EPFL

Disal

Signals, Instruments, and Systems – W11

Field Instruments and Sensor Systems for Environmental Monitoring – Energy Management, Operation Principles, and Deployment

Outline

- Power management in field instruments
  - Power consumption
  - Power generation
  - Power storage
- Sensor systems for environmental monitoring:
  - Motivation
  - The Sensorscope project

Power Management in Field Instruments

Motivation

- Energy is one of the key bottlenecks for autonomous/unattended operation of embedded systems
- Field instruments as extreme examples
  - Power consumption
  - Power generation
  - Power storage

Power Consumption

Power

$$P = U \cdot I$$

Examples:

- MICAz:
  2 * 1,5V battery, 25 mA power consumption → 2*1,5V*0,025A=**80mW**
  (standby: **80 µW**)

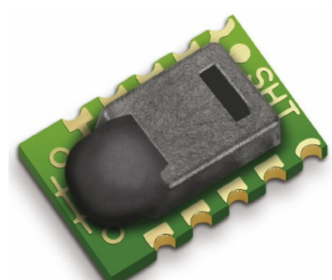
- Campell Scientific:
  3D ultrasonic
  anemometer:
  1,2W or 2,4W

2.4 Power Requirements

VOLTAGE SUPPLY: 10 to 16 Vdc

POWER:
2.4 W @ 60 Hz measurement frequency
1.2 W @ 20 Hz measurement frequency

- SHT1x temperature and humidity sensor:
  2µW – 3mW



Electrical and General Items

Parameter	Condition	min	typ	max	Units
Source Voltage		2.4	3.3	5.5	V
Power Consumption [5]	sleep		2	5	µW
	measuring		3		mW
	average		150		µW
Communication	digital 2-wire interface, see Communication				
Storage	10 – 50°C (0 – 125°C peak), 20 – 60%RH				

Energy

$$E = P \cdot t$$

Examples:

- Rechargeable battery (NiMH):
  1,2V*2000mAh=2400mWh=**2,4Wh**

- Rechargeable battery (LiPo):
  3,7V*1340mAh=4958mWh=**4,958Wh**

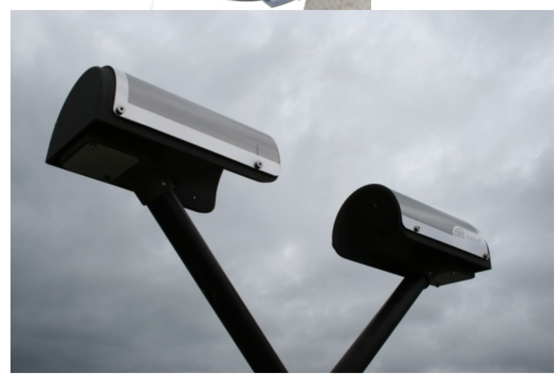
- Communication and computation energy:
  (remember 1 Ws=1 Joule)

	1999 (Bluetooth Technology)	**2004**
Communication	(150nJ/bit)	(5nJ/bit)
	1.5mW*	50uW
Computation		~ 190 MOPS
		(5pJ/OP)

Managing Power Consumption

Consumption vs. capabilities (example 1):

- Disdrometer 1 ("tipping bucket") (≈ 0W)
  - no snow, sleet
  - no robust to freezing
  - no drop statistics
  - resolution
- Disdrometer 2 (laser) (≈ 10W)
  - \+ snow, sleet
  - \+ robust to freezing
  - \+ drop statistics
  - \- expensive
  - \- delicate
- Disdrometer 3 (hot plate) (≈ 100W)
  - \+ snow, sleet
  - \+ robust freezing
  - \+ simple
  - \- drop statistics



Managing Power Consumption

Consumption vs. capabilities (example 2):

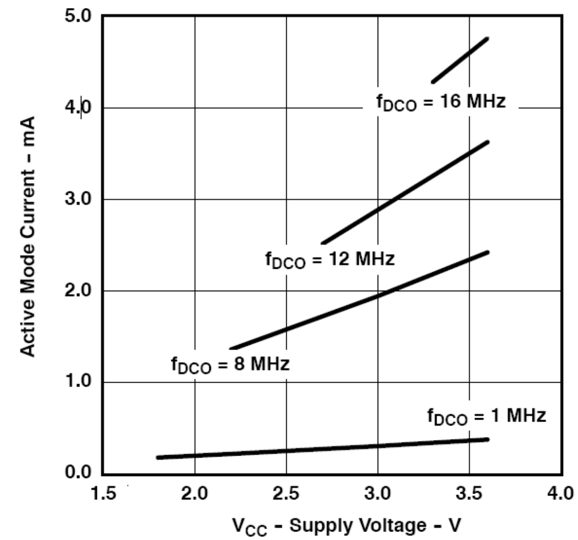
- Anemometer 1 (cup) (≈ 0W)
  - 1D (main direction)
  - no robust to freezing
  - temporal resolution (0.3 Hz)
  - minimal wind speed high

- Anemometer 2 (ultrasonic) (≈ 10W)
  + 2D
  + *some* snow, sleet
  + *some* robustness to freezing
  + temporal resolution
    (up to 60Hz)
  - expensive
- Anemometer 3 (Anemometer 2+heater) (≈ 100W)
  + 2D
  + snow, sleet
  + robust to freezing
  + temporal resolution
  - expensive

Managing Power Consumption

Consumption vs. processing speed:

- $P \sim f_{clock}$
- *Energy/operation = const*

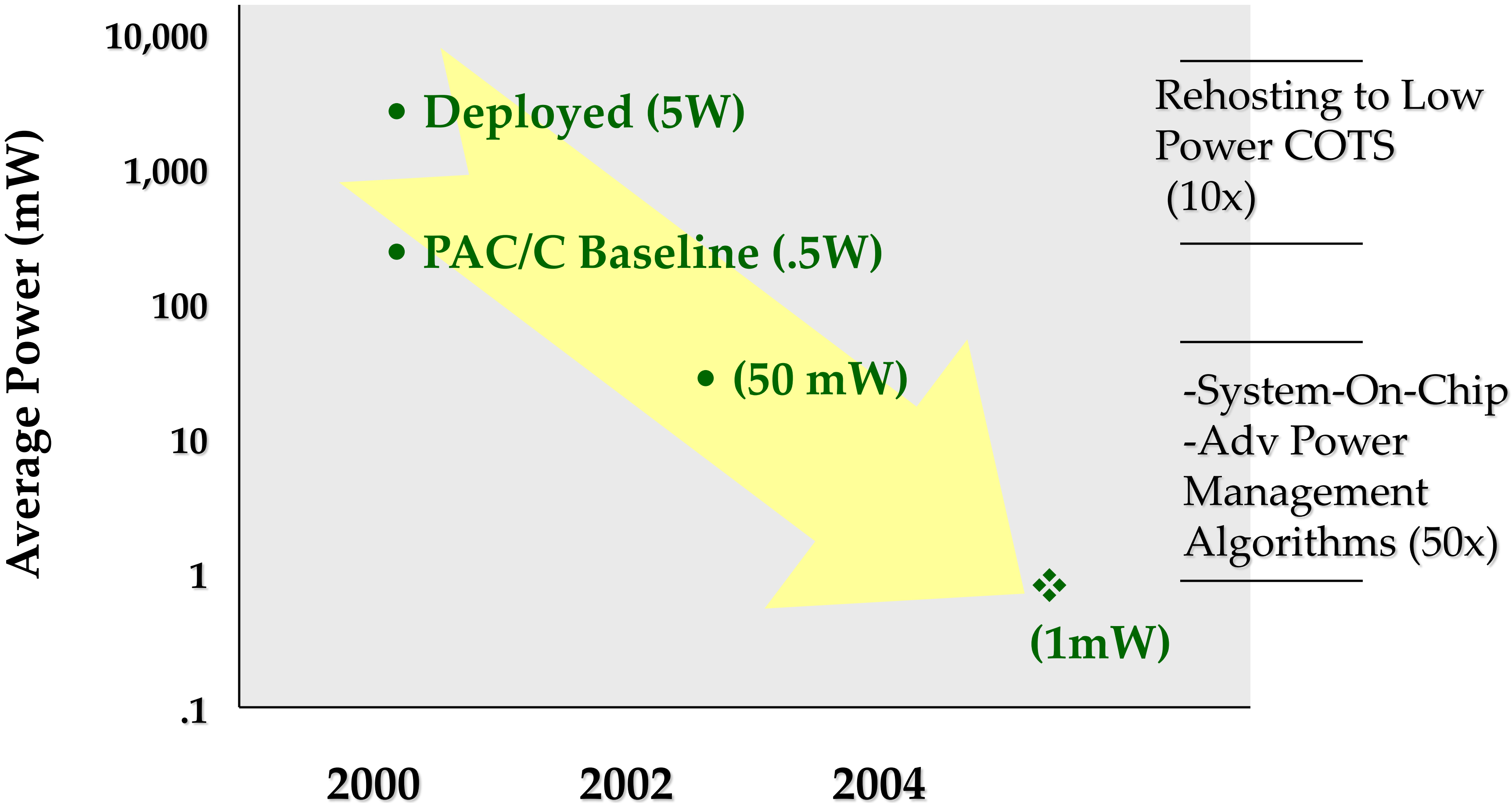


Source: MSP430 data sheet

Consumption vs. transmission power:

- $P=f(P_{RF})$
- sometimes linear: $P \sim P_{RF}$
- often: "sweet spot"

Sensor Node Energy Roadmap



Source: ISI & DARPA PAC/C Program

Communication/Computation Technology Projection

	1999 (Bluetooth Technology)	2004
Communication	(150nJ/bit)	(5nJ/bit)
	1.5mW*	50uW
Computation		~ 190 MOPS
		(5pJ/OP)

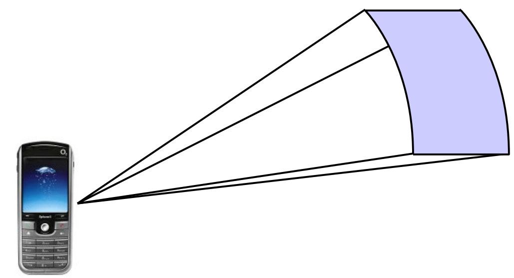
Assume: 10kbit/sec. Radio, 10 m range.

