Algorithmic Aspects of Sensor Networks in Environmental Monitoring

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Overview of the talk

A. Sensor Networks for Environmental Monitoring
B. New Challenges
C. Examples of recent research
D. HOBNET: A green/smart building EU project

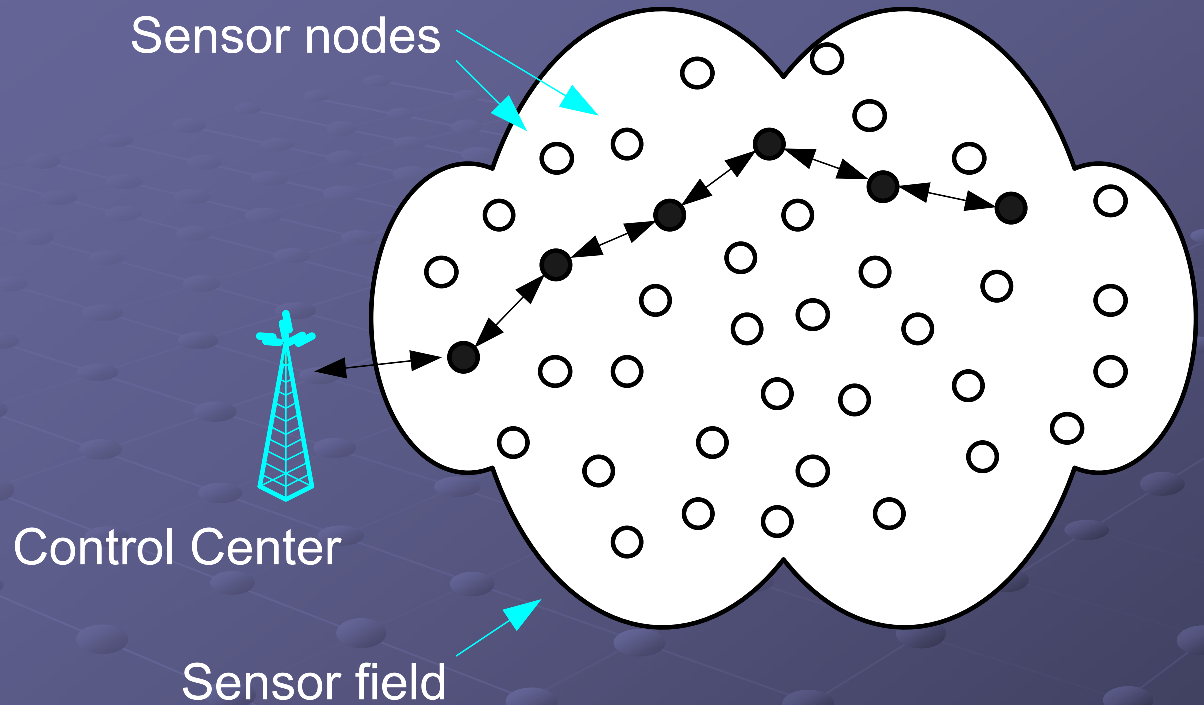
A. Wireless Sensor Networks

- very large number of tiny "smart" sensors
  (slow CPU, some memory, limited battery, wireless)
- densely / randomly deployed in an area
- self-organization, co-operation, locality

an "ad-hoc" wireless network for:

- sensing crucial events
- information propagation

A smart dust "cloud"



- R: the wireless transmission range of each sensor.

- energy dissipation=O(R^2)

=> multi-hop data relaying towards a fixed (or mobile) control center (the "sink" S).

Environmental Monitoring – natural world

– forest fire detection

– flood detection

– precision agriculture

– weather forecast

– planetary exploration

Recent example: monitoring a natural reserve in Brazil

- a natural reserve is near a former mine, which negatively affects it
- biologists suggest that the evolution of the population of frogs in the reserve reflects this impact
- a sensor network deployment can monitor the number of frogs (via acoustic sensors)

Urban Environmental Monitoring

– green buildings (HOBNET project)
– smart cities
– interactive museums
– factories of the future

Common features (urban/natural)

- large/huge numbers of sensors needed
- obstacle presence (walls in buildings/a river or lake in nature)
- frequent failures
- energy/time critical
- long time operation needed

B. New Challenges (I)

- Scalability:
  - huge number of sensor nodes
  - high densities of nodes
  - many complex interactions

  How does protocol performance scale with size?

