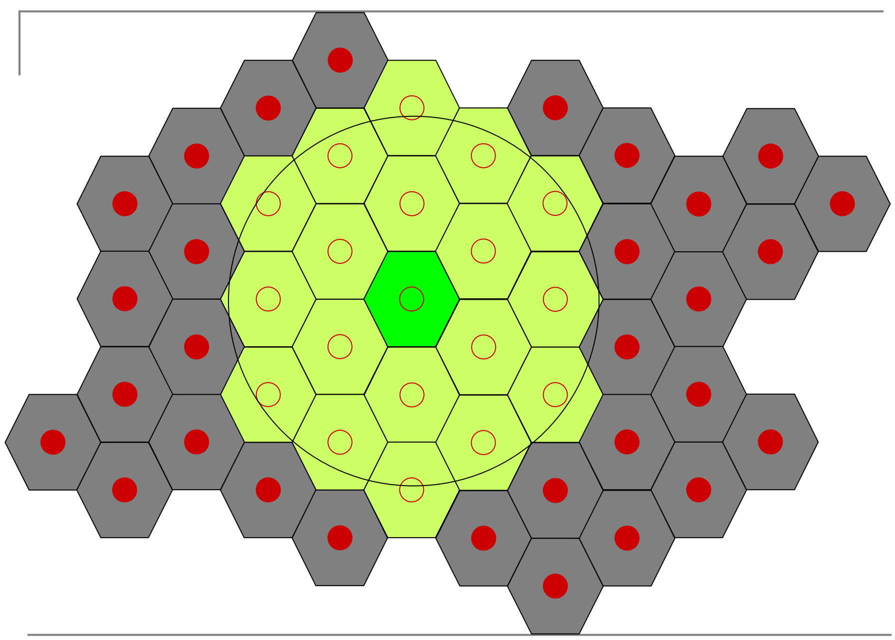

ENS LYON—ARES/INRIA

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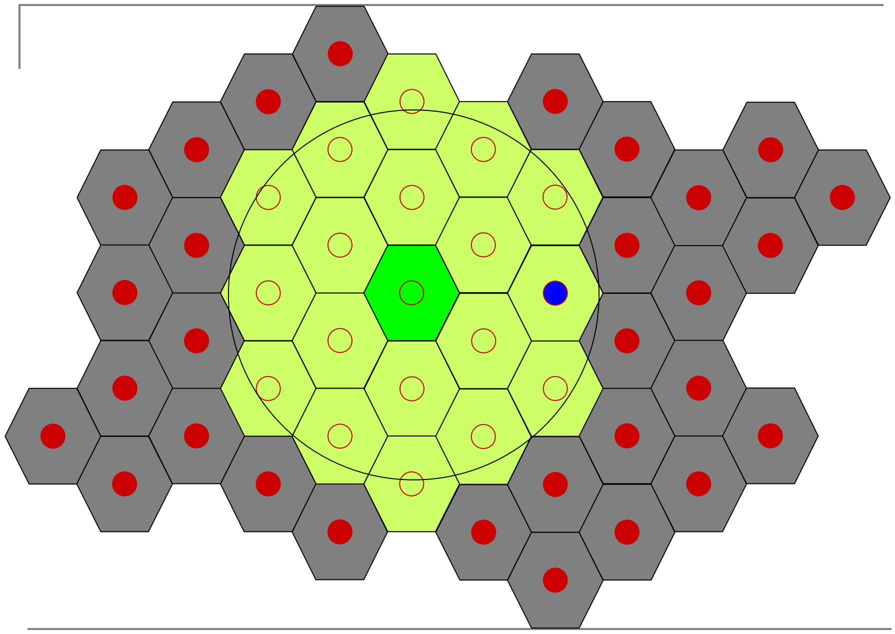

