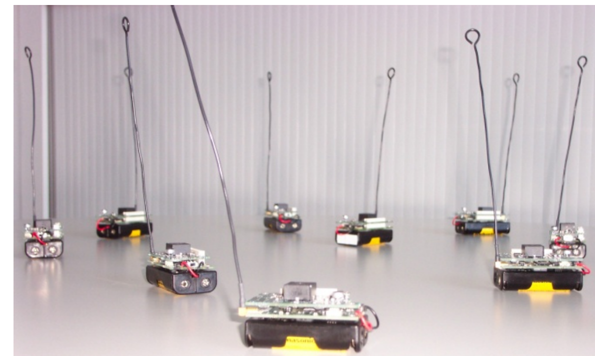
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Distributed Intelligent Systems – W07:

An Introduction to Wireless Sensor Networks from a Distributed Intelligent Systems Perspective

Outline

- Motivating applications
- The Sensorscope project
- Tools used in this course
  - Mica-z
  - 802.15.4 radio for e-puck robots
  - Webots extensions
- Wireless Sensor networks vs. Distributed Intelligent Systems
- Collective decisions and discrete consensus algorithms



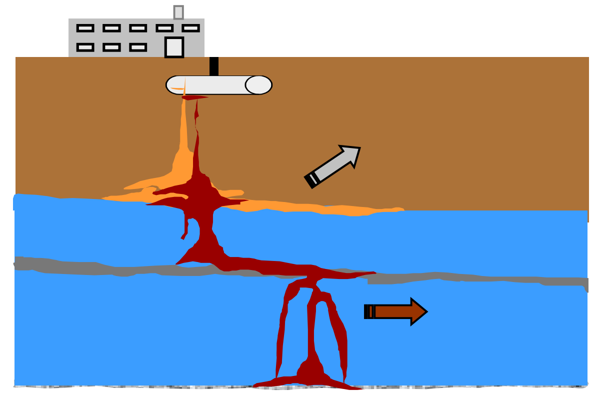
Motivating Applications

Motivation

Seismic Structure response

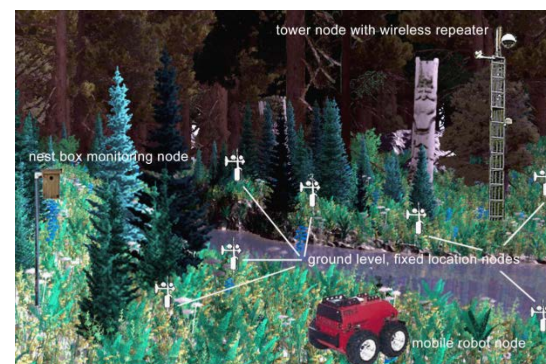
Marine Microorganisms

- Micro-sensors, on-board processing, and wireless interfaces all feasible at very small scale
  - can monitor phenomena “up close”
- Will enable spatially and temporally dense environmental monitoring
- Will enable precise, real-time alarm triggering
- Embedded networked sensing will reveal previously unobservable phenomena



Contaminant Transport

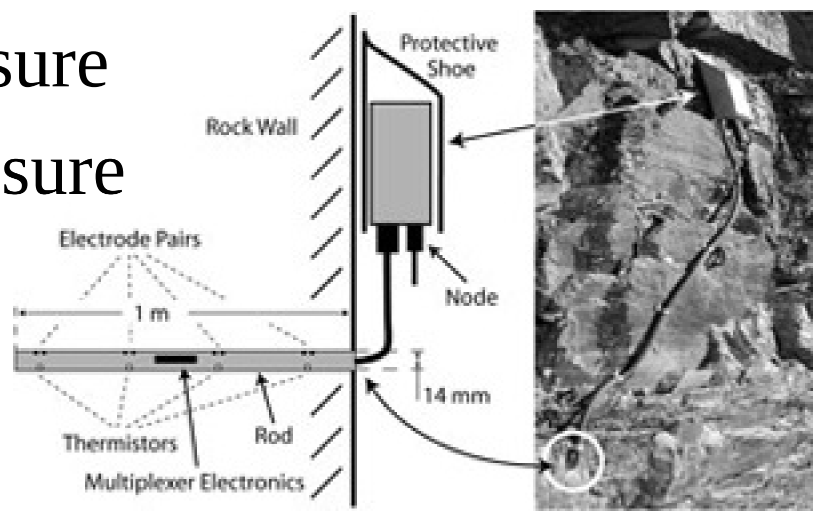
Ecosystems, Biocomplexity



Adapted from D. Estrin, UCLA

Application 1 - *Permasense*

- What is measured:
  - rock temperature
  - rock resistivity
  - crack width
  - earth pressure
  - water pressure

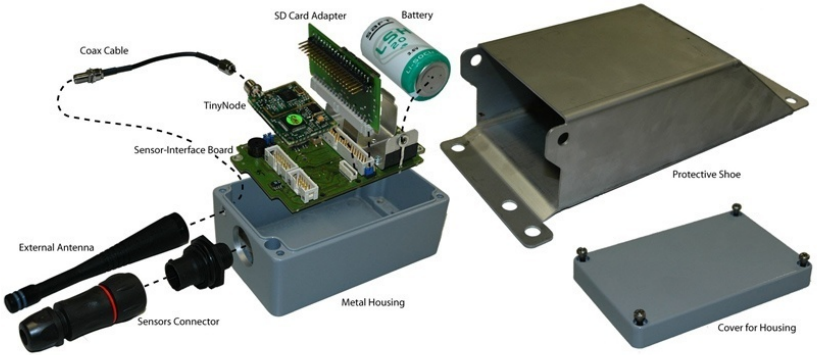


Pictures: courtesy of Permasense

Application 1 - *Permasense*

- Why:

  "[…] gathering of environmental data that helps to understand the processes that connect climate change and rock fall in permafrost areas"

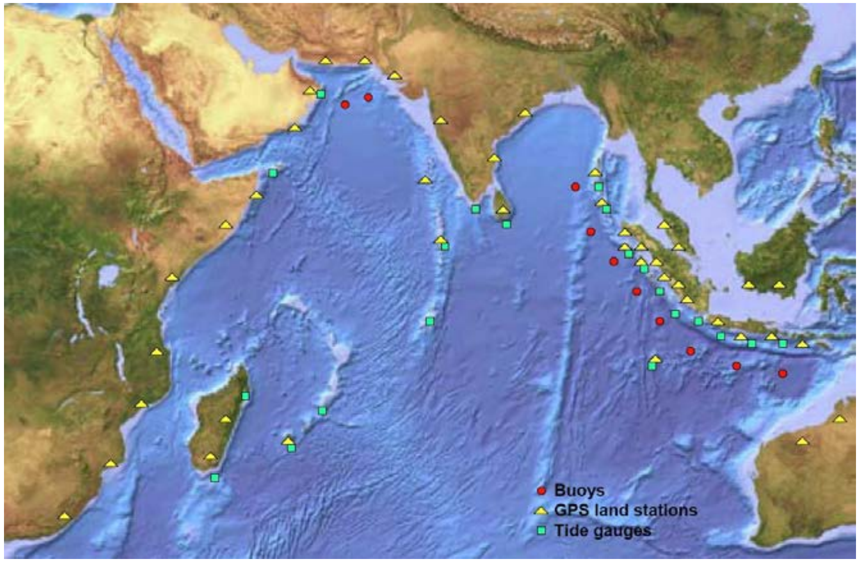


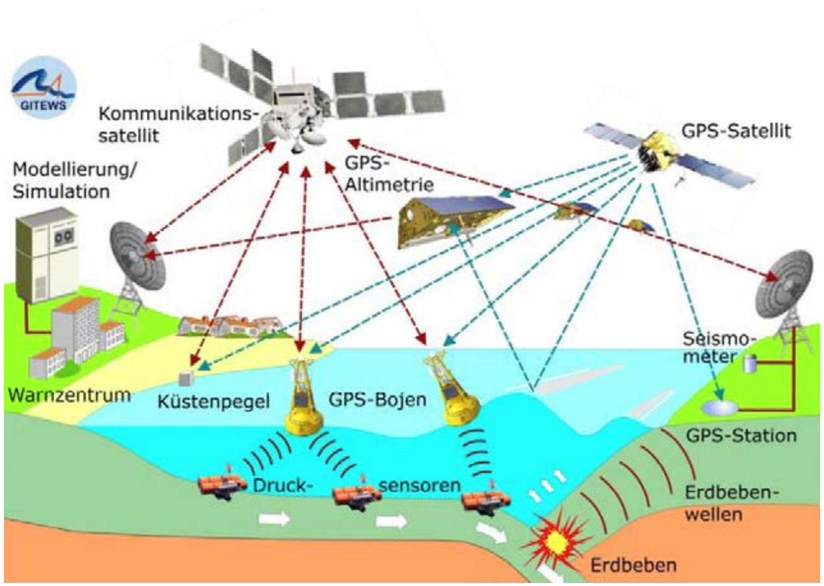
Pictures: courtesy of Permasense

Application 2 - *GITEWS*

German Indonesian Tsunami Early Warning System

- What is measured:
  - seismic events
  - water pressure





Pictures: courtesy of Deutsches GeoForschungsZentrum (GFZ)

Application 2 - *GITEWS*

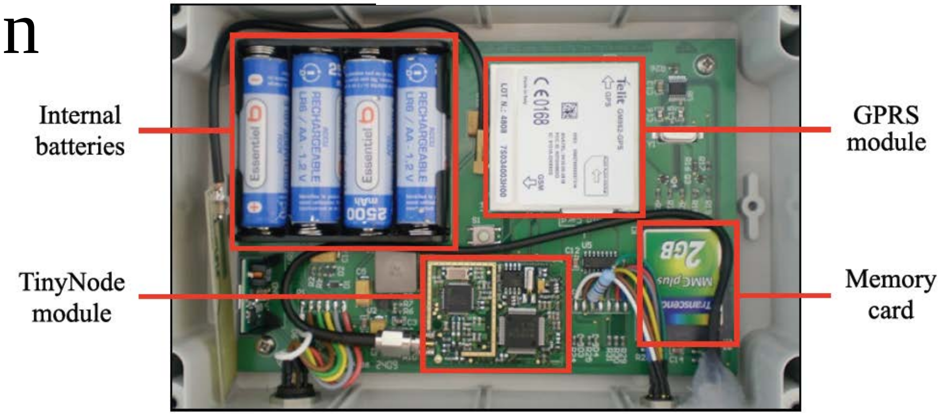
- Why:

  To detect seismic events which could cause a Tsunami. Detect a Tsunami and predict its propagation.

Pictures: courtesy of Deutsches GeoForschungsZentrum (GFZ)

Application 3 - *Sensorscope*

- What is measured:
  - temperature
  - humidity
  - precipitation
  - wind speed/direction
  - solar radiation
  - soil moisture

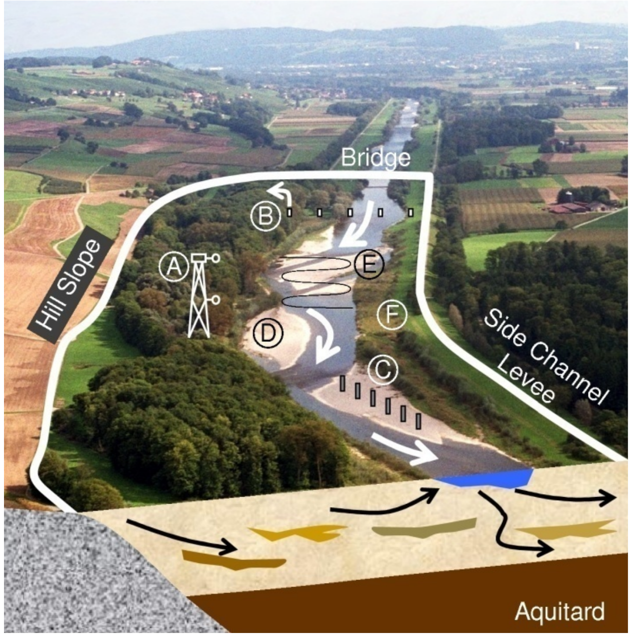


Pictures: courtesy of SwissExperiment

Application 3 - *Sensorscope*

- Why:

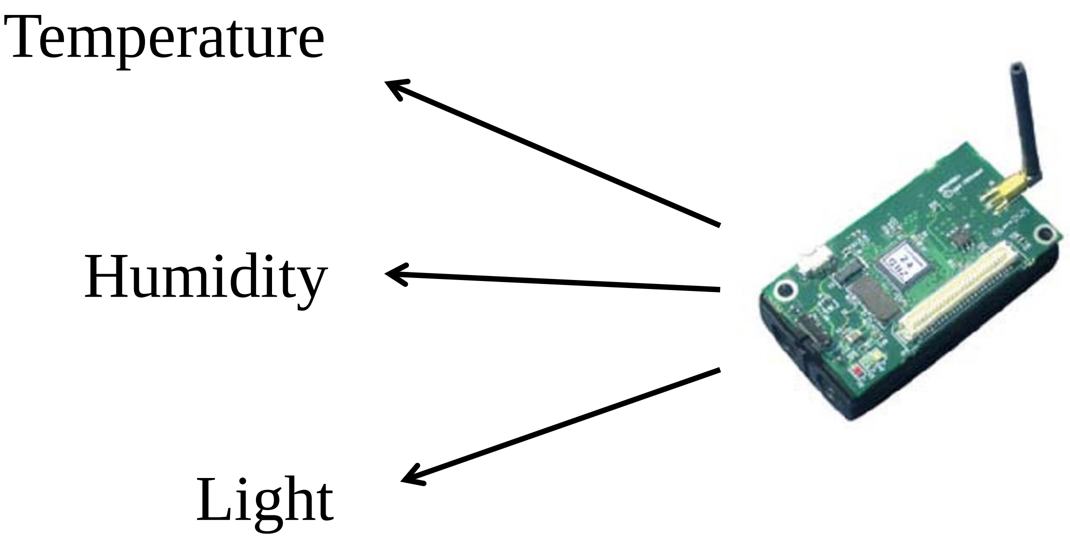
  Capture meteorological events with high spatial density.



