

Course “Algorithmic Foundations of Sensor Networks”

Lecture 1: Introduction / Data propagation algorithms I

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Summary of this Lecture

- Introduction to Wireless Sensor Networks (characteristics, applications, critical challenges, algorithmic properties)
- Thematic structure of the Course
- The problem of data propagation
- Two protocols for data propagation:
 - Directed Diffusion (data-centric)
 - LEACH (cluster-based)

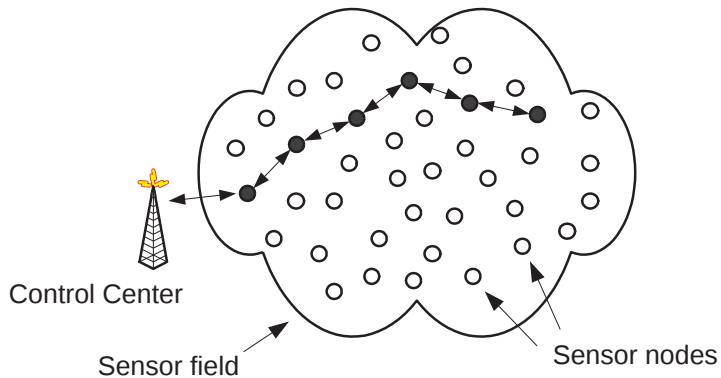
What is a Wireless Sensor Network?

- very large number of tiny “smart” sensors
- severe limitations
- wireless communication
- densely / randomly deployed in an area
- self-organization
- co-operation
- locality

⇒ An “ad-hoc” wireless network for:

- sensing crucial events and ambient conditions
- data propagation

A Sensor Network - Graphical Representation



“Smart” Sensor Nodes

- very small size
- operate on a small battery
- multifunctional sensing
- wireless communication
- limited computing power / limited memory
- low cost

TPR2420 Specifications (TelosB motes)

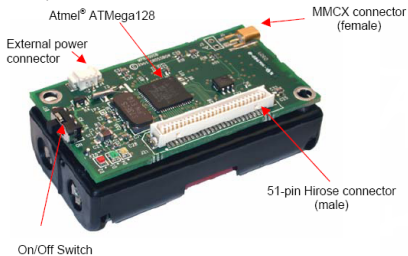
Dimensions	6.5cm × 3.1cm × 2cm
CPU	8 MHz Texas Instruments MSP430
Memory	10KB RAM, 48KB Program flash, 16KB EEPROM, 1MB flash
Power Supply	2X AA batteries
Processor Current Draw	1.8 mA (active current) < 5.1 μA (sleep mode)
Interface	USB
Network	Wireless 250 Kbps at 2.4GHz (802.15.4)
	Radio range depends on configuration and location
Integrated Sensors	Visible Light and IR, Humidity, Temperature

TinyOS Key Facts

Current Version	TinyOS 2.0.2
Users	Over 500 research groups and companies
Software Footprint	3.4 Kb
Architecture	Component-based
Hardware Supported	8 different mote types
Peak load CPU Usage	< 50 %
Prog. Language Used	NesC
Components provided	Sensor Interface
	Basic Multihop Routing
	Radio Communication

Examples of Sensor Motes

Mica2



TelosB / Tmote Sky



Smart vs Traditional Sensors

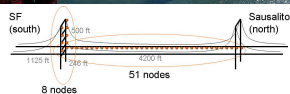
In traditional sensors:

- sensors perform only sensing
- sensor positions are carefully engineered
- deployed far from the area of interest
- data processing only at some central nodes
- larger in size
- constant power supply

Representative Recent Projects (1/2)

Structural Health Monitoring (SHM) of the Golden Gate Bridge

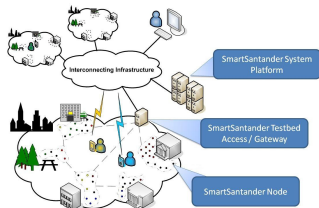
- Design and implementation of a WSN for SHM of the Golden Gate Bridge:
 - 59 Wireless Sensor Nodes.
 - Gathers data about ambient structural vibrations.
 - Gathers data about ambient structural accelerations from wind load.
 - Multihop network.