  Even correctness may be affected by scale

- Efficiency: mainly energy, time. Crucial trade-offs.

New Challenges (II)

- Fault-tolerance (and self-stabilization)
  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? To what extent?

New Challenges (III)

- Inherent trade-offs (e.g. energy vs time, fault-tolerance)
- Competing goals / various aspects
- Application dependence

thus

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

Key Issues

- Technology independent models
  - Models of deployment
  - Models of dynamics
  - Models of collaboration and competition for resources
- Energy management, balancing and complexity formulation
- Scaling laws
  - Global impact of the local sensor interactions
  - Self-organization
  - Adaptation
  - Nature inspired control mechanisms
- Efficient management of mobility
- Heterogeneity even at the sensor level

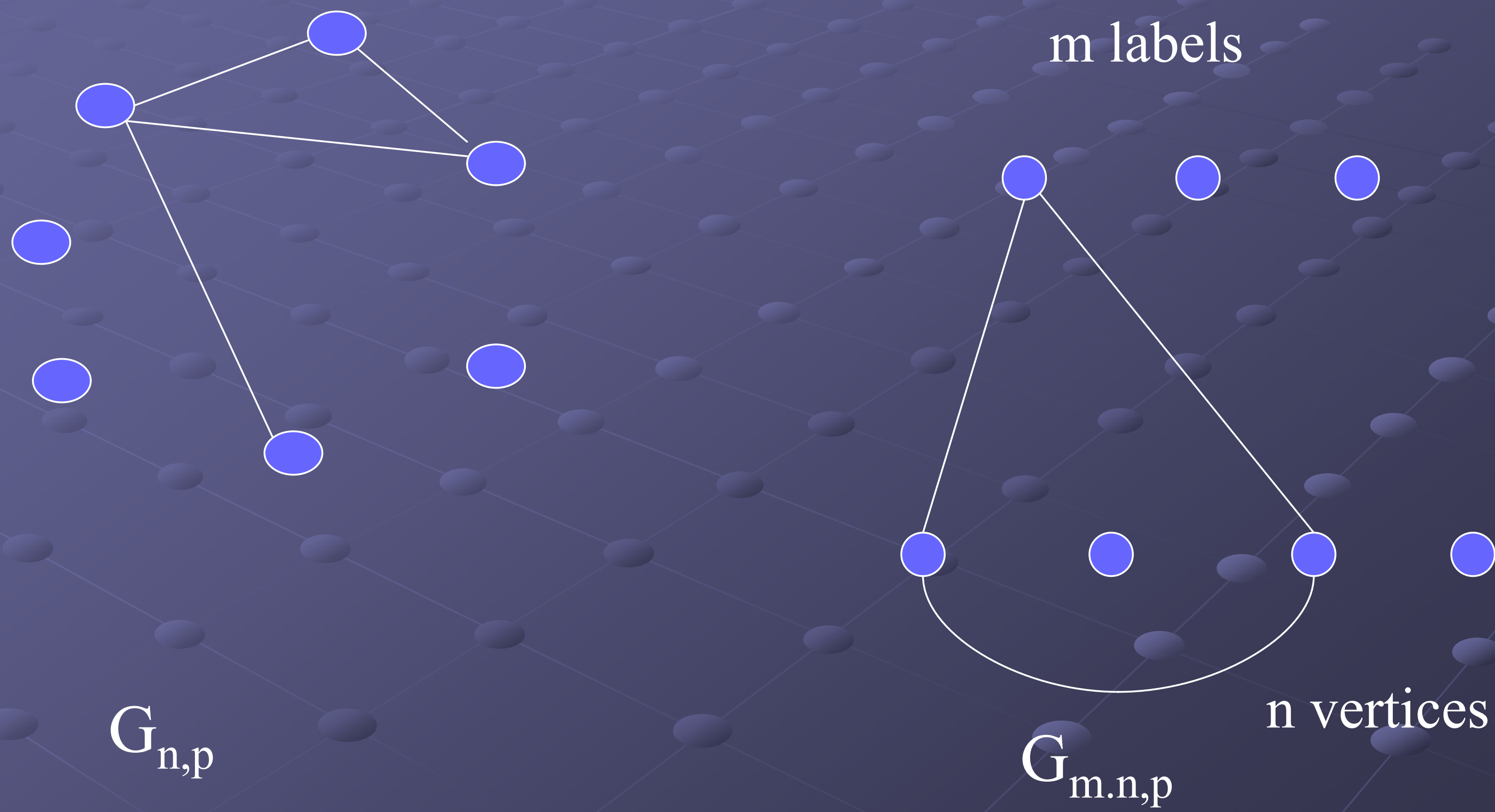
C. Examples of recent research

- New random graphs models
- Global balance via randomized local algorithms
- Trust-based obstacle avoidance