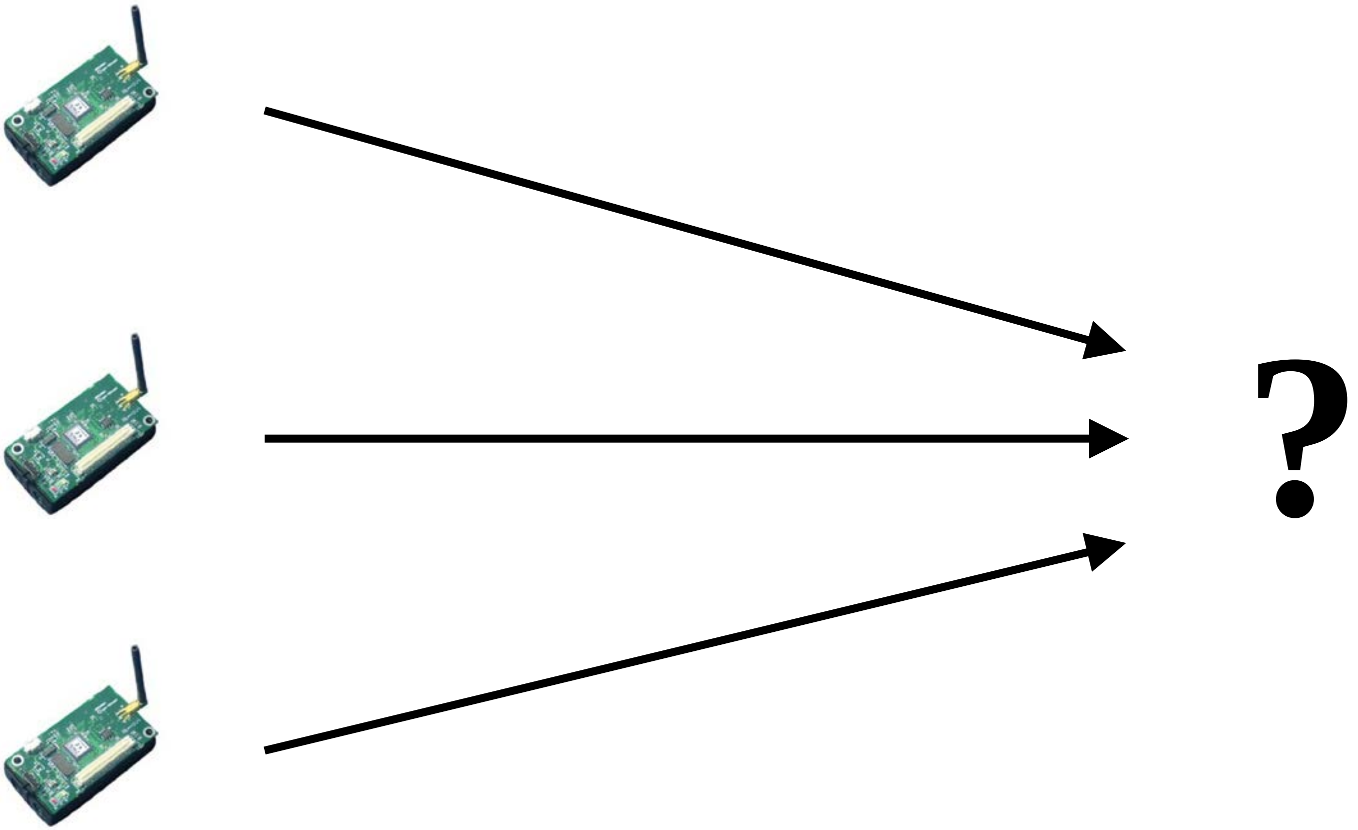
Pictures: courtesy of SwissExperiment

The SensorScope Project

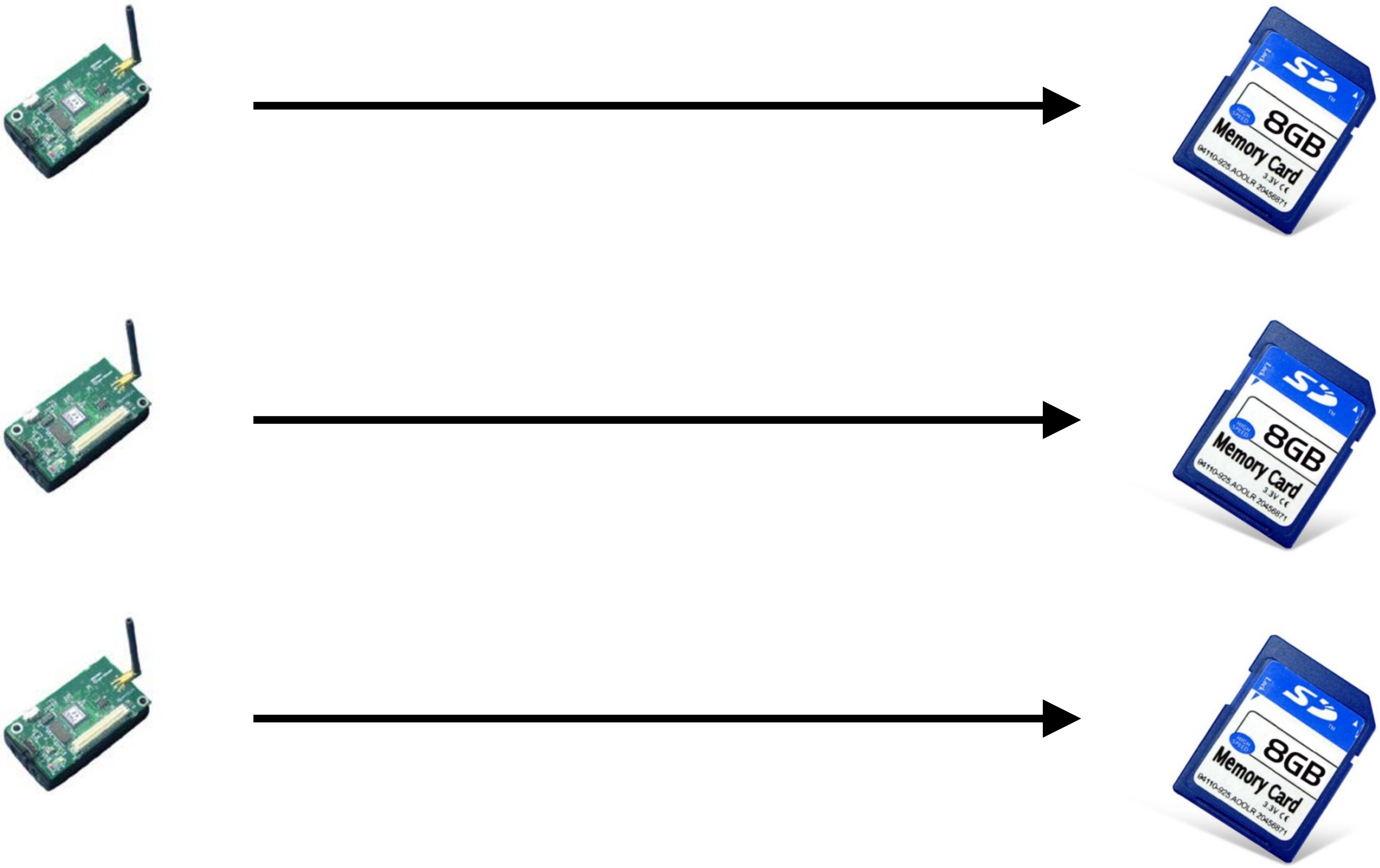
Introduction



Topology



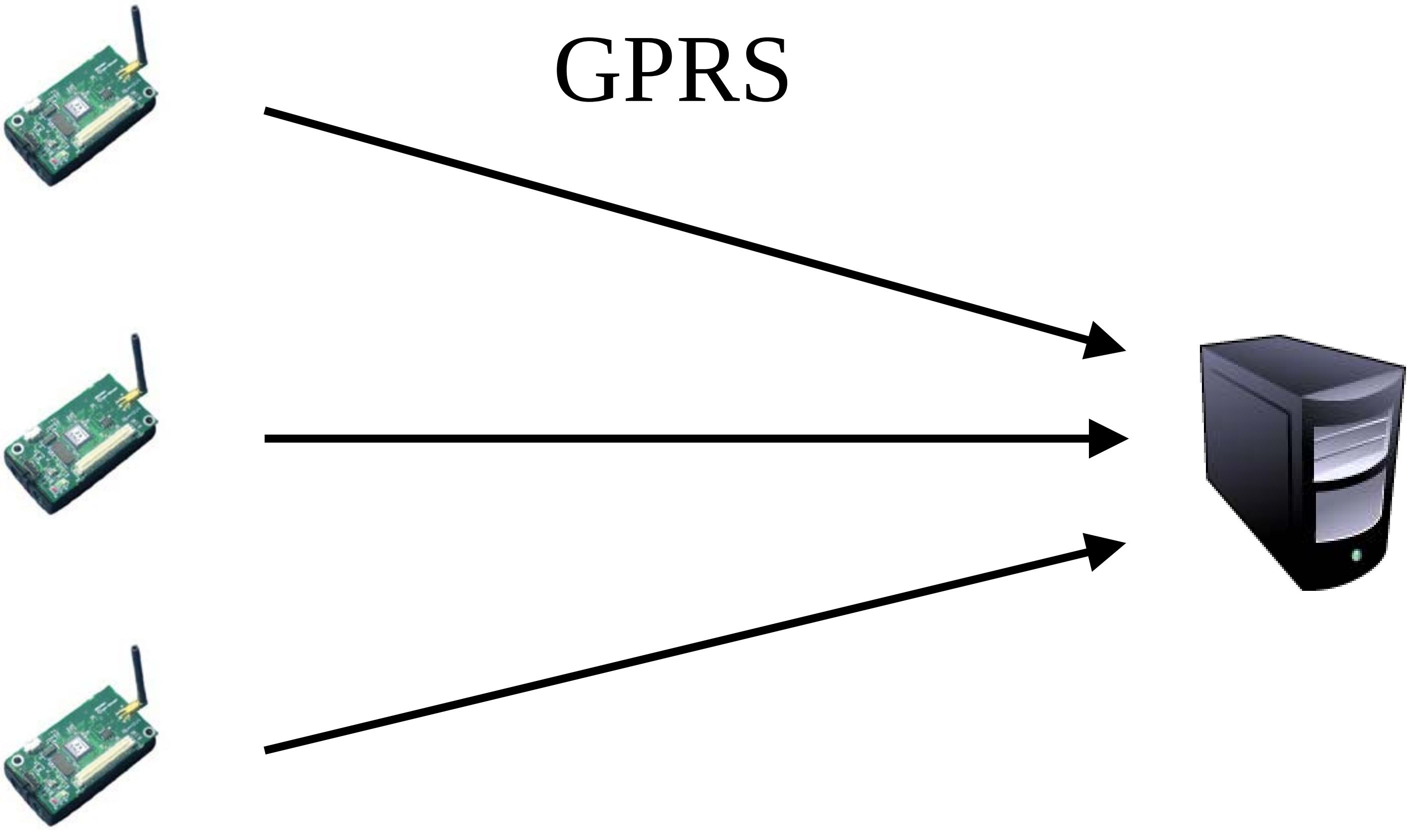
Topology



ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Topology

Topology



Topology

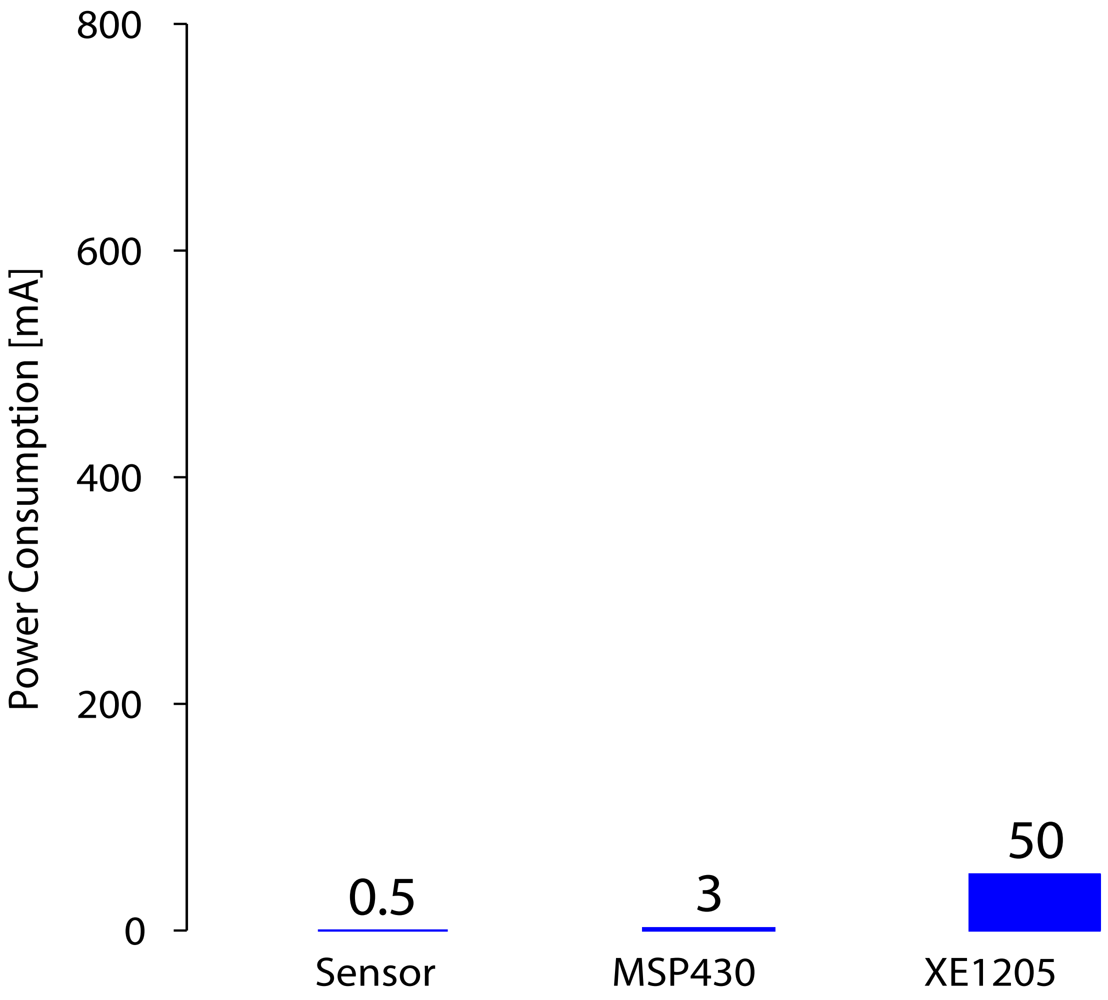
Pros

- Very simple!
- Essentially no restrictions in sensor locations

Cons

- The closest server access point may be quite far from the stations
- A long-range link may consume a lot of energy!