Representative Recent Projects (2/2)

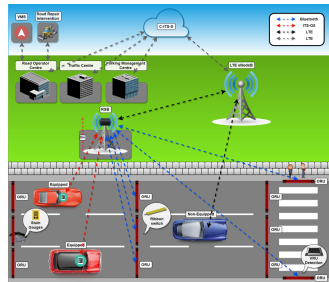
Smart Santander, a city-scale experimental research facility in support of typical applications and services for a smart city

- Santander Facility:
 - Environmental monitoring (temperature, CO, noise, light and car presence), 2000 IoT devices.
 - Parking area management, 400 sensors.
 - Mobile environmental monitoring, environmental sensors installed on 150 public transportation vehicles.
 - Parks and gardens irrigation, 50 devices that monitor temperature, humidity, moisture, anemometer.
 - Augmented reality, 2000 RFID tag/QR code labels in points of interest.



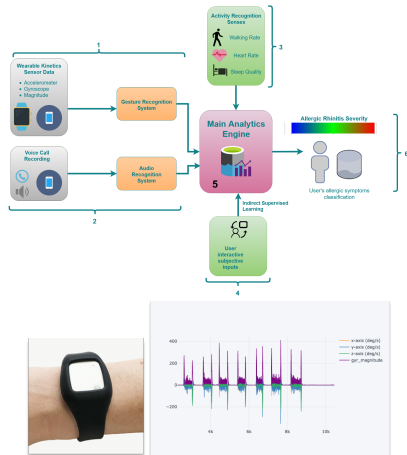
SAFE and green Sensor Technologies for self-explaining and forgiving Road Interactive aPplications (SAFE STRIP) - EU Project

- Development of a prototype wireless sensors system that can:
 - Detect the vehicle speed, direction and type.
 - Monitor road conditions (wet road, ice, traffic, roadworks).
 - Gather environmental measurements (Gas emissions, temperature, humidity).
 - Communicate with drivers.
- Tests in Attiki Odos, Autostrada 22 (Italy), CIDAUT (Spain).
- Cooperation with FIAT, PIAGGIO, SWARCO and several universities.



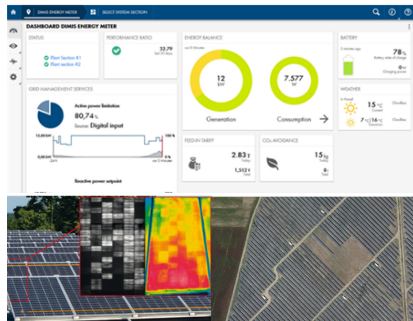
Personal Allergy Tracer (PAT) - National Research Project

- A hybrid holistic system for the allergic rhinitis detection, in cooperation with doctors and medical industry.
- Personalized early detection of symptoms is accomplished by combining:
 - Data collection from smart wristbands, user's smartphones microphone, user's attitude based on symptoms combined with geolocation data.
 - Data analysis: ML for the assessment of the collected by **real patients** Allergic rhinitis gestures.
 - Deep learning models for the recognition of Allergic rhinitis gestures performance.
 - Hidden Markov Models for capturing the voice alteration due to allergic symptoms.
 - Unsupervised learning for disease patterns detection.



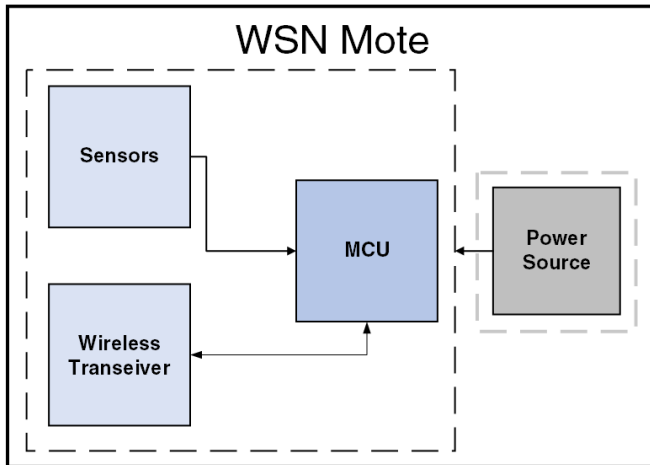
Integrated PV Surveillance, Management and Revitalization System (SMART sensors 4 PV) - National Research Project)