ENS LYON—ARES/INRIA

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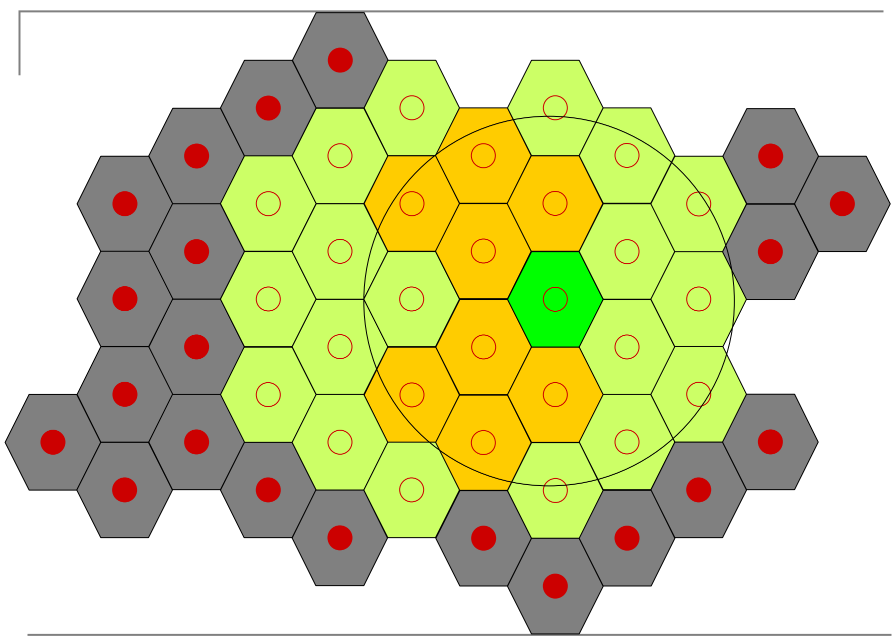