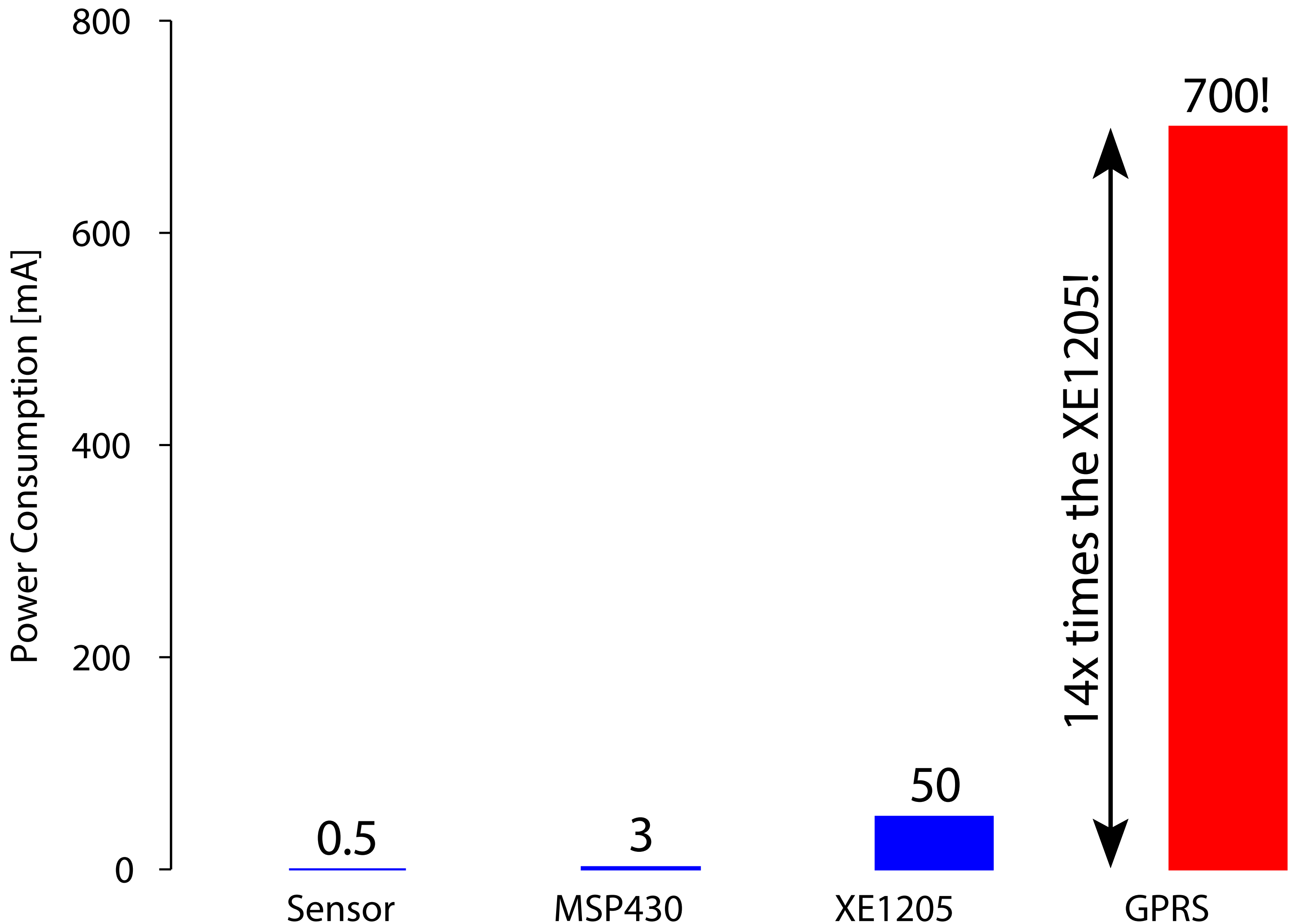
Topology



(Microcontroller)

(Short range radio, up to 2 km)

Topology



800
600
400
200
0
Power Consumption [mA]
0.5
3
50
700!
14x times the XE1205!
Sensor
MSP430
XE1205
GPRS

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Topology

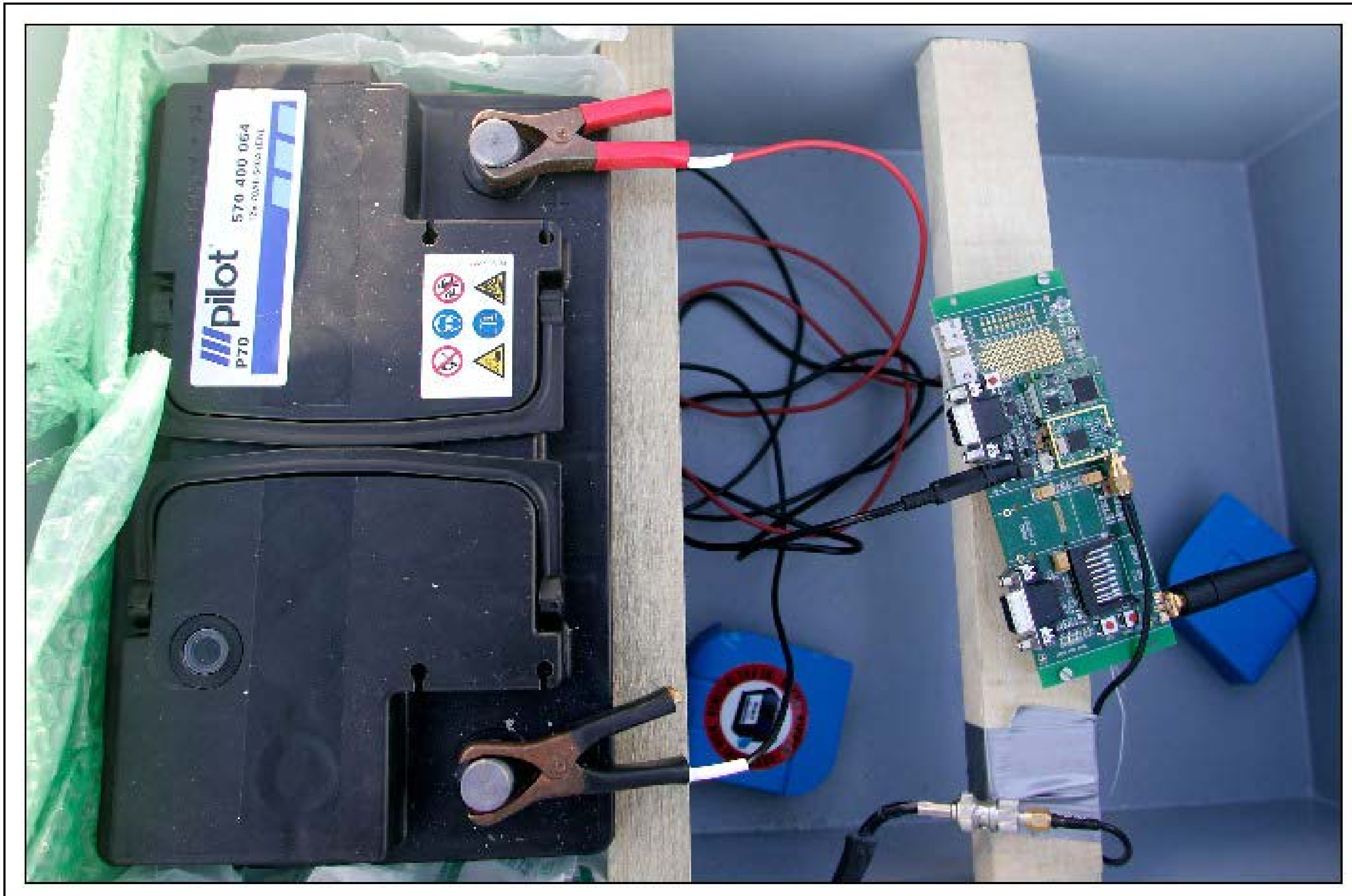
Assuming four AA batteries, 1.2 V, 2000 mAh

- Sensor: **167 days**
- MSP430: **28 days**
- Short range radio: **1.7 days**
- Long range radio: **8 hours**

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

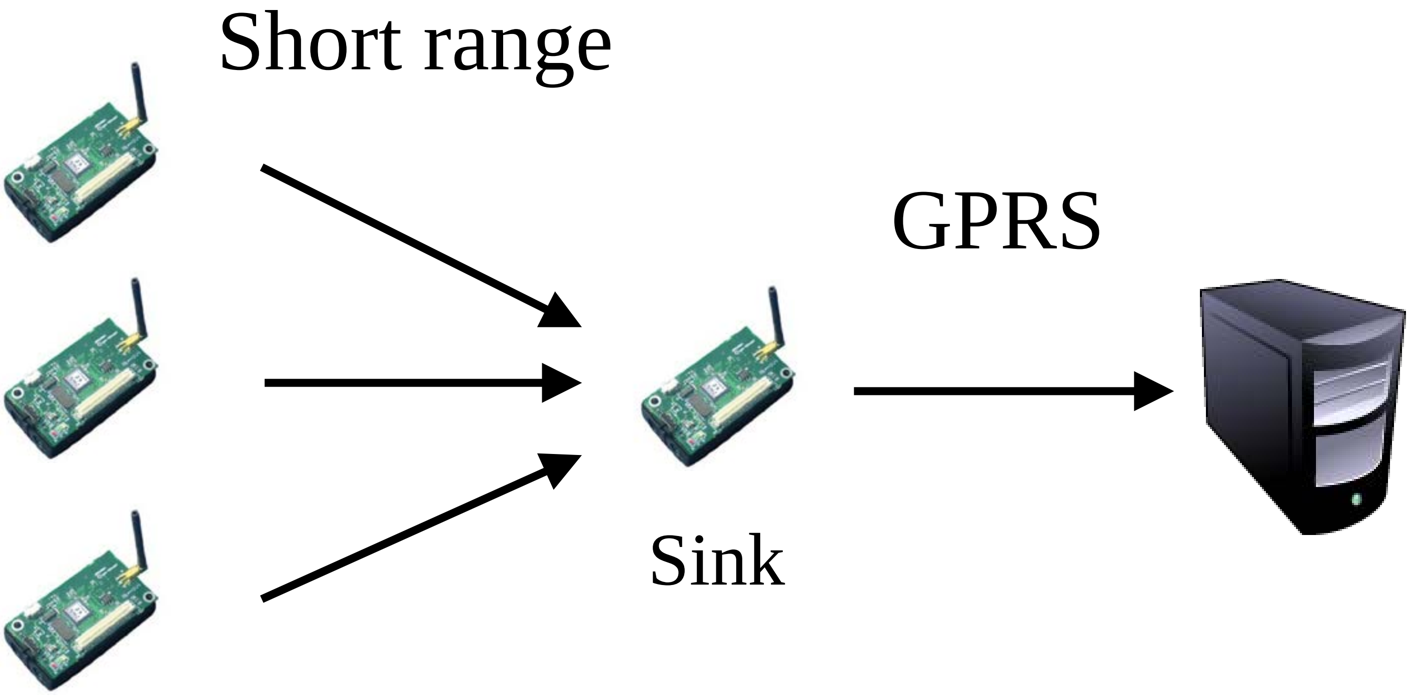
Disal

Topology



ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Topology



Topology

Friis law (power decay in air)