C1. Erdös-Renyi graphs - critique

- $G_{n,p}$: n vertices, include each possible edge with probability p, stochastically independently
- Celebrated model for modern networks
- Limitation in the sensory domain: edge independence is not realistic (e.g. if edges uv and vw exist, then uw possibly also exists, because of the dense interactions).

Random graphs

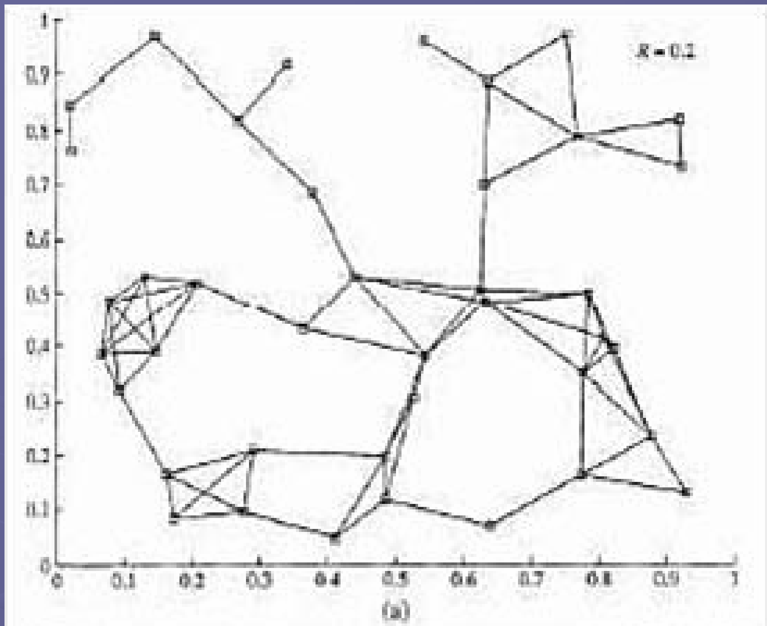


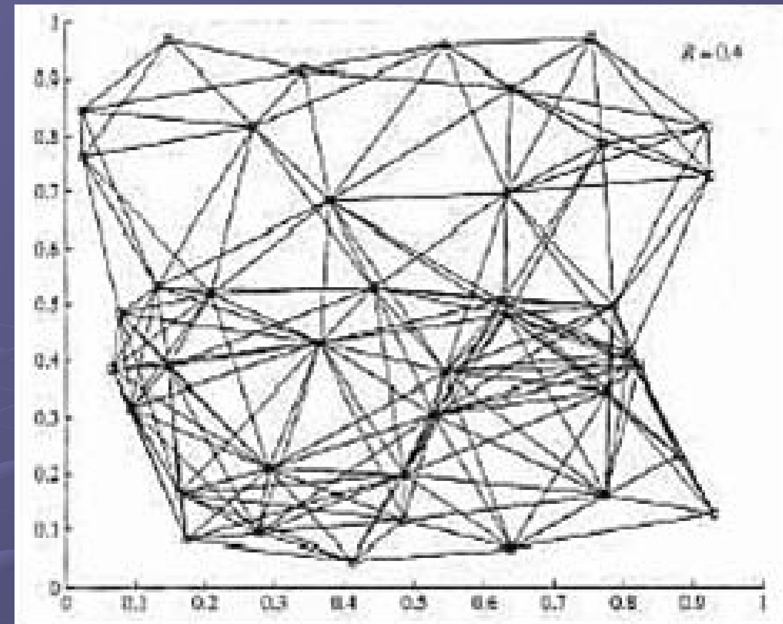
Random Geometric Graphs

- $G_{n,R}$: throw n points in the $[0,1]^2$ plane and join by an edge any 2 points within distance R of each other (R: the wireless transmission range)