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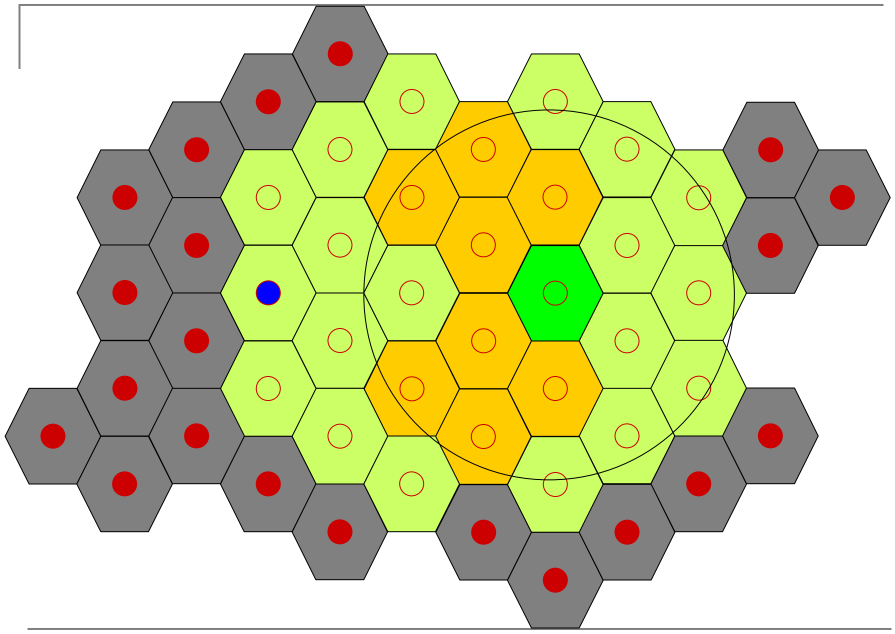
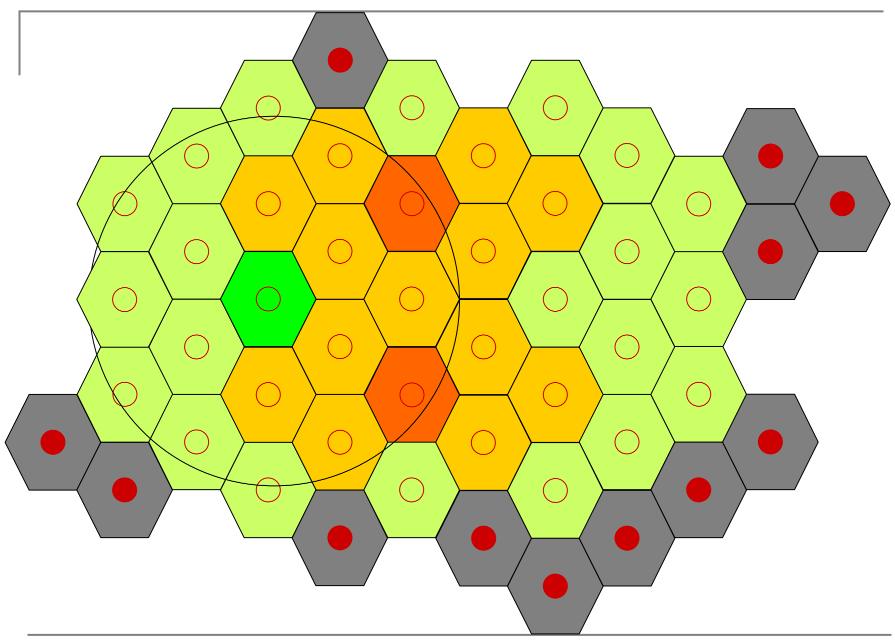
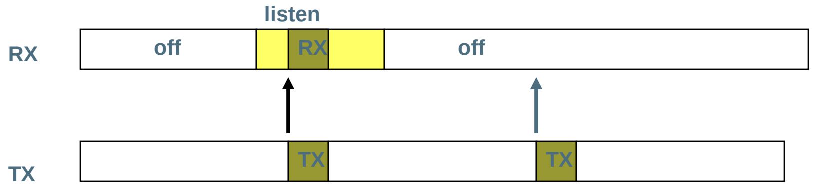




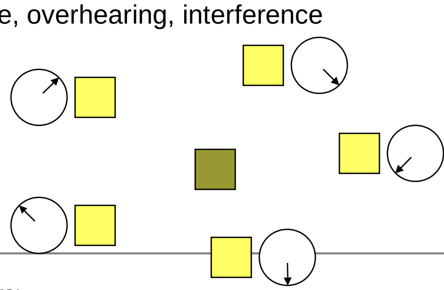
Communication and Power



- Costs power whenever radio is on
  - Transmitting, receiving, or just listening
- Transmit is easy, Rcv is what's tricky
  - Want to turn it on just when there is something to hear
- Two approaches
  - Schedule transmission intervals
    - Statically, dynamically, globally, locally
  - Make listening cheap

TDMA variants

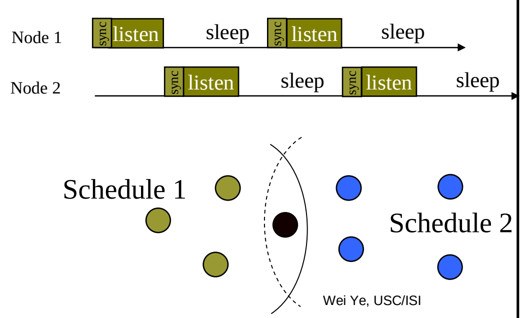
- Time Division Media Access
  - Each node has a schedule of awake times
  - Typically used in star around coordinator
    - Bluetooth, ZIGBEE
    - Coordinator hands out slots
  - Far more difficult with multihop (mesh) networks
  - Further complicated by network dynamics
    - Noise, overhearing, interference