Large cost of communications relative to computation continues

Free Space Path Loss (Friis Law)

From Week 8 slides

- Signal power decay in air:



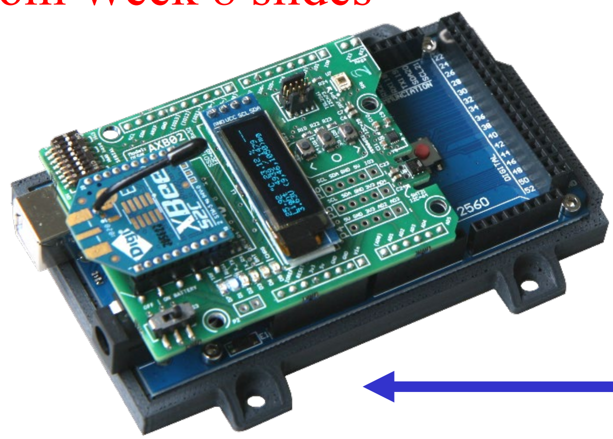
$$L = \left(\frac{4\pi d f}{c} \right)^2$$

$$L_{dB} = 20 \log_{10}(d) + 20 \log_{10}(f) - 147.56$$

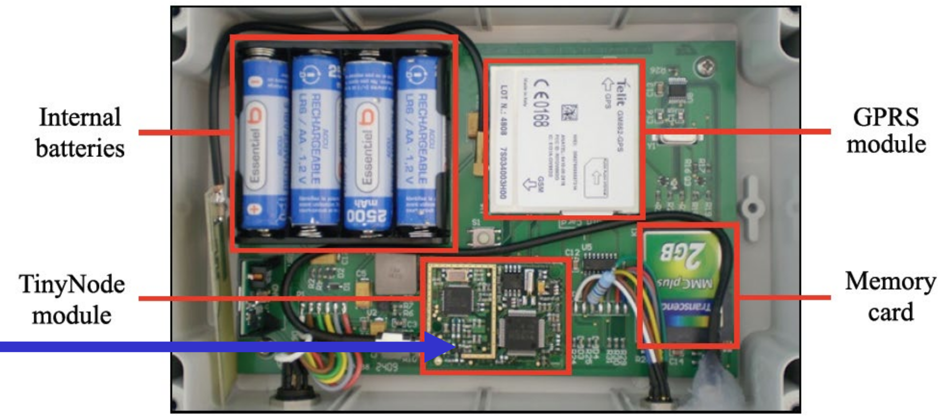
- Proportional to the square of the distance d
- Proportional to the square of the frequency f
  - high frequency = high loss
  - low frequency = low throughput

Ex.: DISAL Arduino Xbee kit vs. TinyNode

From Week 8 slides



Sensorscope data logger



DISAL Arduino Xbee kit

- Microcontroller:
  - ATMega 2560 (low-power)
- Transceiver:
  - Silicon Labs EM357 (part of the Xbee 802.15.4 module)
  - 2.4 GHz carrier
  - Throughput: up to 250 kbps
  - Range: up to 90 m

TinyNode (Shockfish)

- Microcontroller:
  - TI MSP430 (ultra-low power)
- Transceiver:
  - Semtech XE 1205
  - 868 and 915 MHz carriers
  - Throughput: up to 153 kbps
  - Range: up to 2 km

Power Generation

Power generation methods

- Solar
- Wind
- Temperature difference (Seebeck Effect)
- Vibration
- Hydro

Solar Power Generation

100W

1m²

15W

13,5W

9,5W

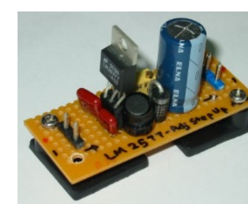
100W/m²

Efficiency: 10-20%

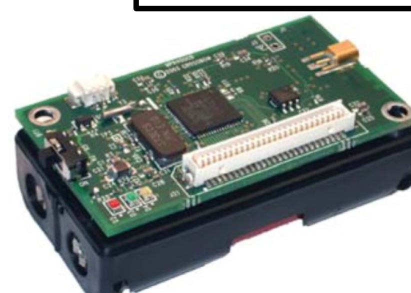
Efficiency: 90%

Efficiency: 70%

Efficiency: 90%



8,5W



0,1m² per W (e.g., 32 x 32 cm²)

Example: SensorScope Station

162x140mm solar panel
12Ah NiMH rechargeable battery

Note based on s. 17 estimation:
average consumption < 220 mW for battery level maintenance!
Compare with s. 31-33 power consumption

Power Storage

Batteries

- primary (non rechargeable, red)
  "often a good idea"
- secondary (rechargeable, blue)

Battery Type	Cost $ per Wh	Wh/kg	Joules/kg	Wh/liter
Lead-acid	$0.17	41	146,000	100
Alkaline long-life	$0.19	110	400,000	320
Carbon-zinc	$0.31	36	130,000	92
NiMH	$0.99	95	340,000	300
NiCad	$1.50	39	140,000	140
Lithium-ion	$4.27	128	460,000	230

- Other important parameters:
  - number of cycles (few 100 – few 1000) optimal conditions
  - cold temperature behaviour
- Interesting alternative: super capacitor
  - 30 Wh/kg
  - expensive
  - very high number of cycles (> 100'000)

From a Single Instrument to a Network

Motivation for Sensor Networks

What if we could monitor events which …

- have a large *spatial* and *temporal* distribution
- require *in-situ* measurements
- take place in hard to access places
- generate data which need to be available in *real-time*

Motivation for Sensor Networks

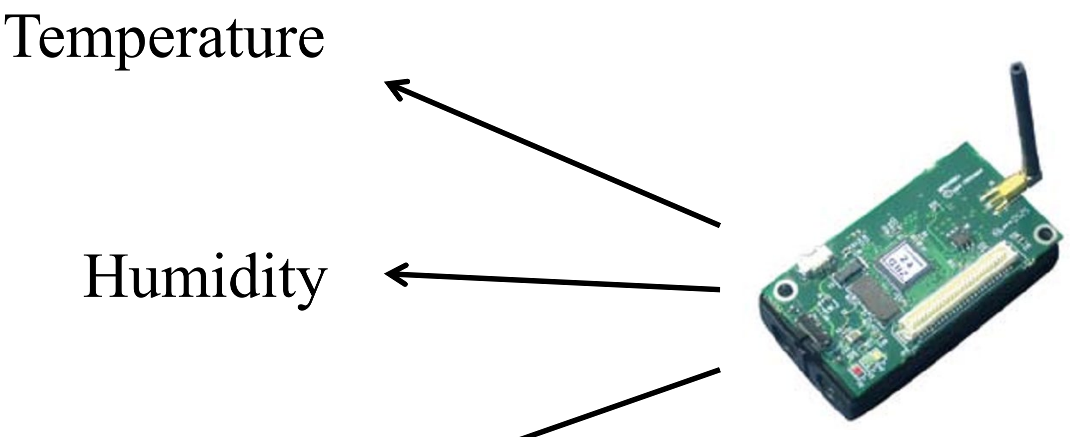
What would we need for that?