- Development of IoT systems for renewable energy sources that aim at:
 - Monitoring and recording of all parameters that determine the operation of a PV panel (physical and electrical).
 - Correlation of various phenomena, which negatively affect the performance of a photovoltaic installation (PID, Hot spots, failure of electrical circuits).
 - Forecasting and repairing potential operational and energy production problems.
 - Control system for timely and valid replacement of a PV panel, when its malfunction is irreversible.
- Cooperation with ECOVAR, ECE dept, Material Science dept.



2 new EU projects within our IoT - Lab

- Indoor air quality monitoring and improvement.
- Zero defect manufacturing: AI-enabled quality control in tunnel pasteurizers.



The Low Energy Challenge

- In a cubic millimeter volume
⇒ current best battery : 1 *Joule*
- For continuous operation over 1 day :
↓
 - power consumption $\simeq 10 \mu W$
⇒ $\left\{ \begin{array}{l} \text{efficient power management strategies needed} \\ \text{efficient networking algorithms required} \end{array} \right.$
- Batteryless operation:
 - Energy harvesting
 - Intermittent computing
- Reduce sensor consumption
⇒ Context sensing ⇒ Use of energy harvesters as
ambient sensors

RF wireless communications (1/2)

- Theoretical model (free space):

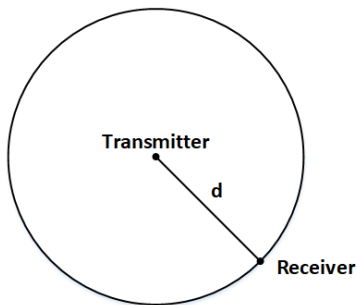
$$P_r = P_t * f\left(\frac{\lambda^2}{d^2}\right)$$

where P_r : received power,

P_t : transmitted power, λ : wavelength

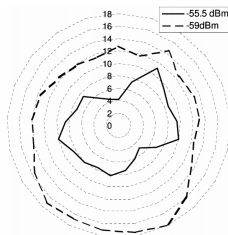
d : distance, f : function depending
also on antenna hardware

- In other words, to transmit a message over distance d , the consumed power is in the order of d^2



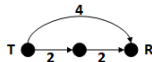
RF wireless communications (2/2)

- In practice:



- The power needed is d^a , where $2 < a \leq 6$ depends on the environment
(urban: $a \simeq 3$, suburban: 3 to 5, industrial: 2 to 3)
- Throughout the course, we will assume $a = 2$.
- Thus, power is not linear in distance $\Rightarrow$ multihop routing needed!

$$2^2 + 2^2 < 4^2$$



Applications (I)

Sensors (devices that detect a physical quantity and produce a measurable output) for a wide variety of conditions:

- temperature (a)
- humidity (a)
- motion (b)
- noise levels (c)
- light conditions (d)
- object presence (e)
- mechanical stress levels on attached objects (f)



(a)



(b)



(c)



(d)



(e)



(f)

- continuous sensing
- detection of a crucial event
- location sensing (including motion tracking)
- local control of actuators (ambient intelligence)
- micro-sensing

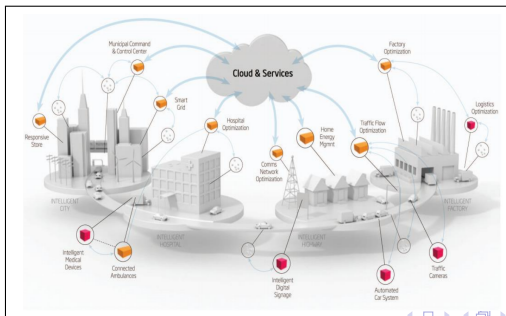
- Environmental applications
 - forest fire detection
 - flood detection
 - precision agriculture
 - weather forecast
 - planetary exploration
- Health applications
 - telemonitoring of human physiological data
 - tracking and monitoring doctors/patients
 - AI-based disease detection

Applications (IV)