- Strength: captures spatial proximity

- Weakness: misses other types of interactions





Theorem (Gupta and Kumar): If $\pi R^2 = \frac{logn+c(n)}{n}$, G(n,R) is connected almost certainly when c(n)$\rightarrow \infty$, while it is almost certainly disconnected when c(n)$\rightarrow -\infty$

$G_{n,m,p}$ Random Intersection Graphs

- $G_{n,m,p}$ space: n vertices, m labels, each vertex chooses randomly, independently labels with probability p and vertices are connected by an edge iff they share at least one common label
- Captures distributed resource sharing, e.g.:

  - vertices: servers, sensors

  - labels: printers, wireless frequencies

  - edges: nodes with conflict

Relevant combinatorial properties

- Existence of very large independent set of vertices

(vertices without edges joining them)

- Few colors suffice to color the graph

(adjacent vertices get different colors)

- The cover time of a random walk is small

(the time to visit all vertices at least once)

Useful for frequency assignment/medium access control and fast communication.

(S.Nikoletseas et al, TCS 2008, TCS 2009, MFCS 2009)

C2. Our Energy Balance Protocol (EBP) - Motivation

- Most protocols tend to "strain" some specific nodes in the network:

  - In a hop-by-hop scheme the nodes closer to the sink tend to be overused.

  - In a direct transmission scheme the distant nodes tend to be overused.

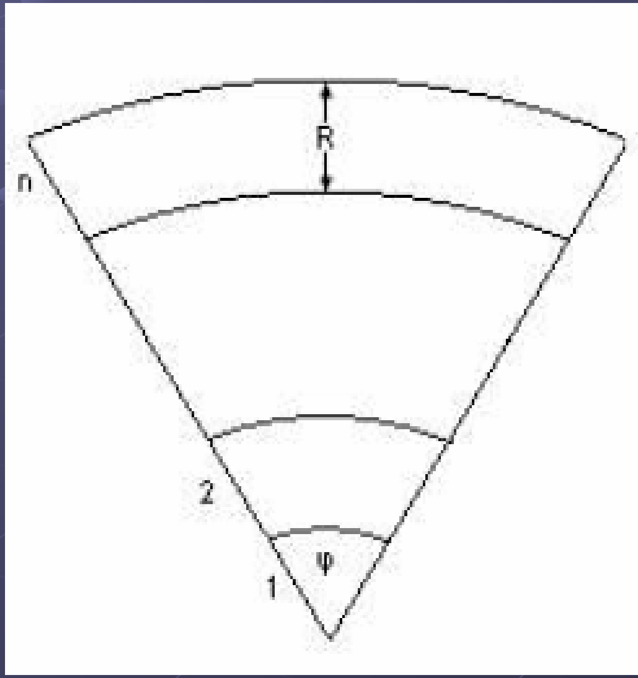
- "How can we achieve equal energy dissipation per node in order to prolong the network lifetime by avoiding early network disconnection?"

The Protocol

- Data Propagation: Each node in sector i propagates messages:

  - to sector $i-1$ with probabilty p_i.

  - directly to the sink with probability $1-p_i$.



- The choice of p_i is made such as the average per sensor energy dissipation is the same for all sensors in the network.

A closed form for p_i

$$p_i = 1 - \frac{3x}{(i+1)(i-1)}$$

- i large (far away)=> better propagate hop by hop
- i small (close to the sink) =>better directly

- A. Jarry, P. Leone, S. Nikoletseas, J. Rolim, “Optimal Data Gathering Paths and Energy Balance Mechanisms in Wireless Networks”, DCOSS 2010.