$$L = \left(\frac{4\pi d f}{c} \right)^2$$

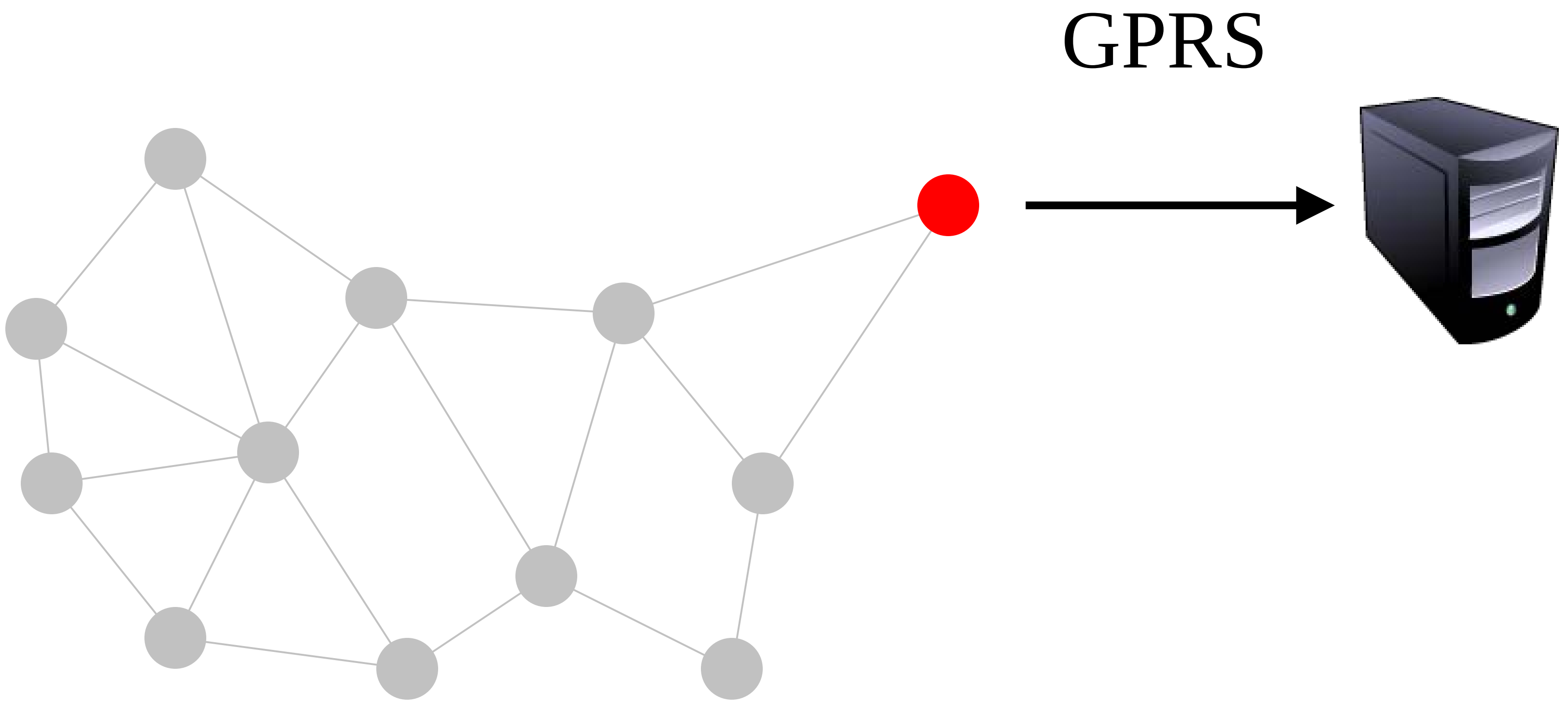
$$P_L = 20 \log \left(\frac{4\pi d}{\lambda} \right)$$

Example: To transmit over 5 Km on 868 MHz we can use:

- One hop of 5 km: **P_L = 106 dB**
- Two hops of 2.5 km: **P_L = 99 dB**
- Five hops of 1 km: **P_L = 92 dB**

Energy is the main issue !!!

Multi-hop WSNs



Multi-hop WSNs

Pros

- Only one car battery in the network
- Extended spatial coverage of the network
- Multiple routes for stations to communicate with the sink
- Auto configurable network (robustness)

Cons

- Significantly more complicated
- Data rate is not increased
- Unable to use directional antennas

Multi-hop WSNs

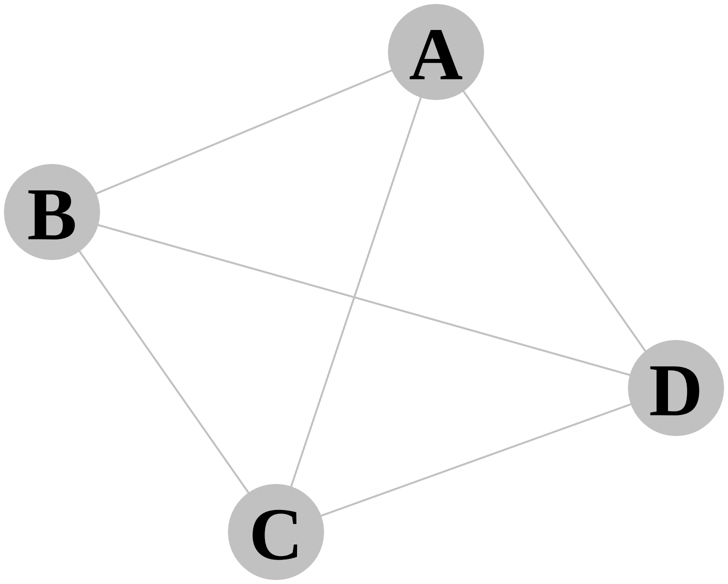
Implementation:

- Neighborhood discovery
- Data routing
- Time synchronization
- Duty-cycling (radio management)

Neighborhood

Hello messages (Beacons) are one common method:

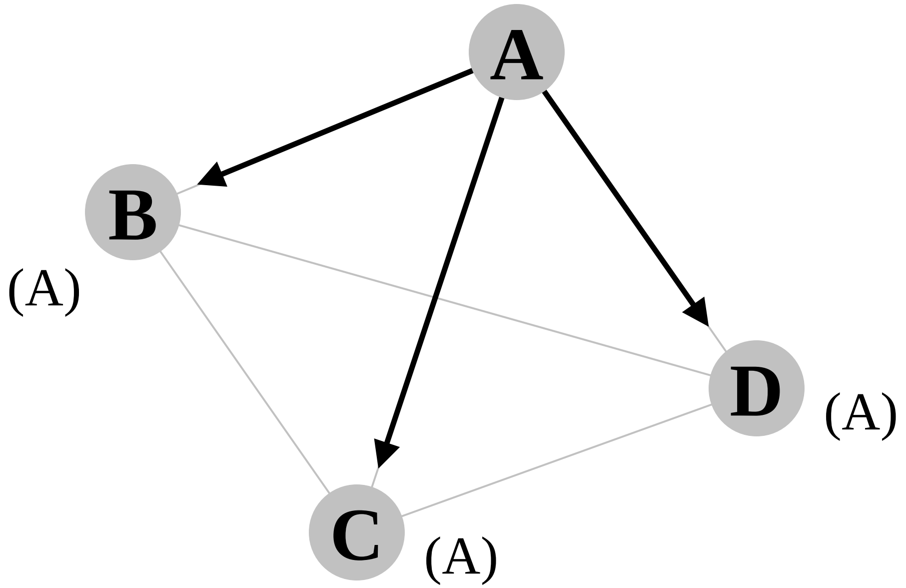
1. Node A sends a HELLO message to its neighbors (B, C, and D).
2. Nodes B, C, and D update their neighborhood table.
3. Node B sends a HELLO message to its neighbors (A, C, and D).
4. …



Neighborhood

Hello messages (Beacons) are one common method:

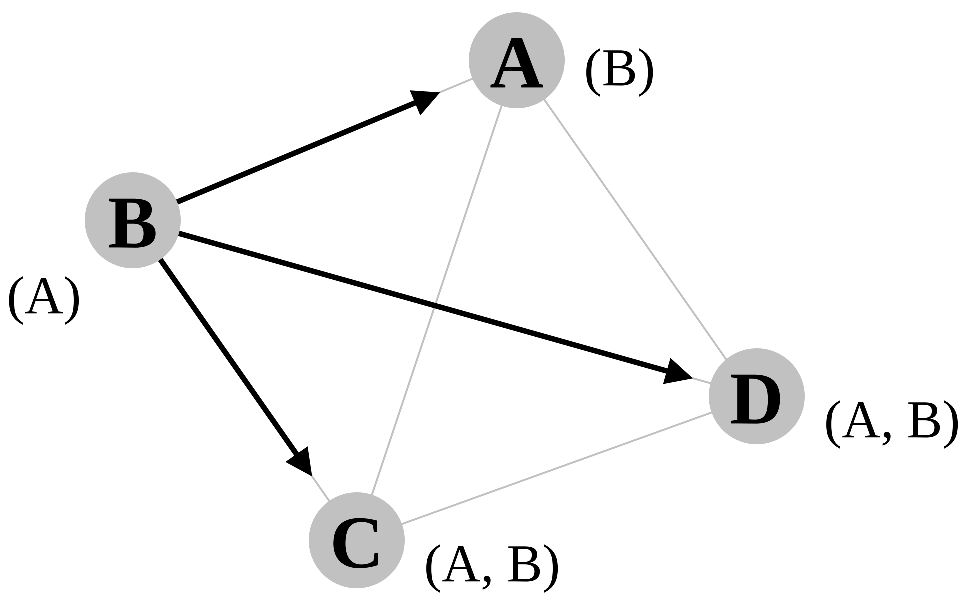
1. Node A sends a HELLO message to its neighbors (B, C, and D).
2. Nodes B, C, and D update their neighborhood table.
3. Node B sends a HELLO message to its neighbors (A, C, and D).
4. …



Neighborhood

Hello messages (beacons) are one common method:

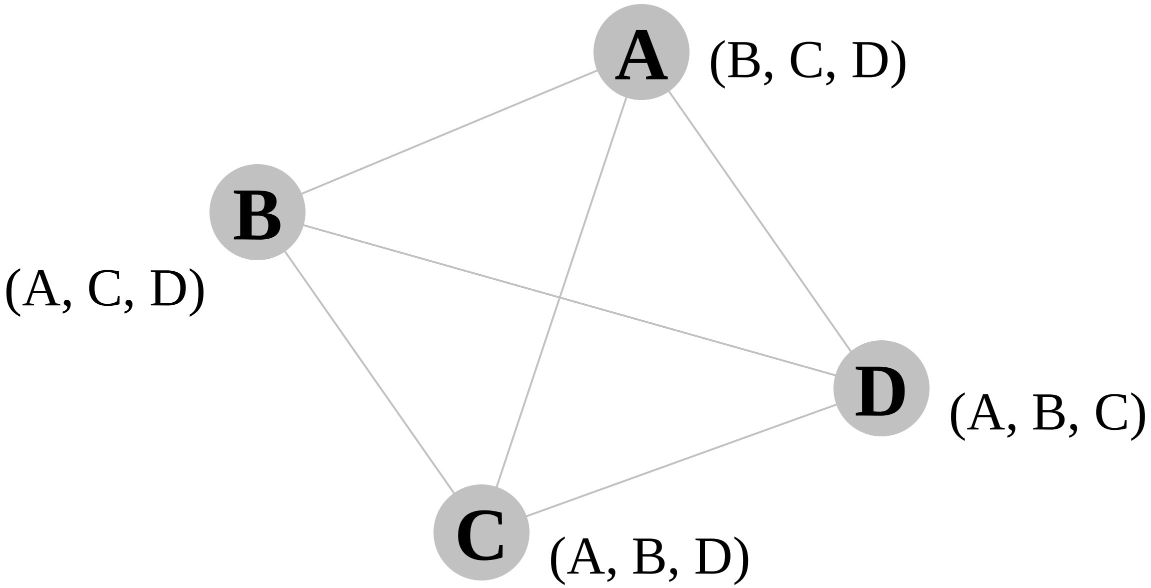
1. Node A sends a HELLO message to its neighbors (B, C, and D).
2. Nodes B, C, and D update their neighborhood table.
3. Node B sends a HELLO message to its neighbors (A, C, and D).
4. …



Neighborhood

Hello messages (beacons) are one common method:

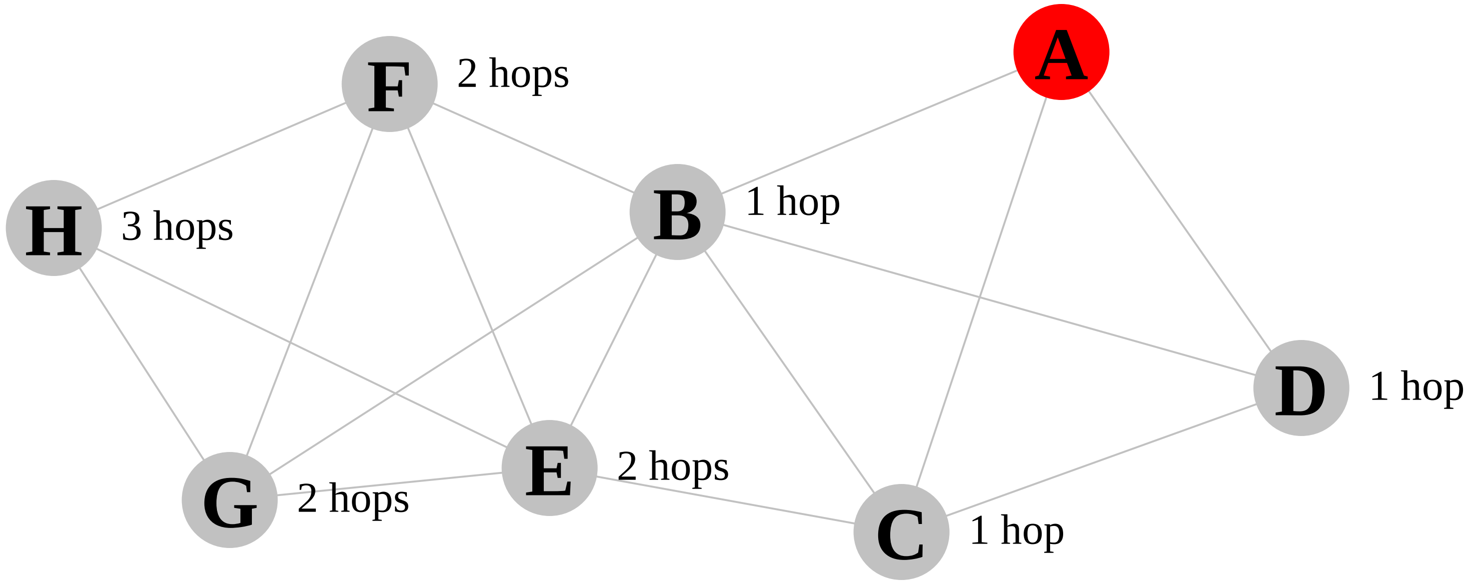
1. Node A sends a HELLO message to its neighbors (B, C, and D).
2. Nodes B, C, and D update their neighborhood table.
3. Node B sends a HELLO message to its neighbors (A, C, and D).
4. …



Neighborhood

What information do we need about our neighbors?