- Home applications
 - home automation (local/remote management of home devices)
 - smart environments (adapt to the people's needs)
- More applications (partial list)
 - inventory control
 - security / military
 - vehicle tracking and detection
 - interactive museum
 - monitoring material fatigue

The Internet of Things (IoT)

- A vision: the Digital and Physical Worlds converge
 - Pervasive Technologies: “The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it” (Mark Weiser)
 - Embedded Sensor Networks: “Google for the Physical World” (Deborah Estrin)
- IoT: massive, seamless, wireless inclusion of everyday objects (clothes, vehicles, glasses etc.) and devices (lights, HVAC, refrigerator etc.) into the WEB, so that they become “smart” and can participate into smart scenarios and services.



Emerging Trends (II)

Mobile Sensing/Crowdsensing

- Current smartphones are truly mobile and include several sensors (light, accelerometer, gyroscope, proximity etc.).
- Sensory readings can be obtained from everywhere and all the time, from the “crowd”.
- Also, these sensor hints can be used to extract human features (e.g. whether somebody is walking or lying etc.).
- The above sensor readings and hints can be exploited to optimize smart scenarios and services, in view of this feedback from the crowd (crowdsourcing).

How Many Sensors are in a Smartphone?



- Light
- Proximity
- 2 cameras
- 3 microphones (ultrasound)
- Touch
- Position
 - GPS
 - WiFi (fingerprint)
 - Cellular (tri-lateration)
 - NFC, Bluetooth (beacons)
- Accelerometer
- Magnetometer
- Gyroscope
- Pressure
- Temperature
- Humidity



Emerging Trends (III)

- Big data /extreme data
- ML/AI methods for IoT data

- *Scalability*
 - huge number of sensor nodes
 - high densities of nodes
 - many complex interactions
- Success rate: percentage of delivered data
 - How does protocol performance scale with size?*
 - Even correctness may be affected by size.

- *Fault-tolerance*

Sensors may

- fail (temporarily or permanently)
- be blocked / removed
- cease communication

due to various reasons

- physical damage
- power exhaustion
- interference
- power saving mechanisms

Can the network *tolerate failures well*?

- *Efficiency*
 - *energy* spent
 - *time* (for data propagation)

New/Critical Challenges (IV)

- Inherent *trade-offs* (e.g. *energy vs time*)
- *Application dependence*
- *Dynamic* changes / heterogeneity



- *variety of protocols* needed / hybrid combinations
- *adaptive* protocols, *locality*
- *simplicity, randomization, distributedness*

Thematic structure of the course - I

- Introduction (technology, applications, challenges, algorithmic performance properties)
- Network deployment, connectivity, coverage
- Data-centric routing (querying, compression)
- Probabilistic data propagation algorithms
- Energy balance and optimization
- Geographic routing and obstacle avoidance algorithms
- Localization and tracking

Thematic structure of the course - II

- Mobile Sensor Networks
- Tutorial on Contiki OS & Project description
- Invited Lecture 1: 5G and IoT
- Invited Lecture 2: Security and IoT
- Invited Lecture 3: IoT in smart health
- Invited Lecture 4: Industrial IoT
- Invited Lecture 5: IoT and smart agriculture

Invited lectures will be given by leading experts. Their material will be part of the final exam.

A “canonical” problem: Local Event Detection and Data Propagation

A single sensor, p , senses a **local event** $\mathcal{E}$. The general **propagation problem** is the following:

“How can sensor p , via cooperation with the rest of the sensors in the network, propagate information about event $\mathcal{E}$ to the control center?”

Representative data propagation protocols

- Directed Diffusion (DD): a *tree-structure* protocol (suitable for low dynamics)
- LEACH: *clustering* (suitable for small area networks)
- Local Target Protocol (LTP): *local optimization* (best for dense networks)
- Probabilistic Forwarding Protocol (PFR): *redundant optimized* transmissions (good efficiency / fault-tolerance trade-offs, best for sparse networks)
- Energy Balanced Protocol (EBP): guaranteeing *same per sensor energy* (prolong network life-time)

Directed Diffusion

- requires *some coordination* between sensors
- creates / maintains some *global structure* (set of paths)
- a paradigm / suite of several protocols
- here: a *tree-based* version