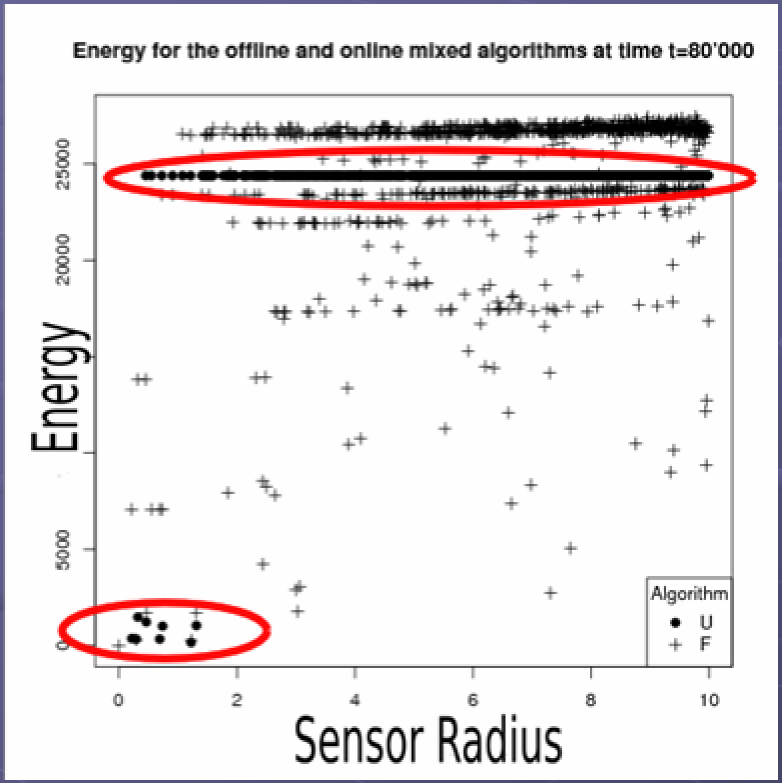
- C. Efthymiou, S. Nikoletseas and J. Rolim, "Energy Balanced Data Propagation in Wireless Sensor Networks", in the Wireless Networks (WINET) Journal, 2006.

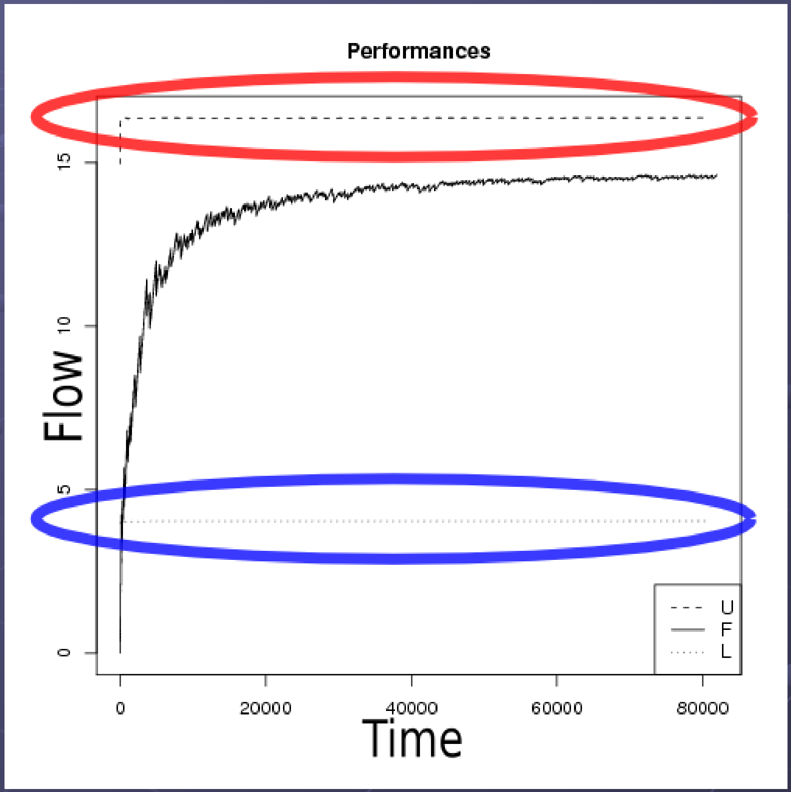
Algorithmic Engineering (I)

- Implementation of protocols:

  - software simulation (in LEDA, MATLAB, ns2 + our extensions)
- more realistic (technical details)
- large scale (hundreds to thousands of sensors simulated)
- visualization of protocol evolution
- validation/fine-tuning of algorithms

Algorithmic Engineering (II)