A device which …

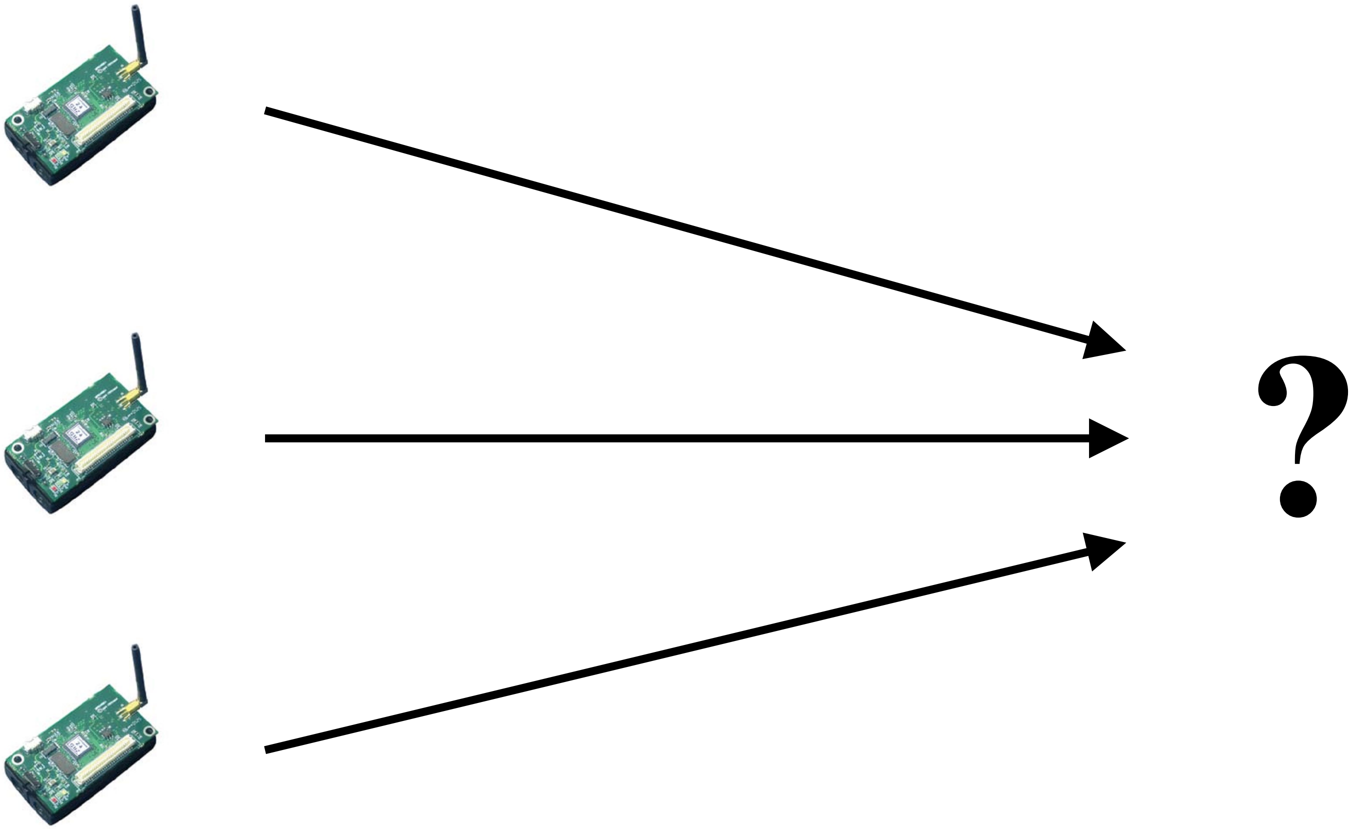
- is cheap – so we can distribute *many* of it
- is reliable – so we can measure for a long *time*
- uses little power – battery/solar cell powered
- has a radio – so it can *communicate*
- can potentially move – so it can potentially *relocate*

The Sensorscope Project

Introduction



Topology



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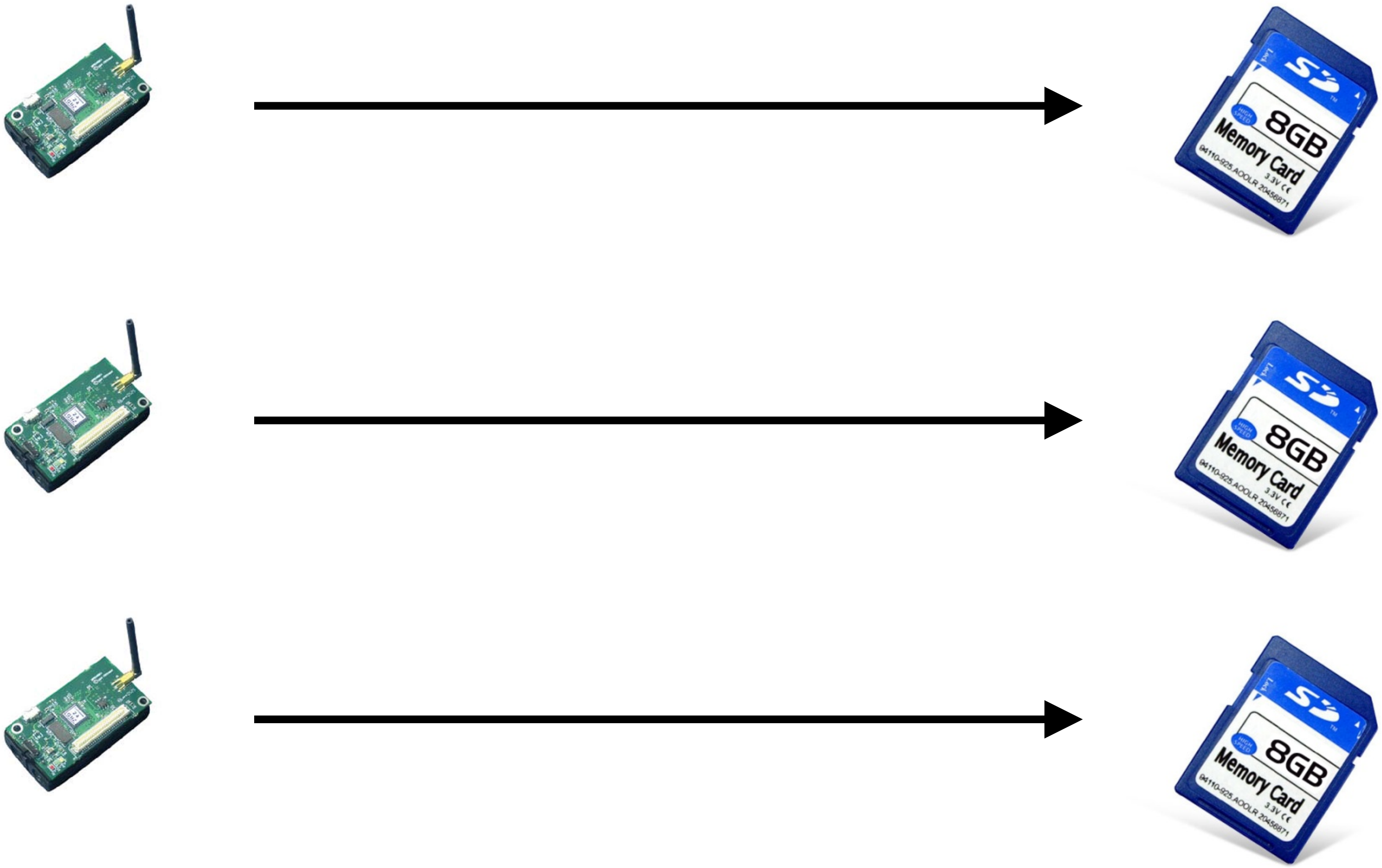

Topology

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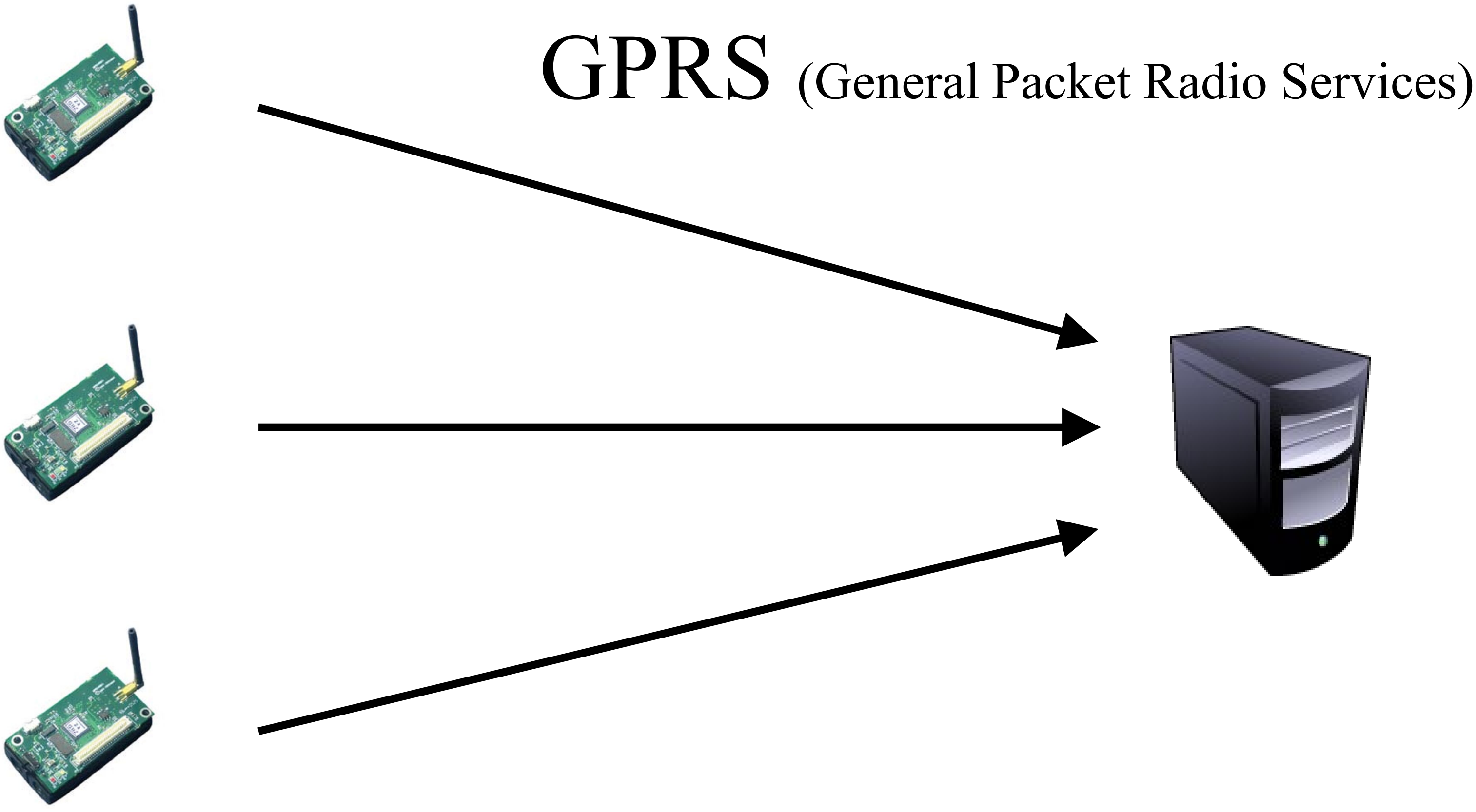