Directed Diffusion elements

- *Interest* messages (issued by the control center)
- *Gradients* (towards the control center)
- *Data* messages (by the relevant sensors)
- *Reinforcements* of gradients (to select “*best*” *paths*)

- An interest contains *the description of a sensing task*.
- Task descriptions are named e.g. by a list of *attribute-value pairs*.
- The description specifies *an interest for data matching the attributes*.

```
type = wheeled vehicle           // detect vehicle location
interval = 10 ms                 // send events every 10 ms
duration = 10 minutes            // for the next 10 minutes
rect = [-100, 100, 200, 400]    // from sensors within rectangle
```

Example of an interest

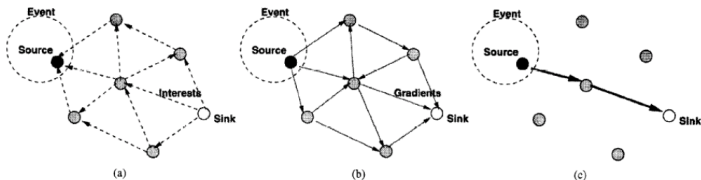
- Interests are *injected* into the network at the *control center*

Gradients

For each interest message received, a gradient is created

Gradients are formed by *local interaction* of neighboring nodes, establishing a gradient towards each other.

Gradients store a *value* (data rate) and a *direction* (towards the sink) for “pulling down” data.



- A sensor that receives an interest it can serve, begins sensing.
- As soon as a matching event is detected, data messages are sent to the relevant neighbors using the gradients established.
- A data cache is maintained at each sensor recording recent history.

Reinforcement for Path Establishment

The sink initially repeatedly *diffuses an interest* for a low-rate event notification, through *exploratory* messages.

The *gradients created* by exploratory messages are called exploratory and have *low data rate*.

As soon as a matching event is detected, exploratory events are generated and *routed back to the sink*.

After the sink receives those exploratory events, it *reinforces one (or more) particular neighbor* in order to “draw down” real data.

The gradients that are set up for receiving high data rate information are called *data gradients*.

Path Establishment Using Positive Reinforcement

To reinforce a neighbor, the *sink re-sends the original interest message* with a *higher rate*.

Upon reception of this message a node *updates the corresponding gradient* to match the requested data rate.

The *selection of a neighbor* for reinforcement is based on *local criteria*, i.e.:

- the neighbor *that reported first a new event* is reinforced.
- the *higher data rate* neighbor is reinforced.
- *more than one neighbors* are reinforced.

The data cache is used to determine which criteria are fulfilled.

Negative Reinforcement

Negative reinforcement is applied when *certain criteria* are met
i.e. a gradient *does not deliver* any new messages for an
amount of time, or *a gradient has a very low data rate*, etc.

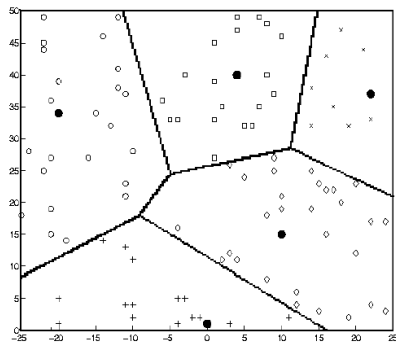
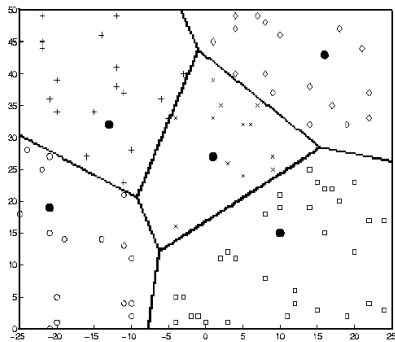
Summary Evaluation of Directed Diffusion

- improves over flooding a lot
- significant energy savings
- performance drops when network dynamics are high

Low Energy Adaptive Clustering Hierarchy (LEACH)

- The network is partitioned in *clusters*.
- Each cluster has one *cluster-head*.
- Each non cluster-head *sends data to the head of the cluster* it belongs to.
- Cluster-heads gather the sent data, compress it and *send it to the sink directly*.