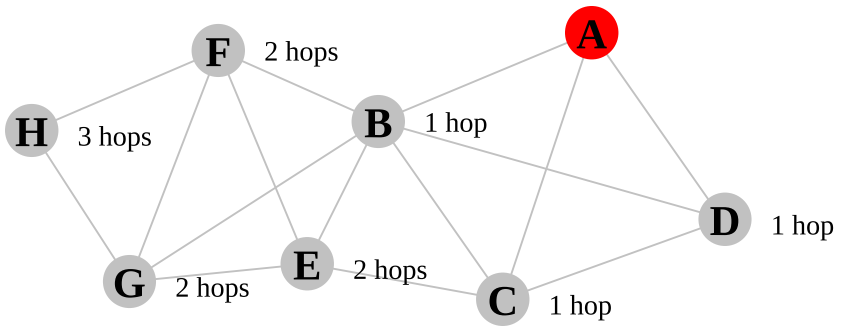
- Distance to sink
- Last time heard
- Link quality



Neighborhood

Node E's neighborhood table

Id	**Age**	**Distance**	**Quality**
B	2 min	1 hop	87%
C	2 min	1 hop	98%
F	4 min	2 hops	74%
G	1 min	2 hops	93%



A few remarks:

- Only the distance to the sink is stored.
- Neighborhood discovery can't be done only once!
- We need to estimate link qualities!

Neighborhood

Variations of simple schema:

- Each node sends X beacons per minute.
- Number of beacons received per minute are stored.
- Quality is estimated over the past Y minutes by counting losses.

Example (X = 10;Y = 4):

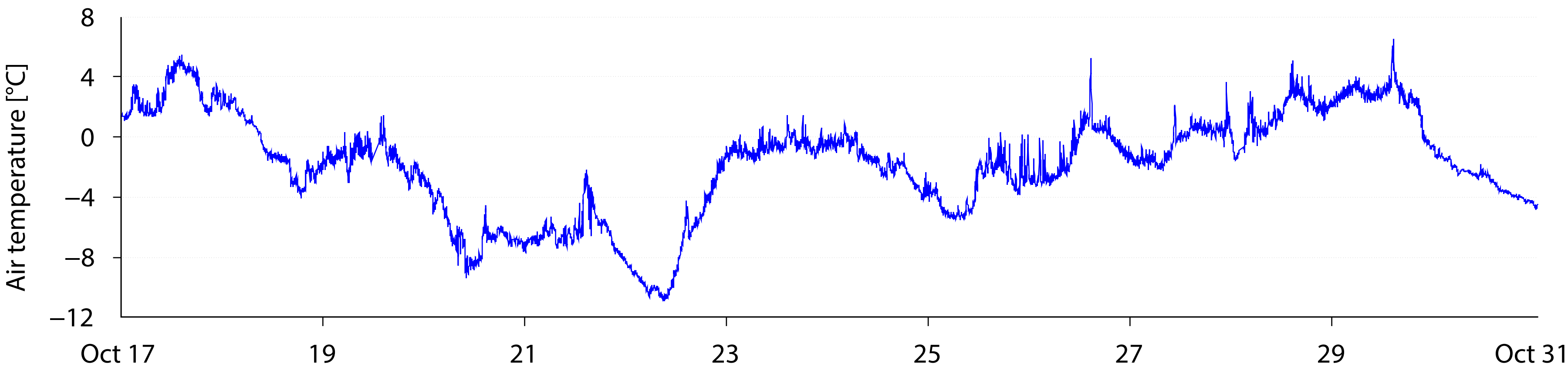
t – 4	t – 3	t - 2	t - 1	
10	7	8	8	Quality = 0.8

t – 4	t – 3	t - 2	t - 1	
7	8	8	6	Quality = 0.71

t – 4	t – 3	t - 2	t - 1	
8	8	6	5	Quality = 0.64

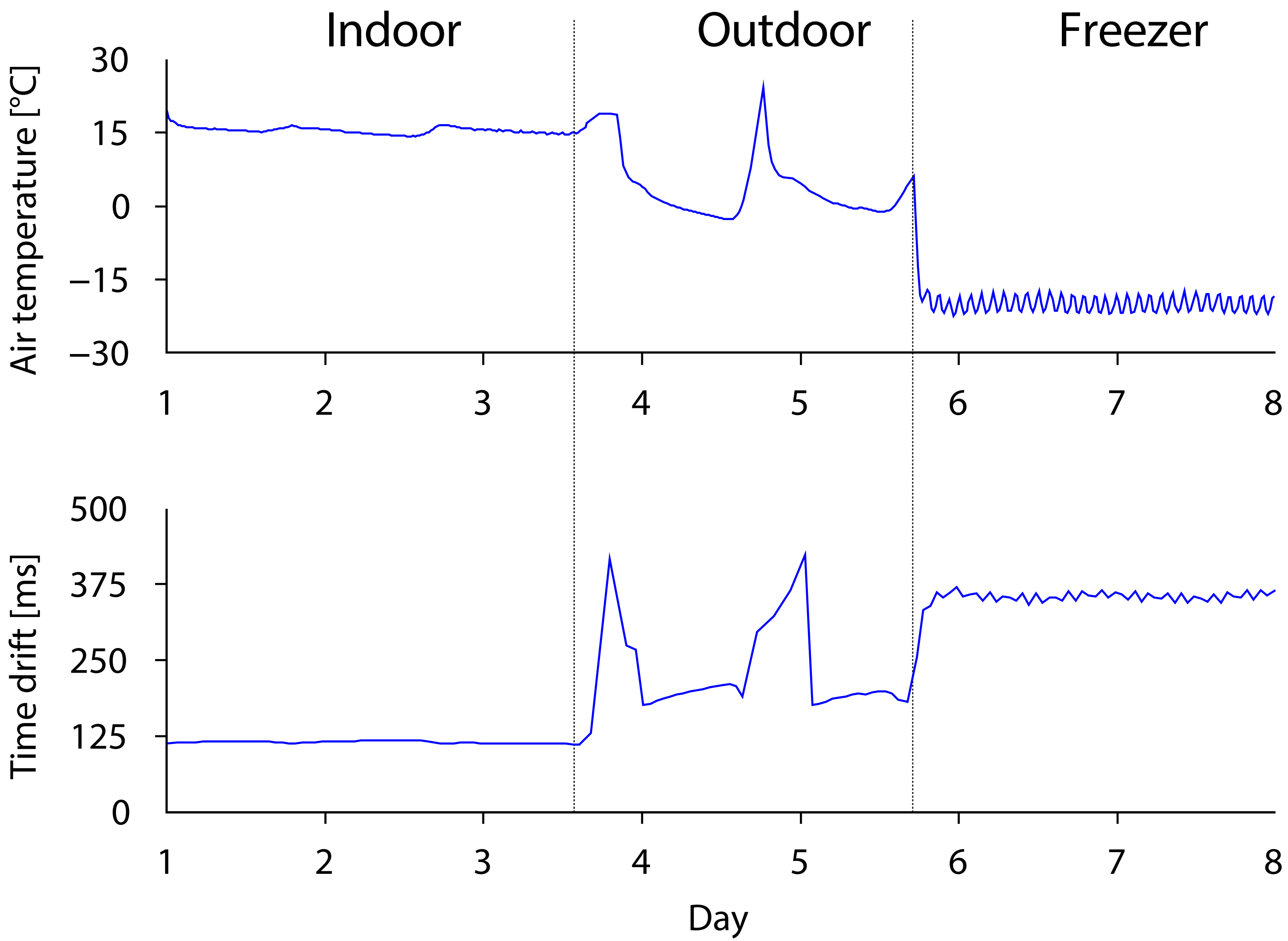
Time Synchronization

Weather conditions, especially temperature and humidity, may have a significant effect on hardware



Crystal oscillators are highly impacted by temperature!

Time Synchronization



Time Synchronization

Nodes need to know the time to:

- Timestamp packets
- Synchronize actions (e.g., taking samples, transmitting data)

How do we get time:

- Fully decentralized: Every node gets the time itself
- Partially centralized: Time is propagated from reference nodes

Time Synchronization

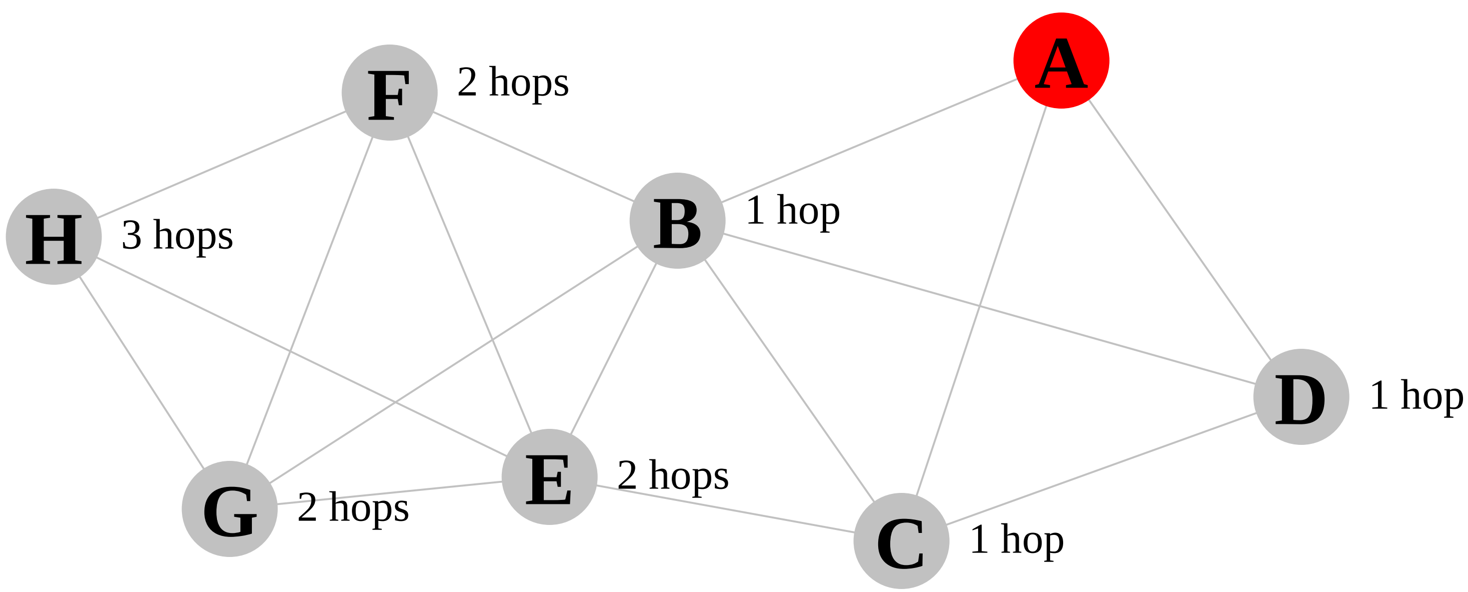
Every node gets the time:

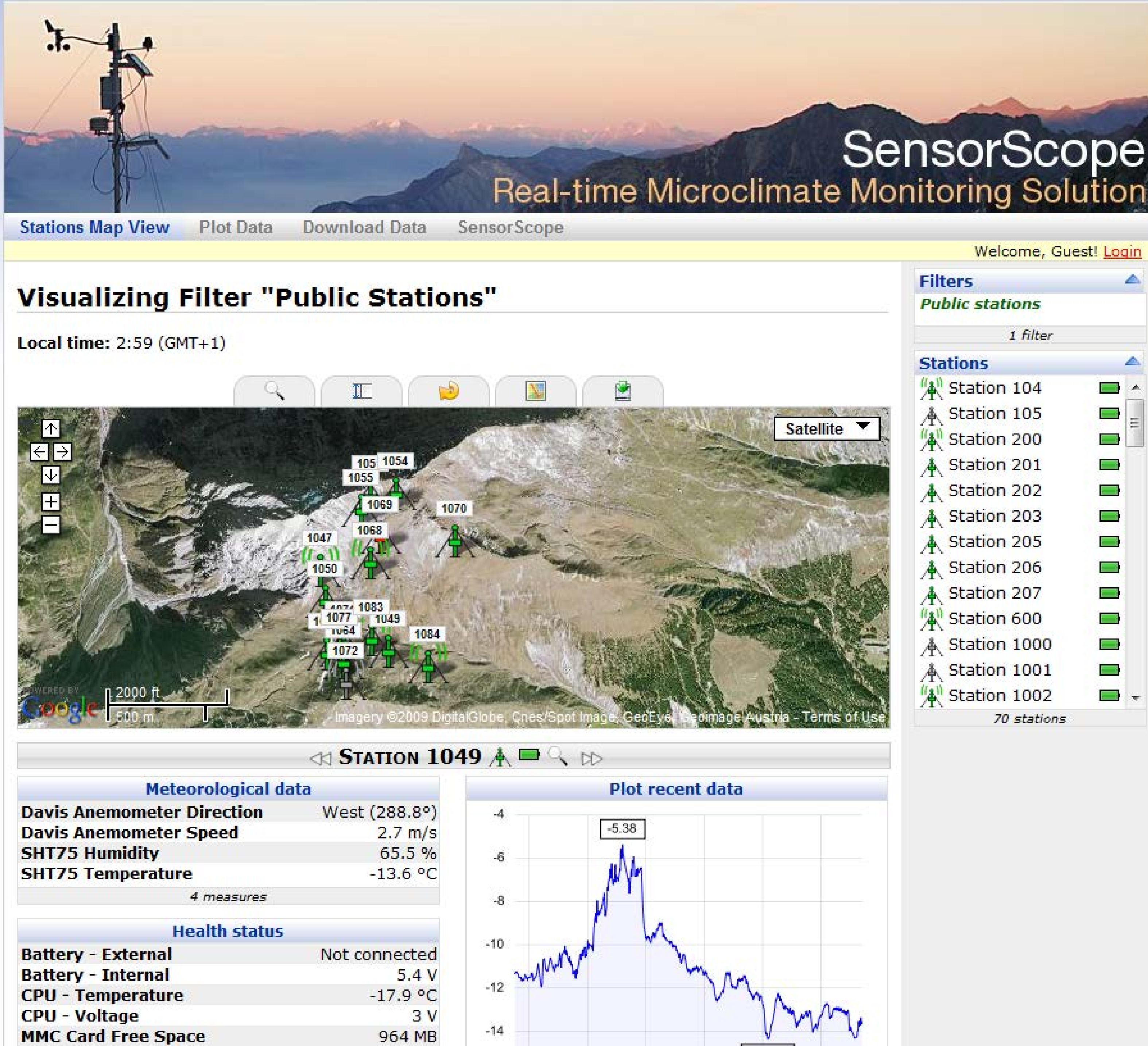
- Atomic clock receivers:
  - Cheap (both energy and $)
  - Complexity
  - Limited coverage
- GPS:
  - Coverage
  - Complexity
  - High cost (energy and $)
- GPRS: same as GPS with less coverage

What about a partially centralized approach?

Time Synchronization

For instance, the sink serve as time reference node




SensorScope
Real-time Microclimate Monitoring Solution
Stations Map View
Plot Data
Download Data
SensorScope
Welcome, Guest! Login
Visualizing Filter "Public Stations"
Local time: 2:59 (GMT+1)
Satellite
Filters
Public stations
1 filter
Stations
Station 104
Station 105
Station 200
Station 201
Station 202
Station 203
Station 205
Station 206
Station 207
Station 600
Station 1000
Station 1001
Station 1002
70 stations
2000 ft
500 m
Imagery ©2009 DigitalGlobe, Cnes/Spot Image, GeoEye, Geoimage Austria - Terms of Use
Station 1049
Meteorological data
Davis Anemometer Direction West (288.8°)
Davis Anemometer Speed 2.7 m/s
SHT75 Humidity 65.5 %
SHT75 Temperature -13.6 °C
4 measures
Health status
Battery - External Not connected
Battery - Internal 5.4 V
CPU - Temperature -17.9 °C
CPU - Voltage 3 V
MMC Card Free Space 964 MB
Plot recent data
-5.38
-4
-6
-8
-10
-12
-14

Hardware and Software Modules used in this Course

MICA mote family

- designed in EECS at UCBerkeley
- manufactured/marketed by Crossbow
  - several thousand produced
  - used by several hundred research groups
  - about CHF 250/piece
- variety of available sensors

MICAz

- Atmel ATmega128L
  - 8 bit microprocessor, ~8MHz
  - 128kB program memory, 4kB SRAM
  - 512kB external flash (data logger)

- Chipcon CC2420
  - Respect 802.15.4 at the physical/MAC layer and therefore can support Zigbee-compliant stacks
- 2 AA batteries
  - about 5 days active (15-20 mA)
  - about 20 years sleeping (15-20 µA)
- TinyOS

Sensor board

- MTS 300 CA
  - Light (Clairex CL94L)
  - Temp (Panasonic ERT-J1VR103J)
  - Acoustic (WM-62A Microphone)
  - Sounder (4 kHz Resonator)

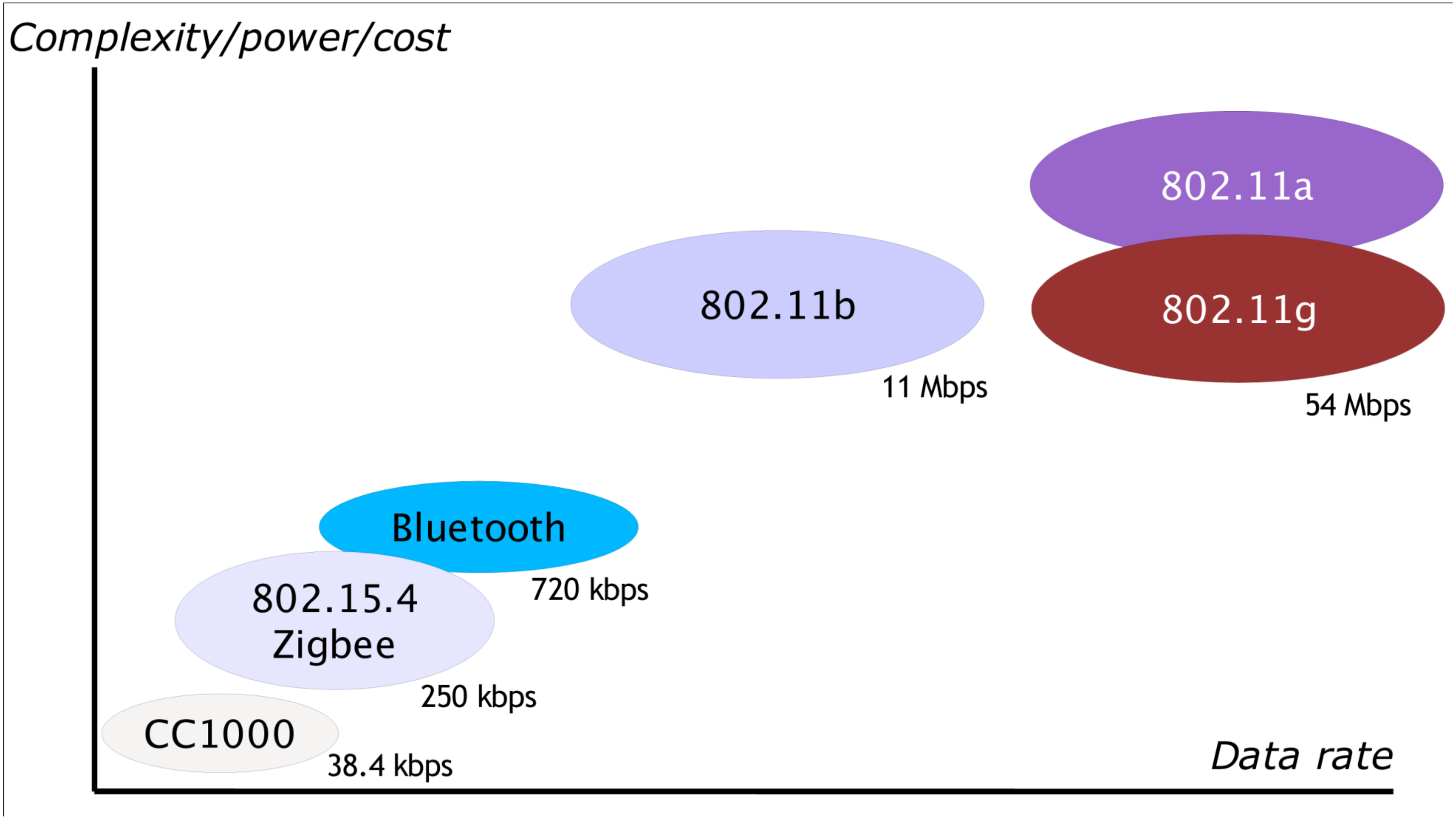
TinyOS

- Minimal OS designed for Sensor Networks
- Event-driven execution
- Programming language: nesC (C-like syntax but supports TinyOS concurrency model)
- Widespread usage on motes
  - MICA (ATmega128L)
  - TELOS (TI MSP430)
- Provided simulator: TosSim

802.15.4 / Zigbee

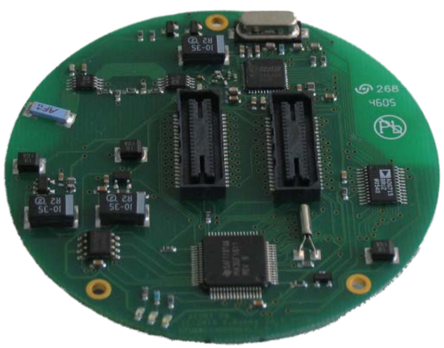
- Emerging standard for low-power wireless monitoring and control
  - 2.4 GHz ISM band (84 channels), 250 kbps data rate
- Chipcon/Ember CC2420: Single-chip transceiver
  - 1.8V supply
    - 19.7 mA receiving
    - 17.4 mA transmitting
  - Easy to integrate: Open source drivers
  - O-QPSK modulation; “plays nice” with 802.11 and Bluetooth

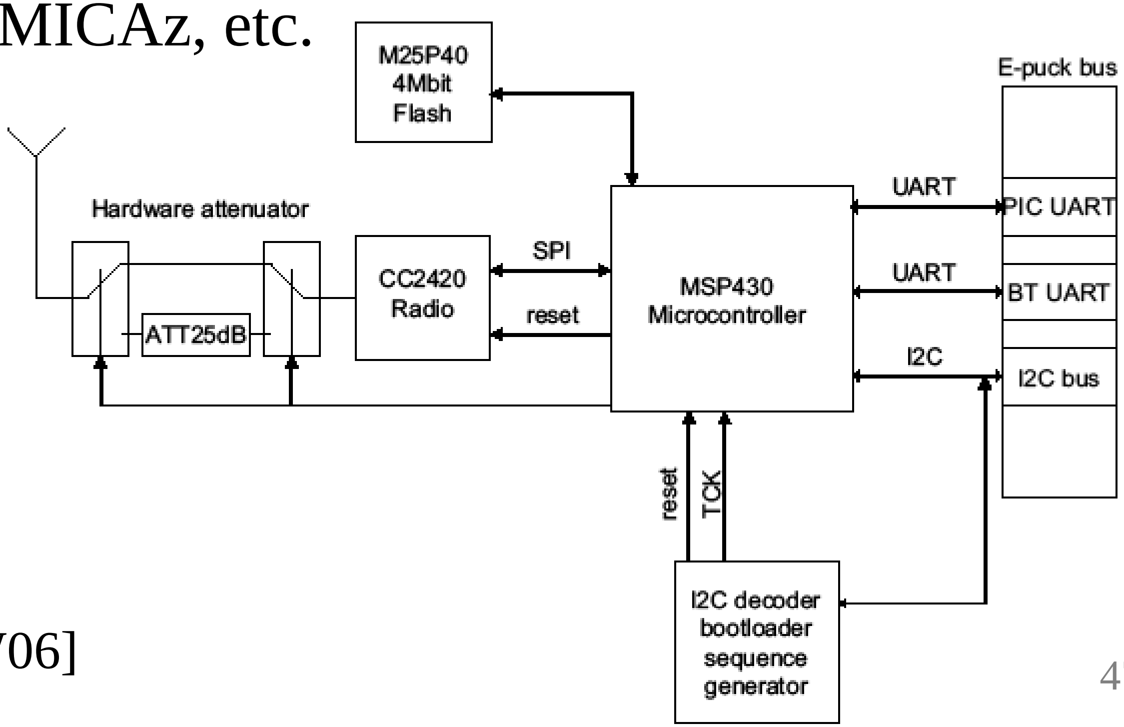
Comparison to other standards



The epuck 802.15.4 Radio

- Custom module designed specifically for short range
- Software controllable (~5cm-5m)
- Radio stack implemented in TinyOS (not fully ZigBee compliant)
- Interoperable with MICAz, etc.