Topology

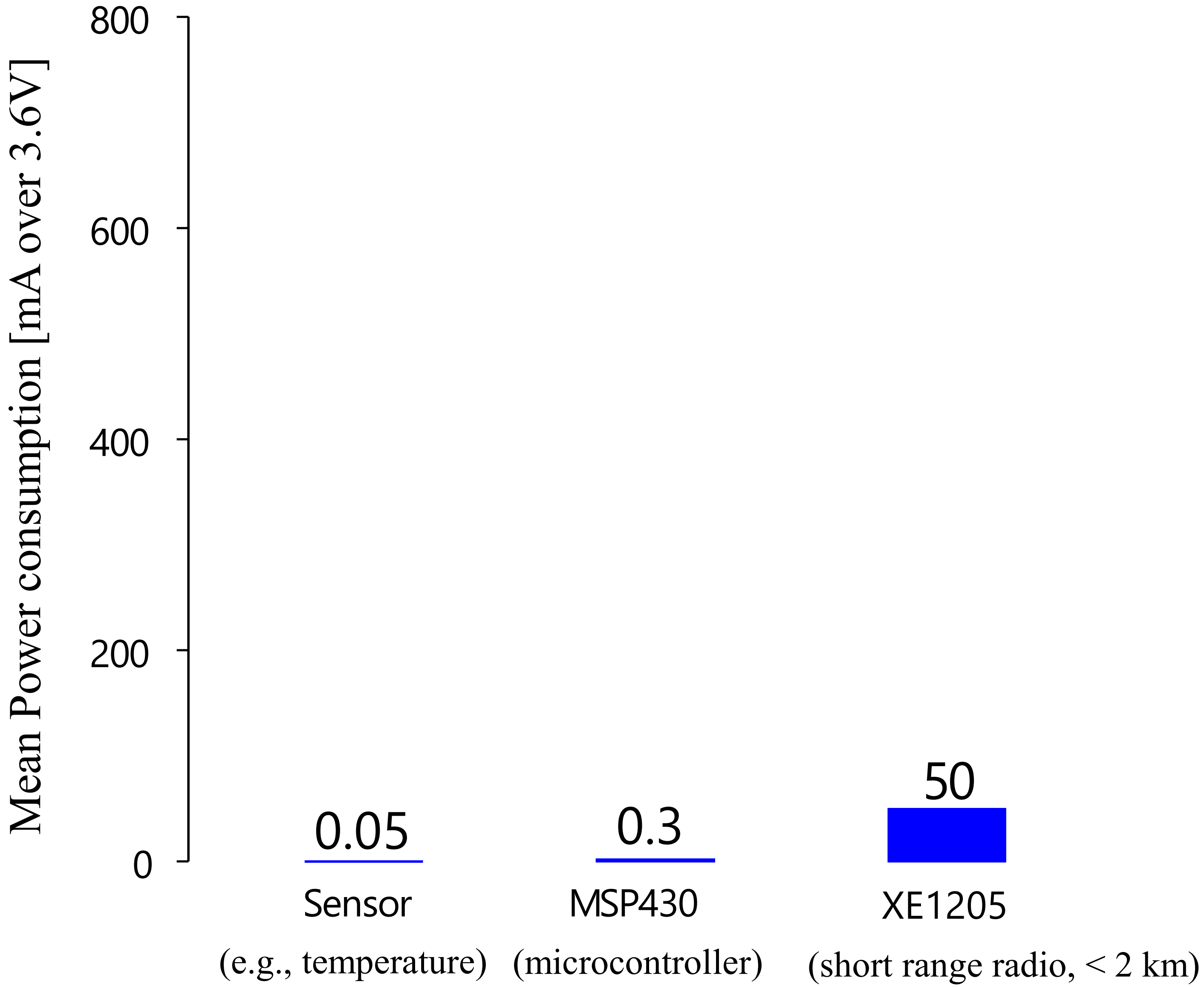
Pros

- Very simple!
- Essentially no restrictions in sensor locations

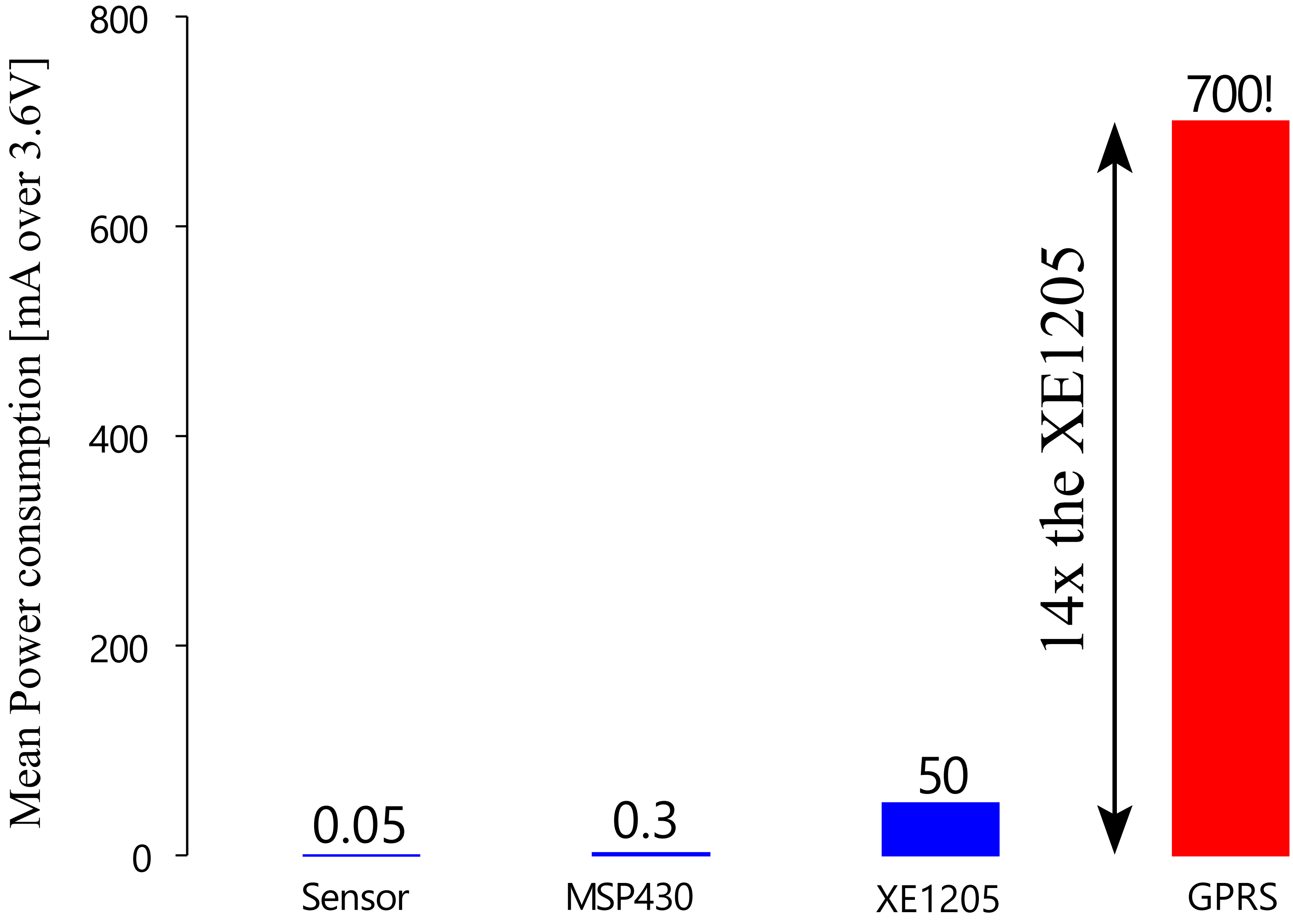
Cons

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

Topology


Mean Power consumption [mA over 3.6V]
800
600
400
200
0
0.05
0.3
50
Sensor
(e.g., temperature)
MSP430
(microcontroller)
XE1205
(short range radio, < 2 km)