Dynamic Clusters



Randomized rotation of cluster-heads

- Node n decides with *probability* $T(n)$ to elect itself *cluster-head*
 P : the desired percentage of cluster heads.
 r : the current round.
 G : the set of nodes that have not been cluster-heads in the last $\frac{1}{P}$ rounds.
- $T(n)$ is chosen so as to get on the average the same number of cluster-heads in each round.

$$T(n) = \begin{cases} \frac{P}{1 - P * (r \bmod \frac{1}{P})} & \text{if } n \in G \\ 0 & \text{otherwise} \end{cases}$$

Cluster-head advertisement

- Each cluster-head *broadcasts* an advertisement message to the rest nodes using a CSMA-MAC protocol.
- Non cluster-head nodes *hear the advertisements* of all cluster-head nodes.
- Each non cluster-head node *decides its cluster-head* by choosing the one that has the stronger signal.

Cluster set-up phase

- Each cluster-head is *informed for the members of its cluster*.
- The cluster-head creates a *TDMA schedule*
- The cluster-head *broadcasts the schedule back* to the cluster members.

- Non cluster-heads
 - *Sense* the environment.
 - *Send* their data to the cluster head during their transmission time.
- Cluster-heads
 - *Receive* data from non cluster-head nodes.
 - *Compress* the data received.
 - *Send* their data *directly* to the base station.

Summary Evaluation of LEACH

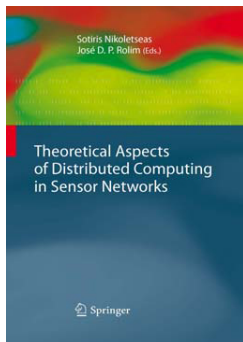
- reduces energy dissipation through *compression of data at cluster-heads*.
- in large networks, *direct transmissions are very expensive*.
- performance drops when the network traffic is high (e.g. many events generated).

- **W.R. Heinzelman, A. Chandrakasan & H. Balakrishnan**, *“Energy-Efficient Communication Protocol for Wireless Microsensor Networks”*, 33rd Hawaii International Conference on System Sciences, HICCS-2000.
- **C. Intanagonwiwat, R. Govindan, & D. Estrin**, *“Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks”*, 6th Annual International Conference on Mobile Computing and Networking (MobiCOM '00), August 2000.

- Ma, D., Lan, G., Hassan, M., Hu, W., and Das, S.K.: *Sensing, Computing, and Communications for Energy Harvesting IoTs: A Survey*, IEEE Communications Surveys Tutorials, vol. 22, no. 2, pp. 1222-1250, 2020.
- Li, S., Xu, L.D., and Zhao, S.: *5G Internet of Things: A survey*, Journal of Industrial Information Integration, vol. 10, pp. 1-9, 2018.
- Akyildiz, I.F., Su, W., Sankarasubramaniam, Y., and Cayirci, E.: *Wireless Sensor Networks: a Survey*. In the Journal of Computer Networks 38 (2002) 393-422.

- *F. Zhao and L. Guibas*, **Wireless Sensor Networks: An Information Processing Approach**, Morgan Kaufmann, 2004.
- *C. Raghavendra and K.Sivalingam* (Editors), **Wireless Sensor Networks**, Springer Verlag, 2006.
- *Bhaskar Krishnamachari*, **Networking Wireless Sensors**, Cambridge University Press, December 2005.

- *S. Nikolettseas and J. Rolim, Theoretical Aspects of Distributed Computing in Sensor Networks*, Springer Verlag, 2011.



- T1.** Challenges for Wireless Sensor Networks
- T2.** Models, Topology, Connectivity
- T3.** Localization, Time Synchronization, Coordination
- T4.** Data Propagation and Collection
- T5.** Energy Optimization
- T6.** Mobility Management
- T7.** Security Aspects
- T8.** Tools, Applications and Use Cases

Oral Exam and Homework

- Oral exam (80%)
- Hands-on homework:
 - Compulsory mote programming project using Contiki OS (20%)
 - Optional written report on a research paper (+1 point)
- Active participation during the lectures will be taken into account