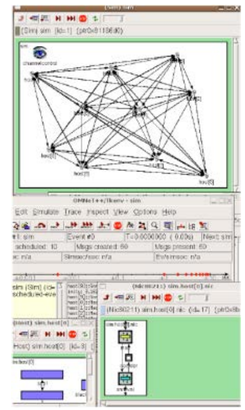


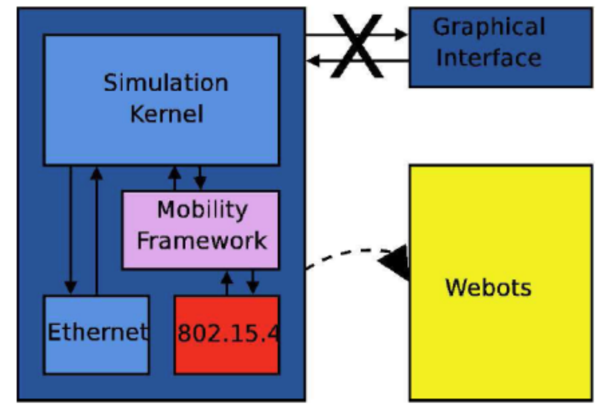
[Cianci et al, SAB-SRW06]

Communication Plug-In for Webots

Original Plug-in

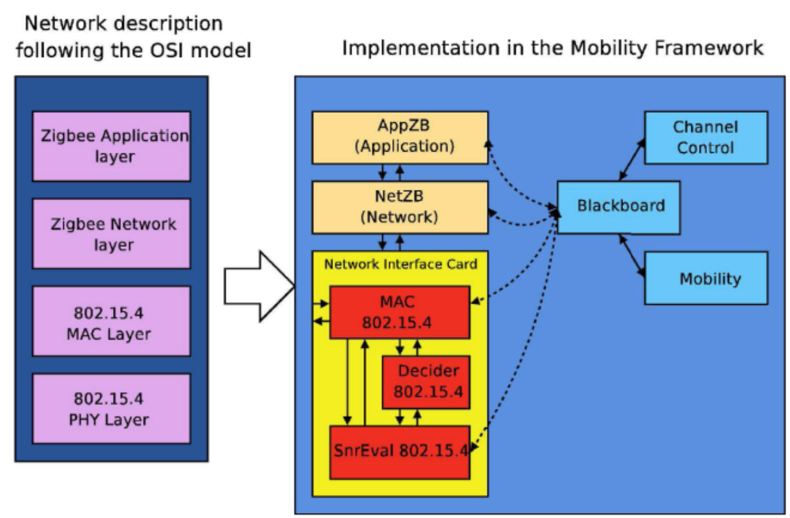
- OmNET++
- OSI framework
- Custom Layers
  - 802.15.4
  - ZigBee
- Physical communication model:
  - semi-radial disk with noise
  - channel intensity fading
- Calibrated with real hardware





New Plug-in

- NS3 (more promising framework)
- 802.11p, uncalibrated
- [Llaster et al. 2017]



ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Wireless Sensor Networks vs. Distributed Intelligent Systems

WSN and DIS

Wireless sensor networks:

- are spatially distributed systems
- exploit wireless networking as main inter-node interaction channel
- typically consist of static, resource-constrained nodes
- energy saving is a crucial driver for the design of WSN
- have nodes which can sense, act (typically no physical movement), compute and communicate in an unattended mode

Are WSN a special class of Distributed Intelligent Systems?

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

WSN and DIS

The potential is there but currently we observe:

- Limited embedded intelligence/adaptation:
  - sensing data are typically only collected for a particular application and rarely used to control node actions: WSN are typically data agnostic!
  - no emphasis on local real-time perception-to-action loop
  - activity pattern (sensing, computing, networking) are typically a priori scheduled
  - static nodes face lower unpredictability than mobile ones
- Limited control distributedness
  - the fact that WSN are spatially distributed does not necessarily mean distributed control: the existence of a sink allows for centralized control which in turn often promote energy saving

WSN vs. Networked Multi-Robot Systems

Networking is common, sensor nodes = mobile robots without self-locomotion capabilities or mobile robots = sensor nodes with self-locomotion capabilities. So minimal difference? Not really …

- Mobility changes completely the picture of the problem: more unpredictability, noise, … .
- Self-locomotion even more so: real-time control loop at the node level + energy budget breakdown radically different
- Typically different system performance metrics and therefore different objectives pursued at design stage

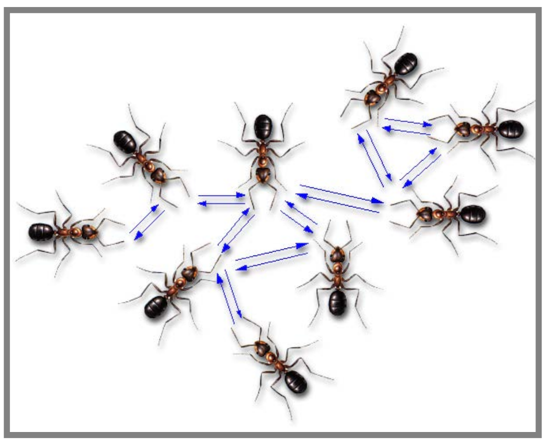
Collective Decisions using WSN

- Collective decisions can be taken as benchmarking framework for testing distributed intelligent algorithms
- They do not involve necessarily mobility; interactions can happen via radio
- Discrete consensus algorithms (e.g., voting scheme) can be deployed on a WSN for reaching a collective decision

Collective Decisions

Understanding Collective Decisions

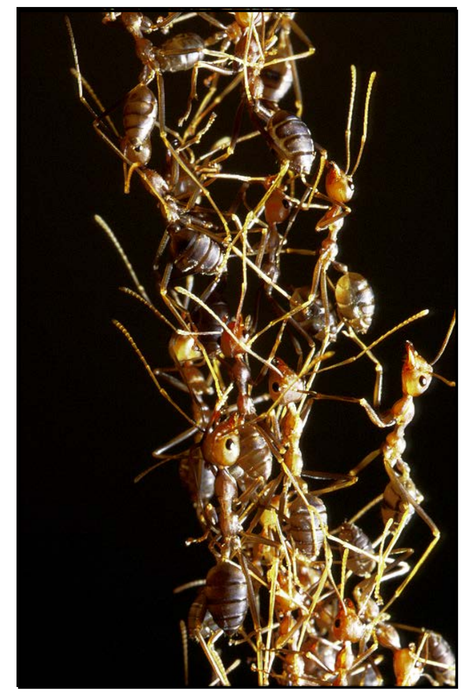
- Local rules and appopriate amplification and/or coordination mechanisms can lead to collective decisions
- Modeling to understand the underlying mechanisms and generate ideas for artificial systems



Individual behaviors and local interactions

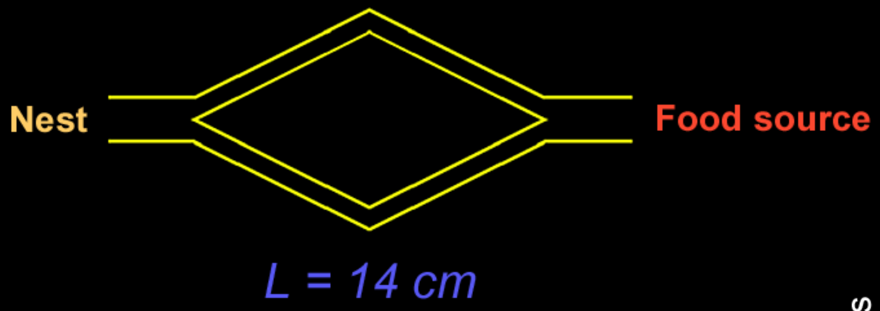
Modeling

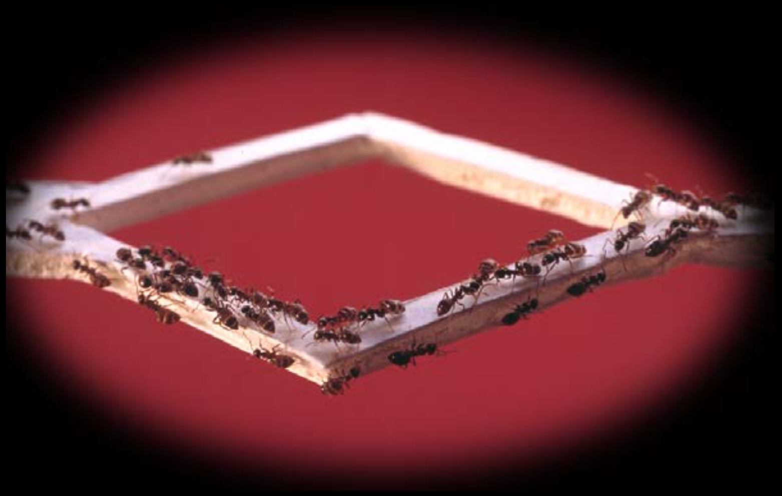
Ideas for artificial systems



Global structures and collective decisions

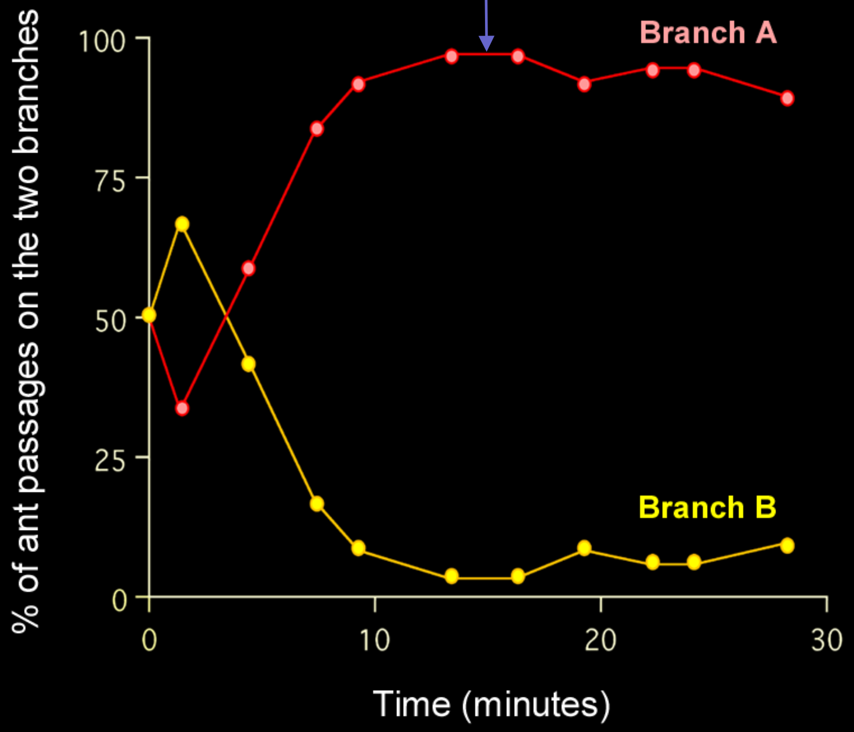
Example 1: Selecting a Path (W1)



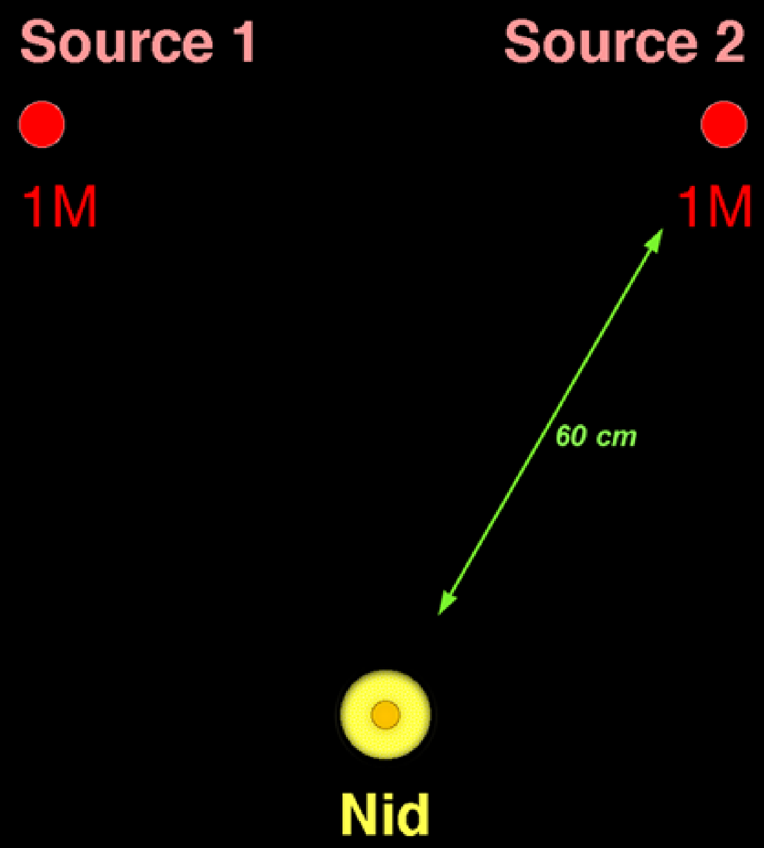


(Deneubourg *et al.*, 1990)

Choice occurs randomly



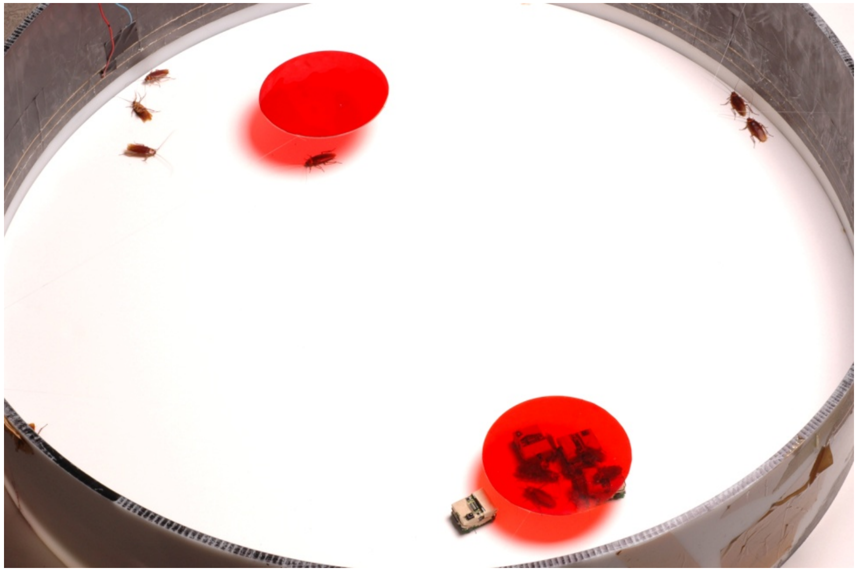
Example 2: Selecting a Food Source (W1)



Example 3: Selecting a Shelter

- *Leurre*: European project focusing on mixed insect-robot societies (http://leurre.ulb.ac.be)

- A simple decision-making scenario: 1 arena, 2 shelters
- Shelters of the same and different darkness
- Groups of pure cockroaches (16), mixed robot+cockroaches (12+4)
- Infiltration using chemical camouflage and statistical behavioral model
- More in week 14