Topology

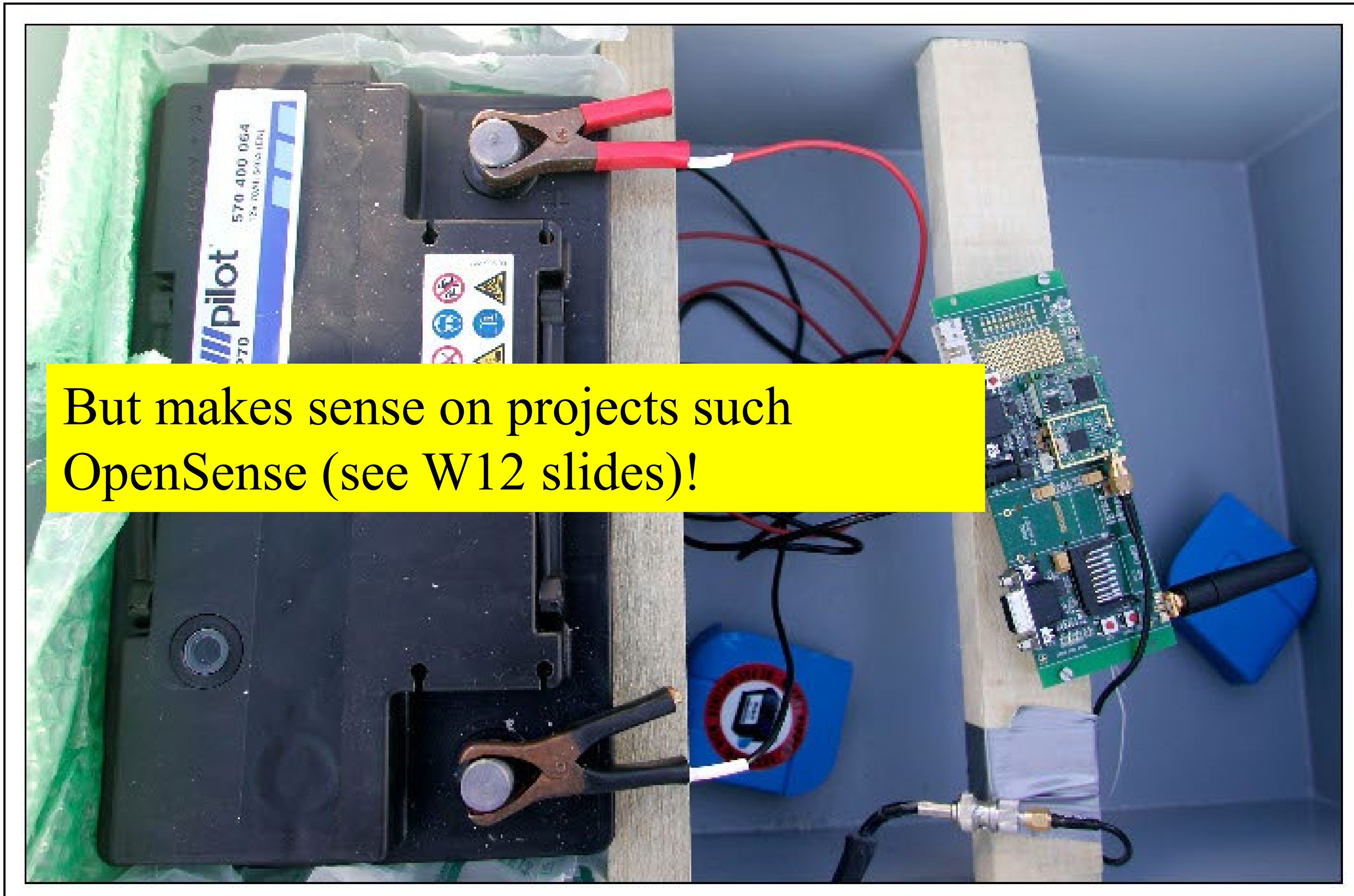

Mean Power consumption [mA over 3.6V]
800
600
400
200
0
0.05
0.3
50
700!
14x the XE1205
Sensor
MSP430
XE1205
GPRS

Topology

Assuming four AA batteries NiMH, i.e. 1.2 V, 2000 mAh (total energy 9.6 Wh) and only one of the components below always active:

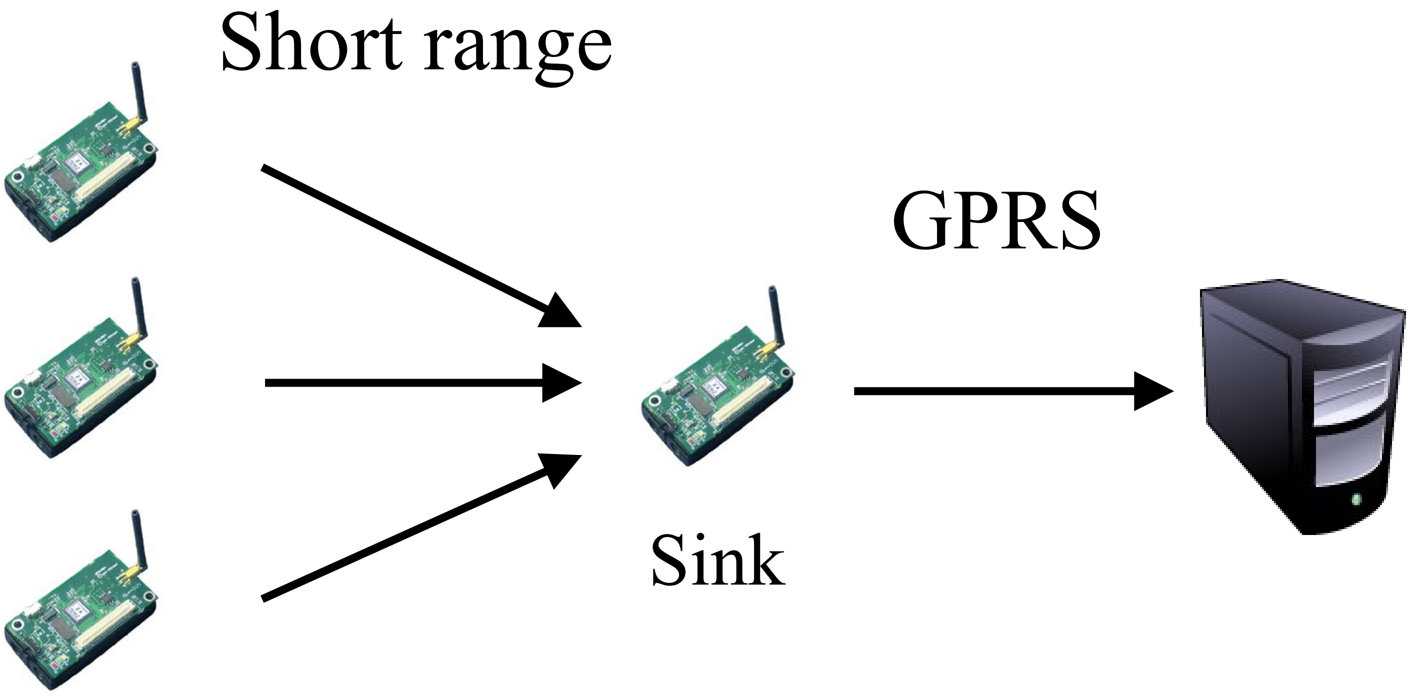
- Sensor: **6 years**
- MSP430: **1 year**
- Short range radio: **2 days**
- Long range radio: **4 hours**

Topology



But makes sense on projects such OpenSense (see W12 slides)!

Topology



Topology

Recall Friis law again:

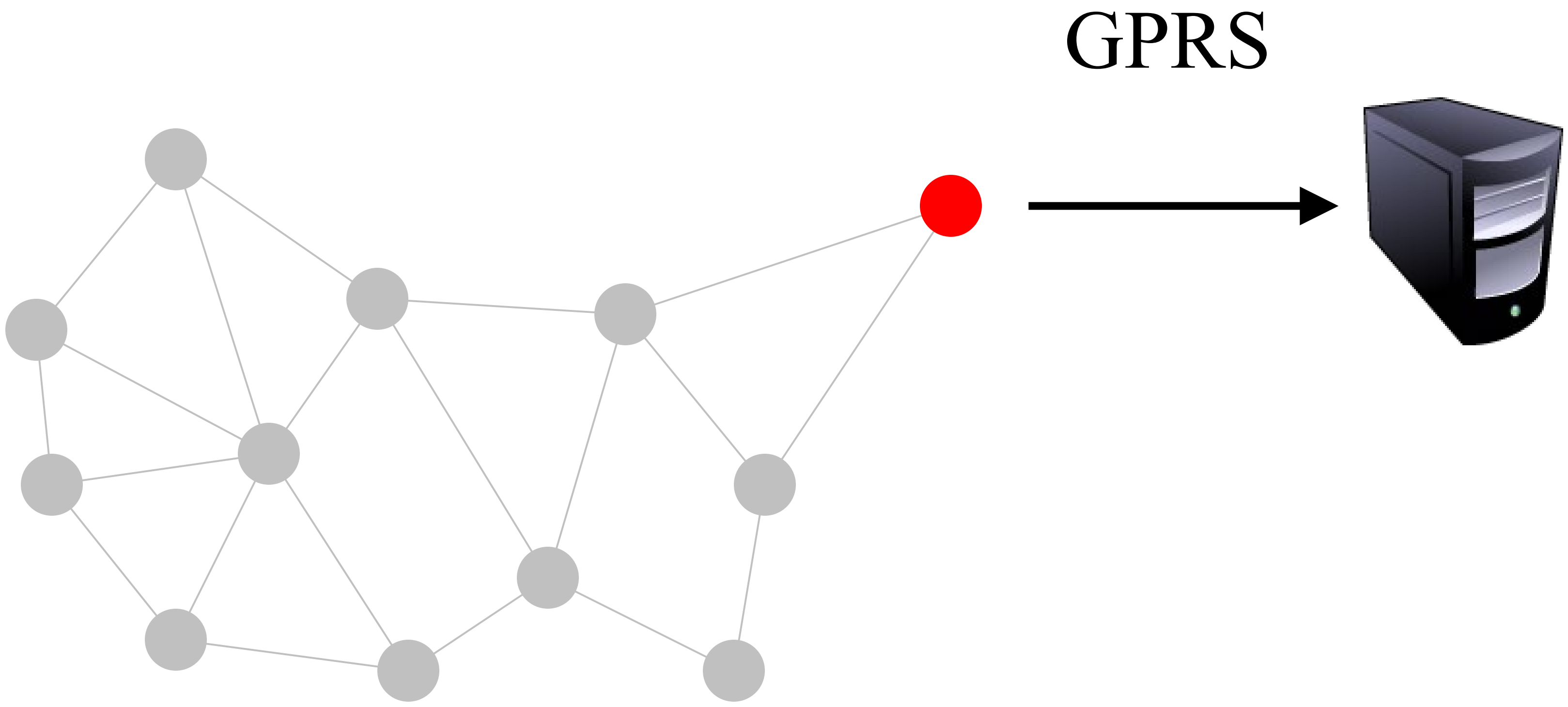
$$L = \left(\frac{4\pi d f}{c} \right)^2$$

Example: To transmit over 5 Km, using a 868 MHz carrier, we can:

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

Energy is the main issue !!!