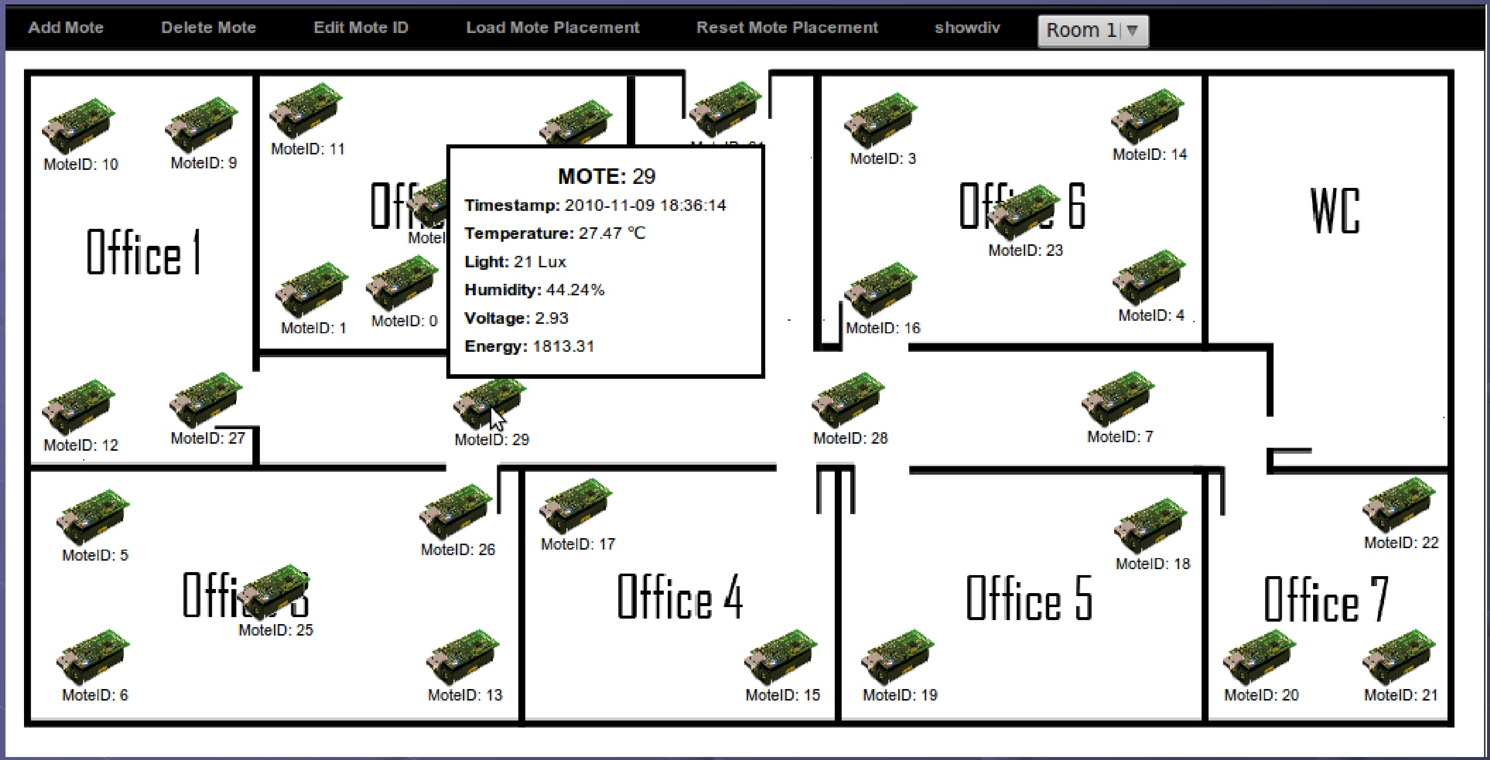




flow = messages received/energy spent

- F: our algorithm
- U: maximum possible flow (offline, computed by a LP)
- L: maximum possible flow without direct transmissions