[Halloy et al., *Science*, Nov. 2007]

Example 4: Selecting a Direction

Converging on the direction of rotation (clockwise or anticlockwise):

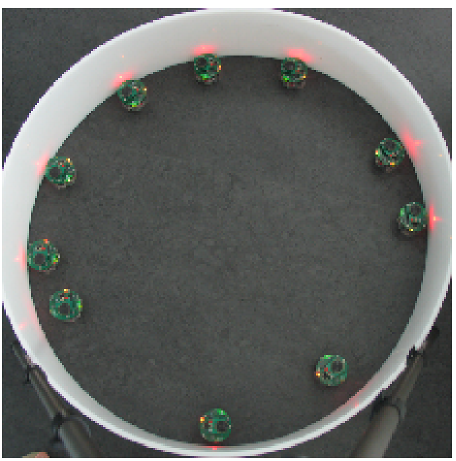
• 11 Alice I robots

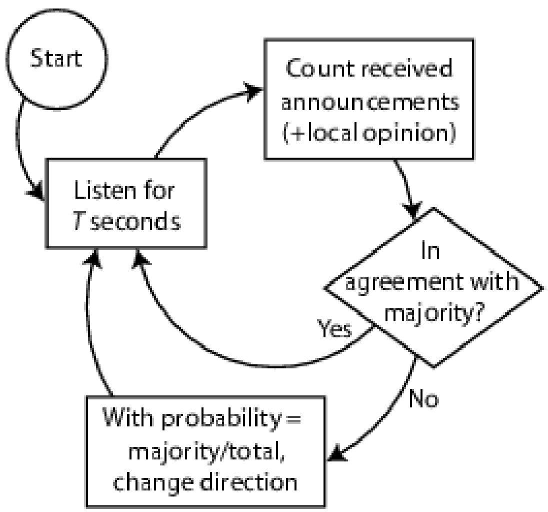
• infrared-based local communication

• Idea: G. Theraulaz (and A. Martinoli); implementation: G. Caprari, W. Agassounon

Set-up and Discrete Consensus Algorithm

- 10 robots execute wall-following behavior (CW or CCW, initially random)
- announce their current direction on the radio channel



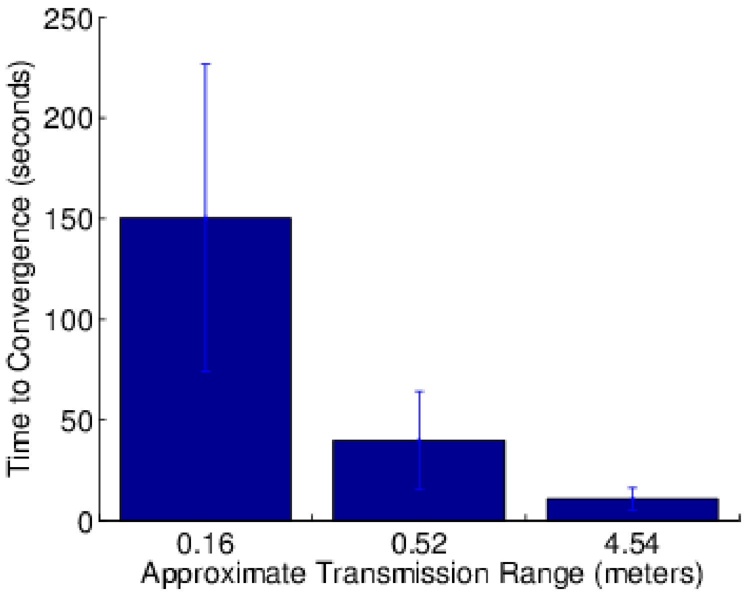


- # of votes not constant
- probabilistic decision
- communication range affects time to convergence.

[Cianci et al, SAB-SRW 06]

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

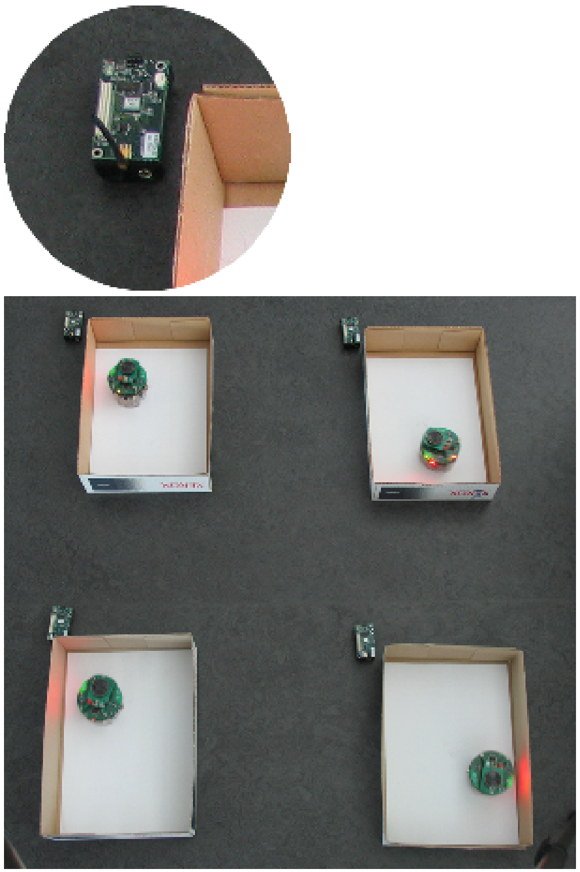
Some Results



- Larger communication ranges (neighborhoods) yield faster convergence
- Smaller communication ranges suffer more from partial perception; the majority near any given node may not reflect the majority in the system at a specific time

[Cianci et al, SAB-SRW 06]

Alternative Scenario: Networking Sensor Nodes and Robots

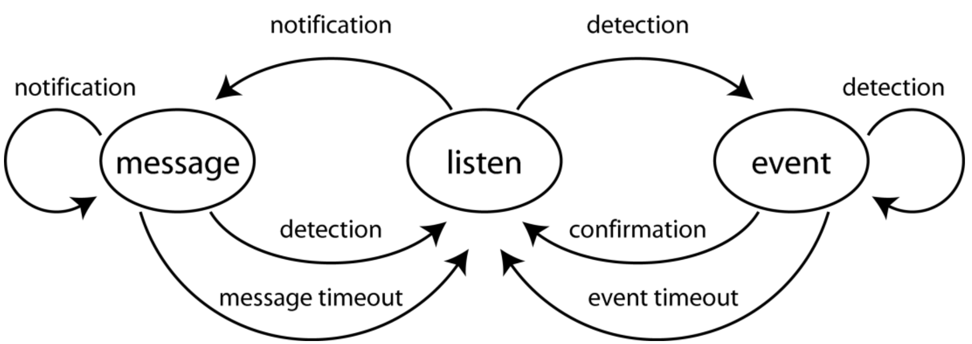


[Cianci et al, SAB-SRW 06]

- A similar experiment was performed in a classroom laboratory exercise
- Each pair of students has a robot in an isolated arena
- near one side of the arena, the robot is able to communicate with a node in a sensor network, which shares the information with other nodes in the network, so that they may inform their corresponding robots
- Convergence to a collective decision was also reached in this case (though a full suite of systematic experiments were not performed)

Example 5: Assessing Acoustic Events

- In some situations, event detection may trigger a costly process (i.e. human intervention, fire brigade, etc…)
- A simple consensus mechanism may help limit false positives (e.g., require *k* nodes to agree on detection before reporting)

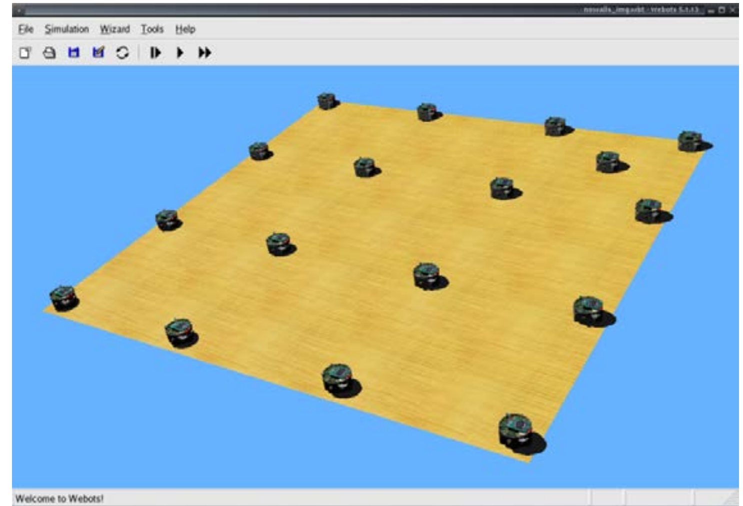


Example with k= 2

[Cianci et al., ICRA 2008]

Set-up

Physical



Simulation (Webots)

- 1.5 x 1.5m tabletop arena
- 16 sensor nodes (static e-pucks)
- 1 sound source (mobile e-puck)
- Sound and network plug-ins in Webots

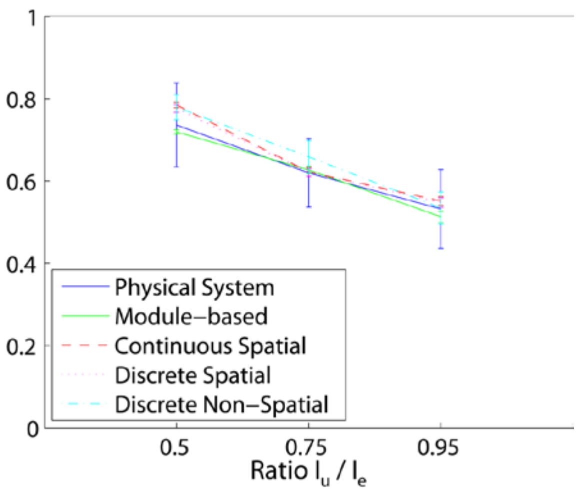
Metrics and Experiments

- Events characterized by two intensities are presented to the network:
  - Events with targeted intensity I_e
  - Events with undesirable intensity I_u (50%, 75%, 95% of I_e)
- Each experiment involves 100 events with the targeted intensity and 100 with the undesirable intensity
- Results report performance over 20 runs of the same experiment
- Performance metric:

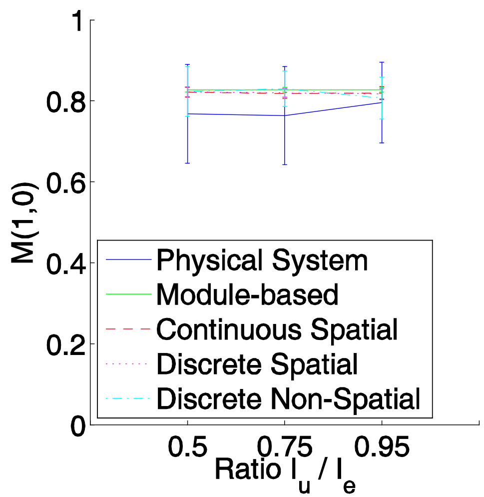
$$M_E(\alpha,\beta) = \alpha \frac{E_{det}}{E_{tot}} + \beta\left(1 - \frac{E_{fp}}{\max\left(E_{fp}, E_{tot}\right)}\right)$$

E_{det} : the number of targeted events reported
E_{tot} : the total number of targeted events presented
E_{fp} : the number of false positives reported

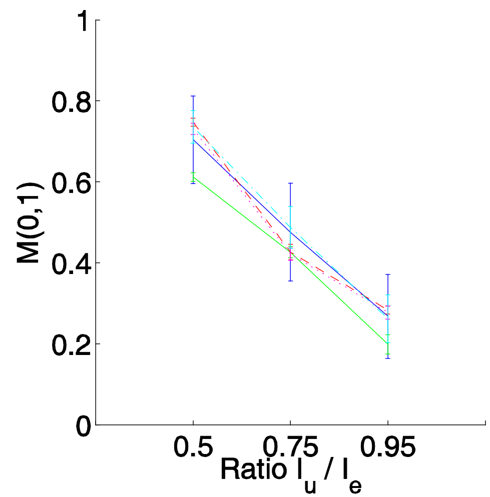
Metrics



$M_E(0.5, 0.5)$
Composite



$M_E(1, 0)$
Detected events



$M_E(0, 1)$
False positives

Note: focus on “Physical System” (real robots) and “Module-based” (Webots)

[Cianci et al., ICRA 2008]

Conclusion

Take Home Messages

- WSNs represent a very promising technology for a number of applications
- Commonalities and synergies between distributed, networked multi-robot systems and WSNs are appearing but their potential need still to be further investigated and formalized
- Collective decisions represent interesting benchmarks for testing distributed consensus algorithms on WSNs
- Various forms of consensus algorithms have been considered; some of them involve locally and globally discrete decisions, other locally and globally continuous, and other again a combination of both discrete and continuous components at local and global level

Additional Literature – Week 7

- Permasense http://www.permasense.ch
- GITEWS – the German Indonesian Tsunami Early Warning System
  http://www.gitews.de
  ftp://ftp.cordis.europa.eu/pub/fp7/ict/docs/sustainable-growth/workshops/workshop-20070531-jwachter_en.pdf
- Sensorscope http://www.sensorscope.ch/
- Course list:
  http://www-net.cs.umass.edu/cs791_sensornets/additional_resources.htm
- TinyOS:
  https://github.com/tinyos
- Smart Dust Project
  http://robotics.eecs.berkeley.edu/~pister/SmartDust/
- UCLA Center for Embedded Networking Center
  http://auvac.org/people-organizations/view/386
- Intel research Lab at Berkeley
  https://en.wikipedia.org/wiki/Intel_Research_Lablets
- NCCR-MICS at EPFL and other Swiss institutions
  http://www.mics.org