Multi-hop Sensor Network



Multi-hop Sensor Network

Pros

- Only one car battery in the network
- The sensor network has extended monitoring coverage
- 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

Pre-condition

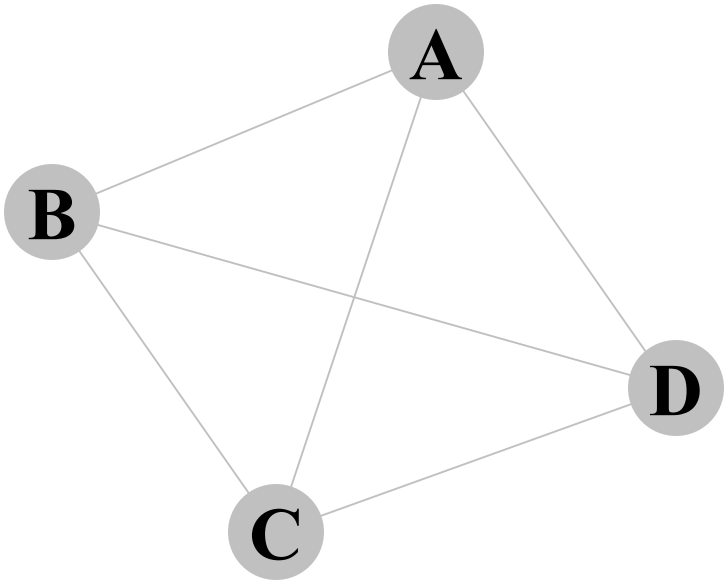
- **Time synchronization**
- Duty-cycling (radio management)

Pre-condition

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. …



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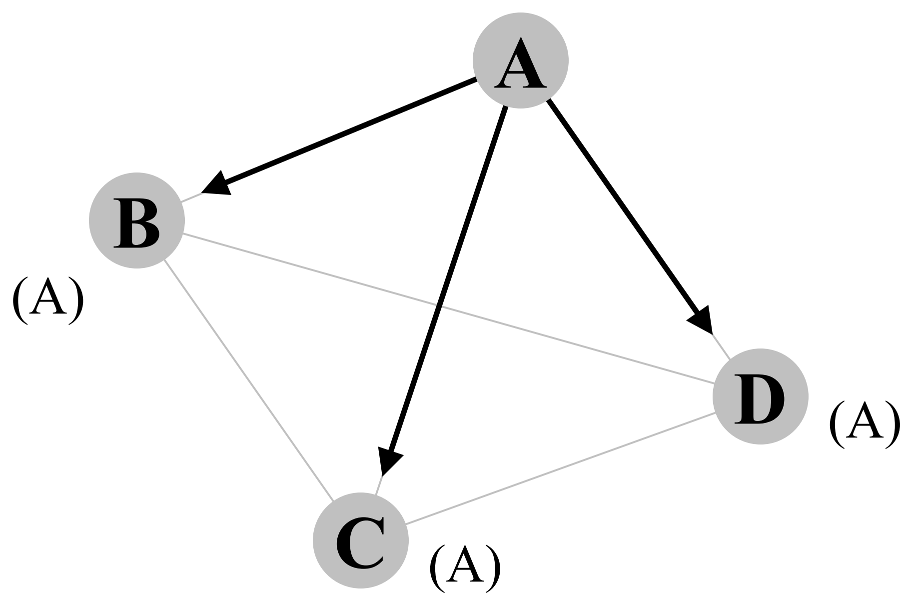

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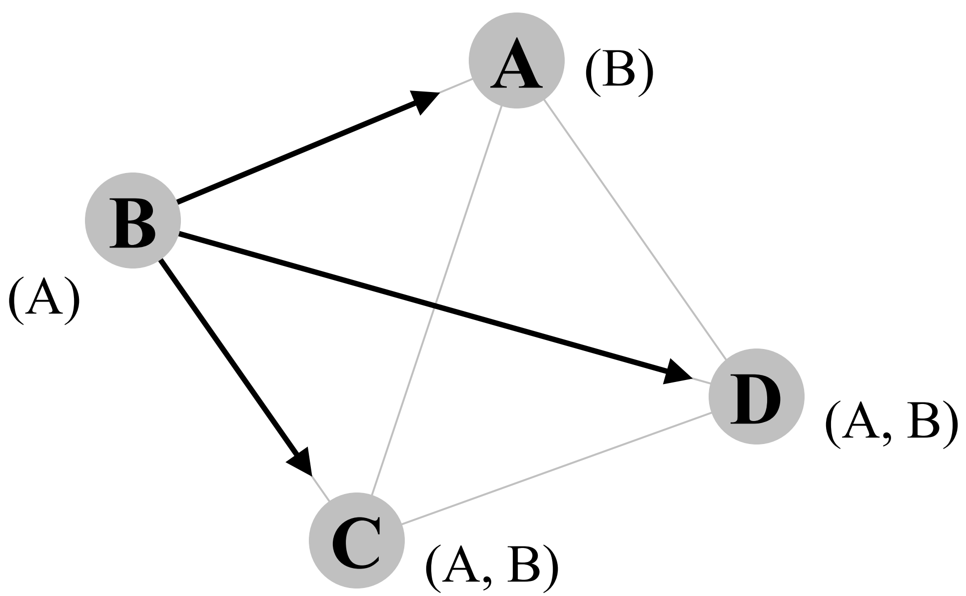

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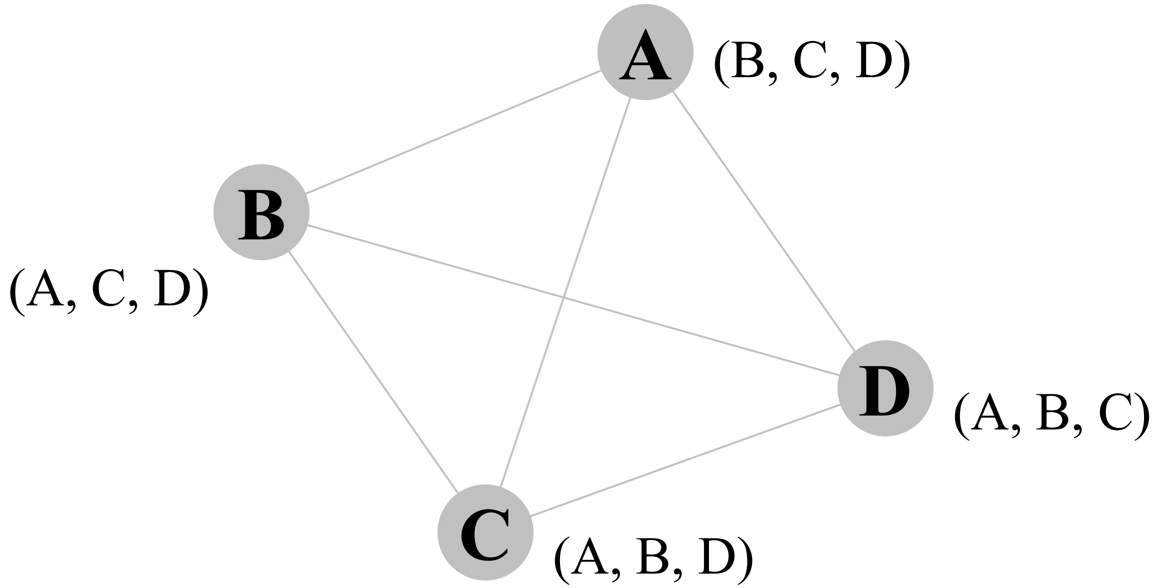
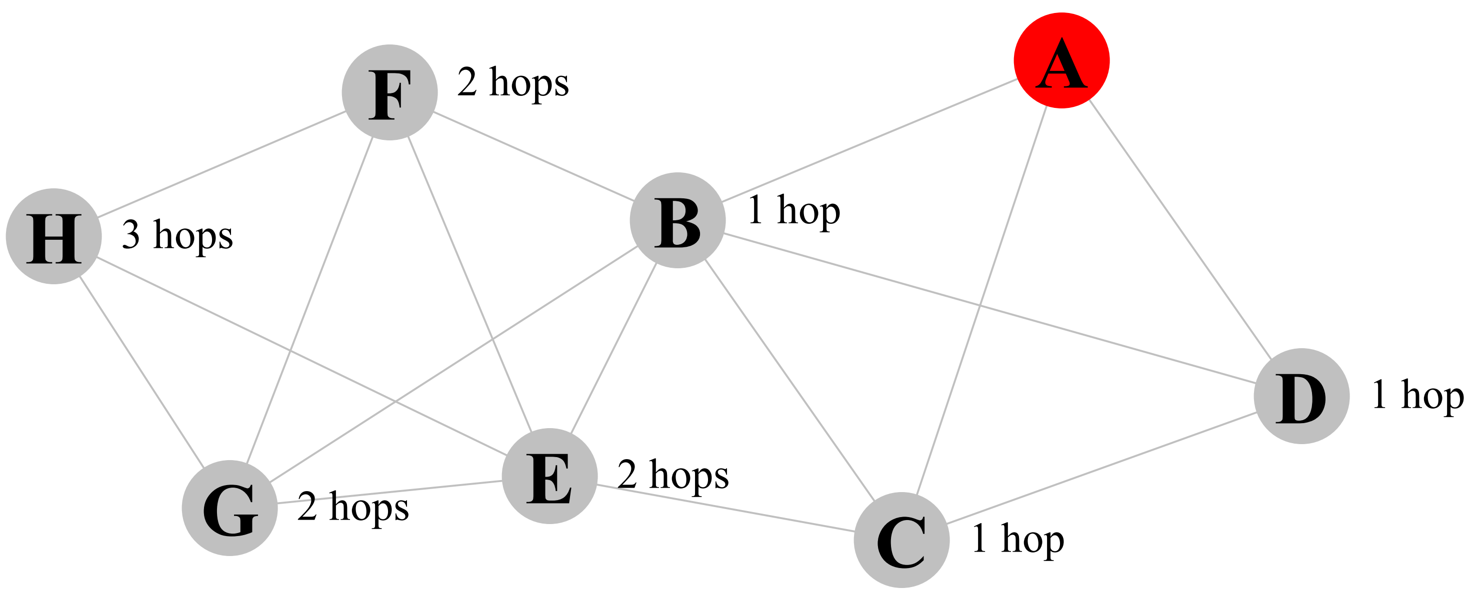