S-MAC

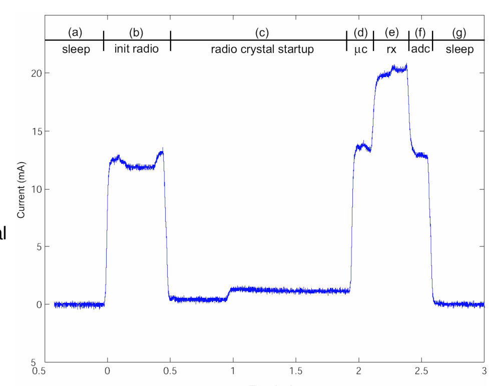
Ye, Heidemann, and Estrin, INFOCOM 2002

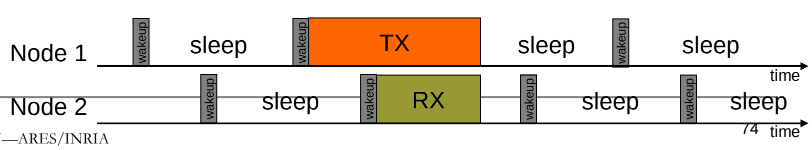
- Carrier Sense Media Access
- Synchronized protocol with periodic listen periods
- Integrates higher layer functionality into link protocol
  - Hard to maintain set of schedules
- T-MAC
  [van Dam and Langendoen, Sensys 2003]
  - Reduces power consumption by returning to sleep if no traffic is detected at the beginning of a listen period



Low Power Listening (LPL)

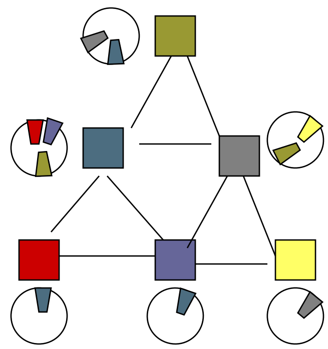
- Energy Cost = RX + TX + Listen
- Scheduling tries to reduce listening
- Alternative, reduce listen cost
- Example of a typical low level protocol mechanism
- Periodically
  - wake up, sample channel, sleep
- Properties
  - Wakeup time fixed
  - “Check Time” between wakeups variable
  - Preamble length matches wakeup interval
- Robust to variation
- Complementary to scheduling
- Overhear all data packets in cell
  - Duty cycle depends on number of neighbors and cell traffic





Communication Scheduling

- TDMA-like scheduling of listening slots
- Node allocates
  - listen slots for each child
  - Transmission slots to parent
  - Hailing slot to hear joins
- To join listen for full cycle
  - Pick parent and announce self
  - Get transmission slot
- CSMA to manage media
  - Allows slot sharing
  - Little contention
- Reduces loss & overhearing
- Connectivity changes cause mgmt traffic



Communication Trade-offs

- Connectivity graph is not static
  - Complicates explicit scheduling
- Time Synchronization
  - Time of reference required for rendezvous
- Low-power listening (preamble sampling)
  - Reduce the cost to listen
  - Allows coarser time synch and more flexible schedules

Small Technology, Broad Agenda

- Social factors
  - security, privacy, information sharing
- Applications
  - long lived, self-maintaining, dense instrumentation of previously unobservable phenomena
  - interacting with a computational environment
- Programming the Ensemble
  - describe global behavior, synthesis local rules that have correct, predictable global behavior
- Distributed services
  - localization, time synchronization, resilient aggregation
- Networking
  - self-organizing multihop, resilient, energy efficient routing
  - despite limited storage and tremendous noise
- Operating system
  - extensive resource-constrained concurrency, modularity
  - framework for defining boundaries
- Architecture
  - rich interfaces and simple primitives allowing cross-layer optimization
- Components
  - low-power processor, ADC, radio, communication, encryption, sensors, batteries

The Time is Right

- Don’t be afraid to go out and tackle REAL problems.
- They often reveal interesting challenges.
- The technology is (just barely) ready for it.
- There is much innovation ahead.