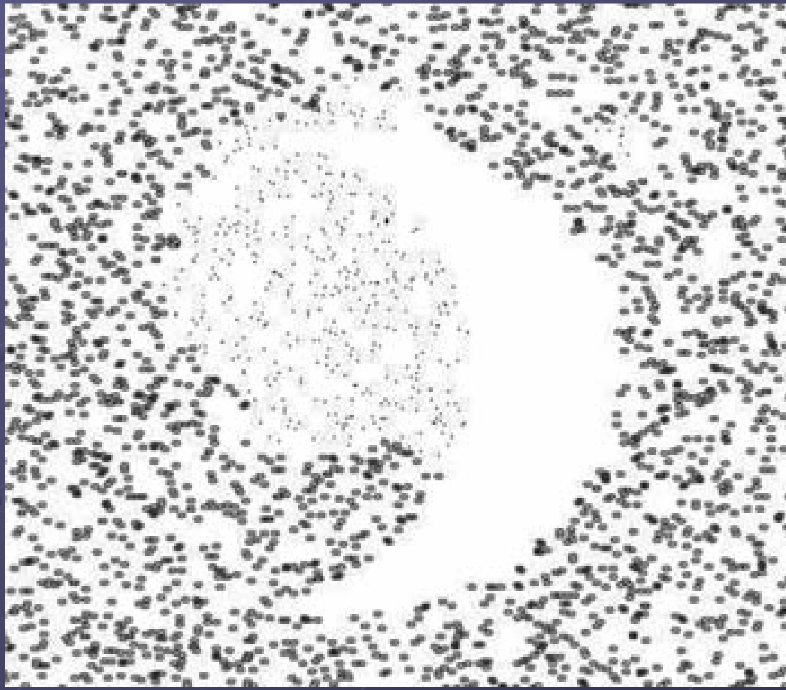
Our local test-bed



- 70 sensors (TELOS B, IRIS, ENOCEAN, SUNSPOT), 15 rooms
- robots (moway, surveyor)
- actuators (control lights, open windows, control the HVAC)
- energy meters
- web interface

C3. Trust based obstacle avoidance

- Trust=E(p) = a/a+b
- Sensors near the obstacle spread their “bad reputation” in the network, marking the broader region in front of the obstacle.
- Data propagation avoids that marked region



(L. Moraru, P. Leone, S. Nikoletseas and J. Rolim, in the Wireless Communication and Mobile Computing (WCMC) Journal, 2010).

D. The HOBNET EU Project

HOlistic Platform Design for Smart Buildings of the Future InterNET (www.hobnet-project.eu)

(FIRE - Future Internet Research & Experimentation)

Participants

1. Computer Technology Institute (Coordinator), Greece.
2. Ericsson Serbia, Serbia.
3. Mandat International, Switzerland.
4. Sensinode, Finland.
5. University College Dublin, Ireland.
6. University of Edinburgh, Scotland.
7. University of Geneva, Switzerland

Selected smart/green building services

- light control
- HVAC optimization
- tracking of mobile entities
- content delivery
- control access
- emergency management

Main Objectives

a) an **all IPv6/6LoWPAN infrastructure** of buildings and how IPv6 can integrate heterogeneous technology (sensors, actuators, mobile devices etc)

b) novel **algorithmic models and scalable solutions** for energy efficiency and radiation-awareness, data dissemination, localization and mobility

c) rapid development and integration of **building management applications**, and their deployment and monitoring on FIRE test beds

d) **6lowApp standardization** towards a new embedded application protocol for building automation

Approach/Innovation

- we take **a holistic approach** addressing critical aspects at different layers (networks, algorithms, applications/tools) in an integrated way.
- rather than an application-agnostic infrastructure, the project addresses the **specific R& D area of intelligent Building Management Systems (BMS).**
- the **interoperability challenge considering a variety of** wireless devices and various hardware and software types for each device.

Conclusions

- Multidisciplinary research area
- Rich interdisciplinarity within CS
- We focused on algorithmic aspects
- Many other aspects are very important as well:

  - languages, operating systems, middleware

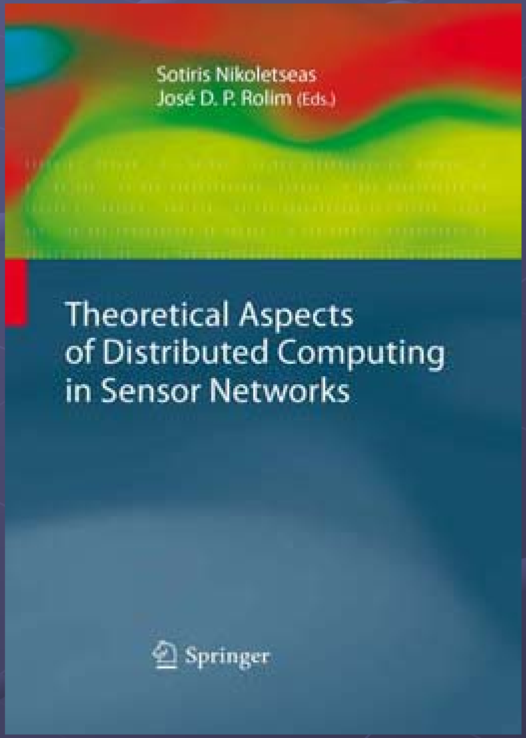
  - architectures (node and system level)

  - application development methodologies

  - case studies, real world deployments

Our new book

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



Themes

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