Neighborhood

What information do we need about our neighbors?

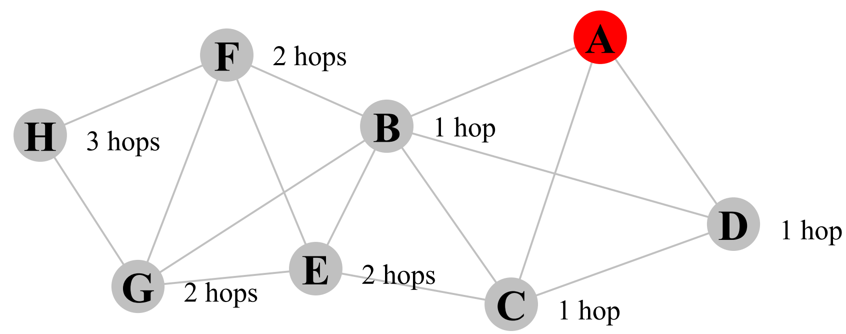
- Distance to sink
- Last time heard
- Link quality



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 in # of hops
- 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):

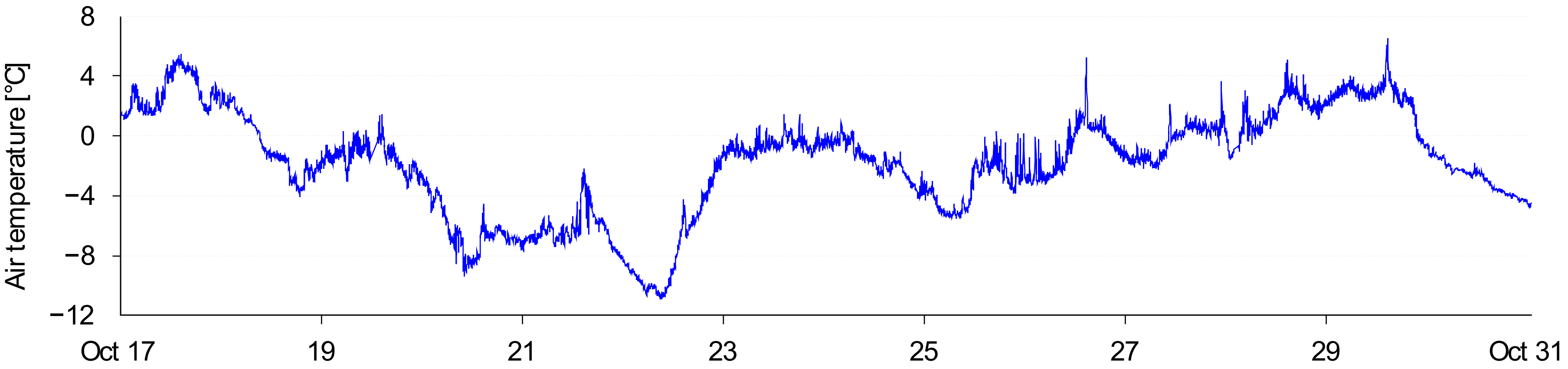
t – 4	t – 3	t - 2	t - 1	
10	7	8	8	Quality = 0.8

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

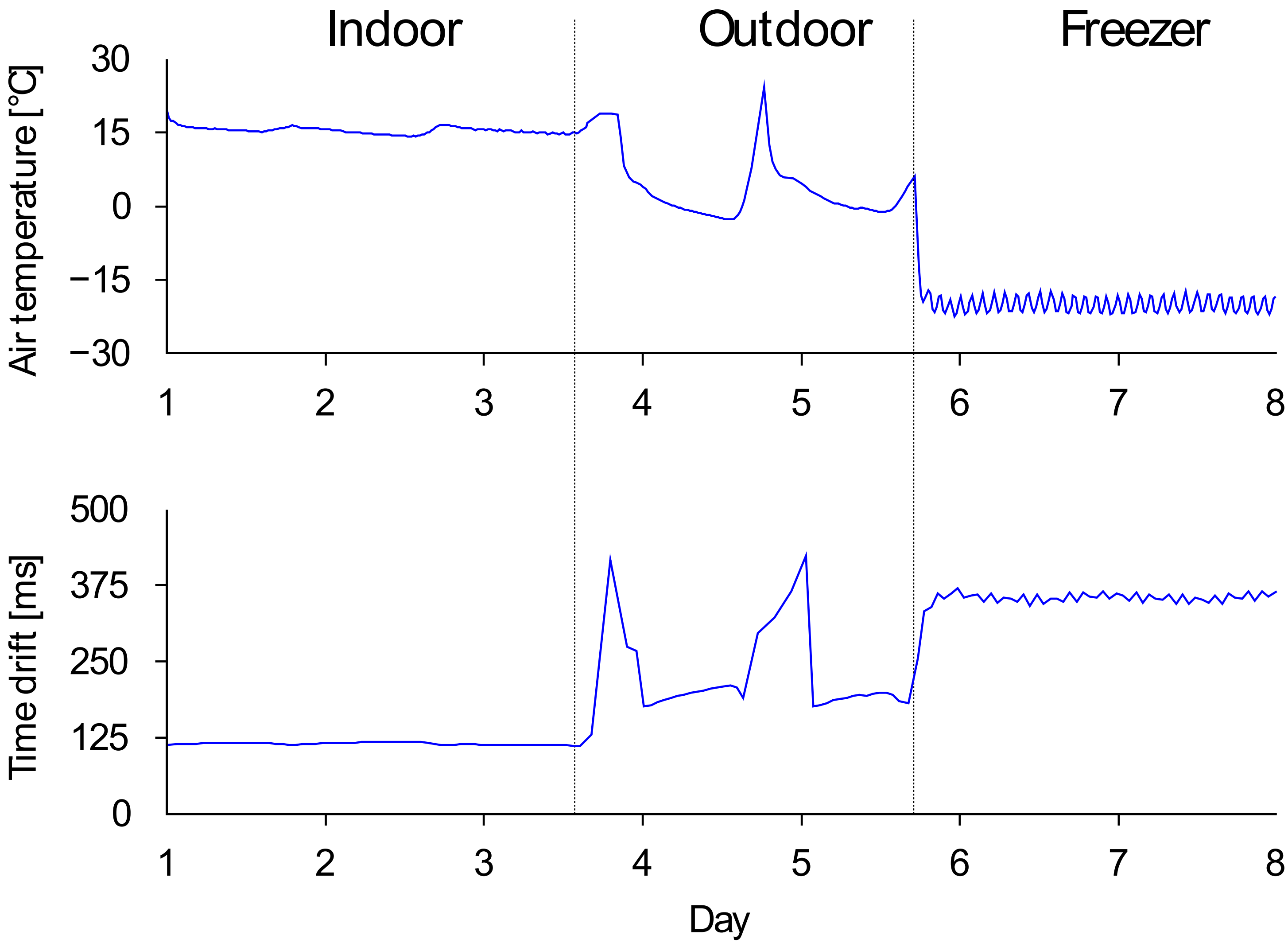
Time Synchronization

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

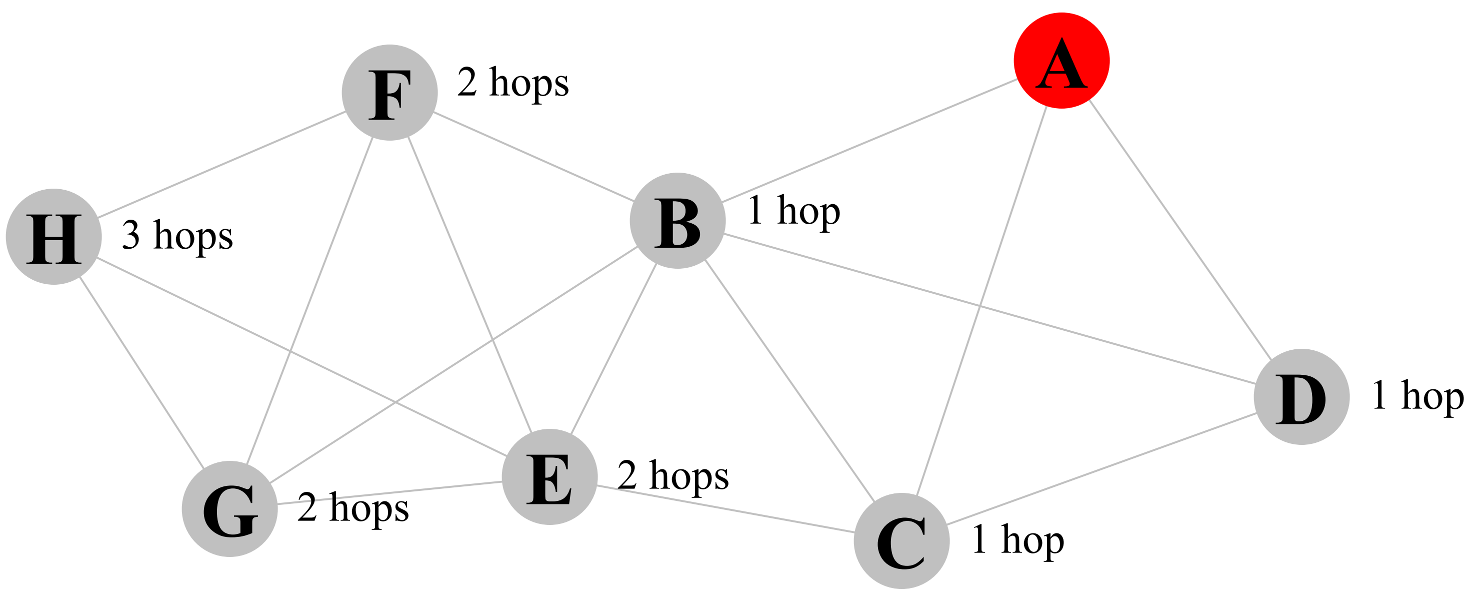
Every node gets the time:

- 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?

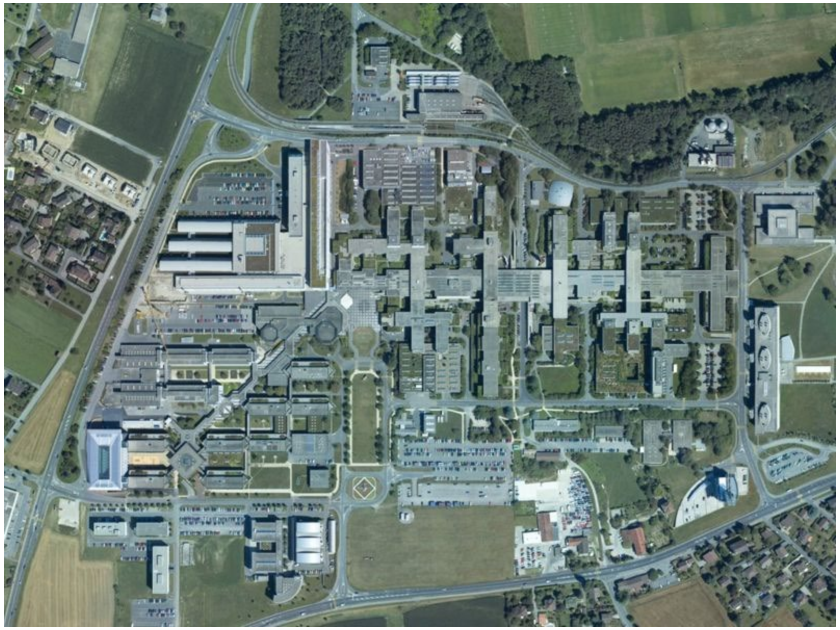
Time Synchronization

For instance, the sink serve as time reference node leveraging the anyway needed GPRS connection



SensorScope

Many previous successful deployments

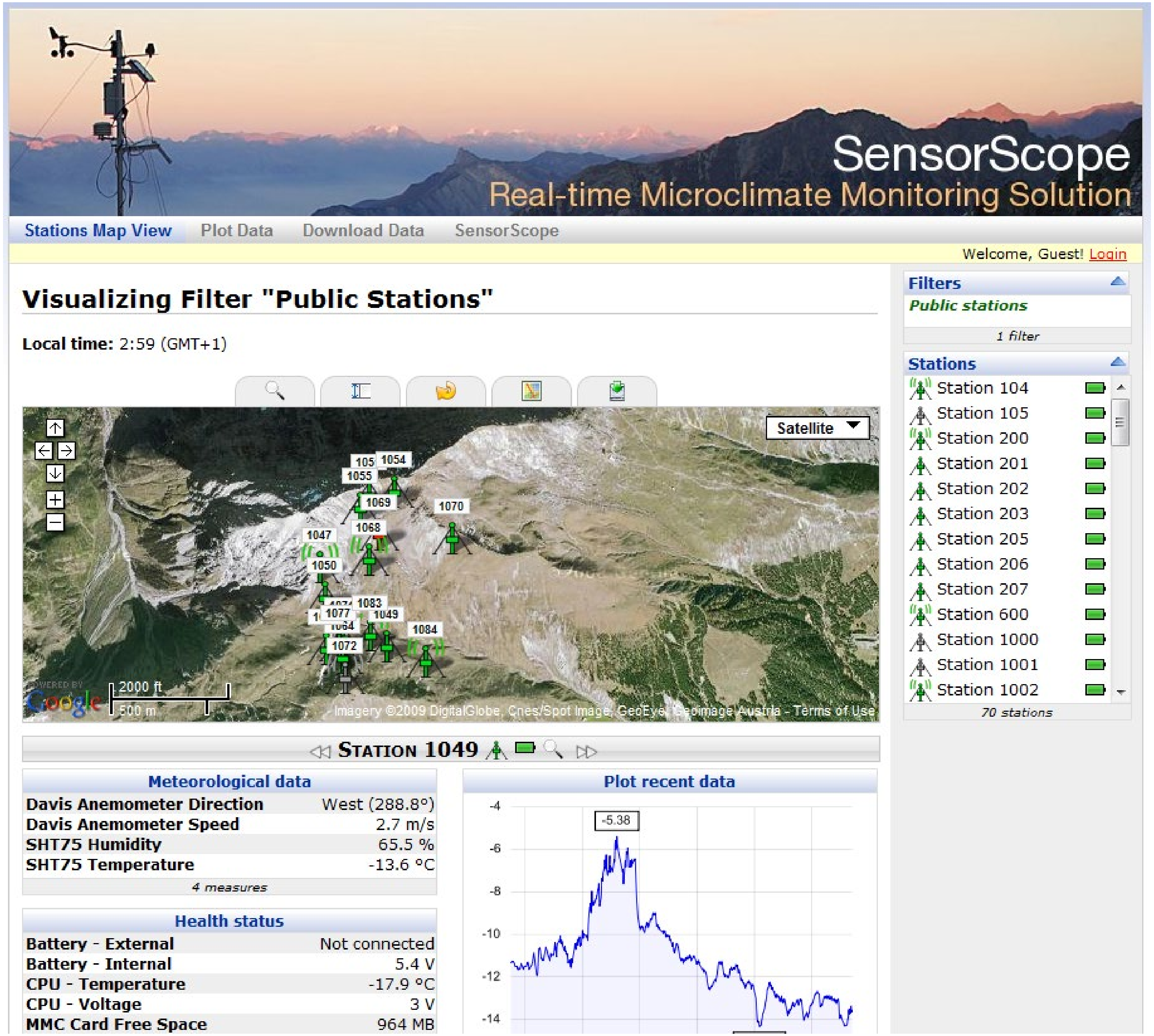


97 stations deployed at EPFL (one year)

SensorScope

Many previous successful deployments

16 stations deployed at Le Génépi to monitor conditions leading to dangerous mudslides (two months)



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
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
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

Conclusion

Take Home Messages

- Power is most often the key design constraint in embedded systems, even more for field embedded systems/instruments if operating in unattended mode
- Efficient power management strategies can decrease the consumption by several orders of magnitude
- Power is comparably difficult to generate and store
- Sensor networks enable environmental monitoring in remote locations and of difficult-to-measure processes
- Real-world deployments may be highly unpredictable!

EPFL

Additional Literature – Week 11

Books

- Shearer F., "Power Management in Mobile Devices", Elsevier, 2008.

Papers

- Culler D., Estrin D., and Srivastava M., "Guest Editors' Introduction: Overview of Sensor Networks". *IEEE Computer*, Vol. 37, No. 8, pp.41-49, 2004.
- Corke P., Wark T., Jurdak R., Hu W., Valencia P., Moore D., "Environmental Wireless Sensor Networks", *IEEE Proceedings*, Vol. 98, No. 11, pp. 1903-1917, 2010.

Pointers

- Sensorscope: http://sensorscope.epfl.ch/
- Permasense: http://www.permasense.ch/
- GITEWS: http://www.gitews.de
- CENS: https://en.wikipedia.org/wiki/Center_for_Embedded_Network_Sensing