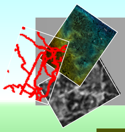
Optimal Design, Management and Energy Conservation of Environmental Sensor Networks (ESNs)



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Outline

Advances of ICTs in Digital Economy

- Enable ICTs in Digital Economy
  - ✓ Location Based Services (context-aware services)
  - ✓ Wireless Internet
  - ✓ Wireless Sensor Networks (WSN)
  - ✓ Web-based document management
  - ✓ Security
  - ✓ Ontology and Semantic in the Web
  - ✓ Flash memories

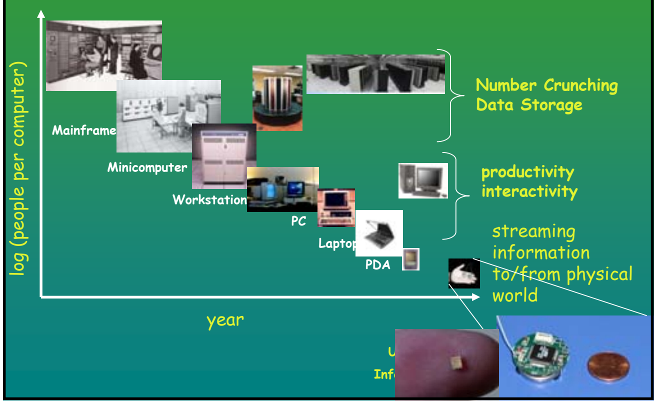
Sensors Everywhere

" While the last 50 years have been dominated by a march to ever more complex computers, the next few decades will see the rise of simple sensors by the billions."
Business Week

- Which prospective application domains and concrete applications are of particular value?
- What hardware/software requirements are needed to support such applications?
- How can we better coordinate the mostly isolated and disconnected research activities on sensor networks?

Sensors Everywhere

New Class of Computing



Proactive computing….

- Moving from human-centered to human-supervised computing
  - 150 million PCs versus 8 billion embedded computers
  - Only 2% of computers are PCs
- Getting physical
  - embedded computers
- Getting real
  - Real-time, fast responses from computers need to be arbitrated

Ubiquitous computing

"The most profound technologies are those that disappear: e.g., writing does not require active attention, but the information to be conveyed is ready for use at a glance (Periphery / calm technology)."

Mark Weiser, PARC, 1991

- We should not be required to live in computer's world (OS, virtual reality). Instead, computers should become invisible and ubiquitous (disappear in background) in our physical world.
- Already computers in light switches, thermostats, stereos and ovens help to activate the world.
- For such a technology, localization & scalability are critical (Location-aware devices, Wireless communication, Micro-kernel OS, Distributed computing).

Technology Push

Advances in:

- Complementary metal-oxide-semiconductor (CMOS) miniaturization.
- Micro-sensors (Micro-Electro-Mechanical Systems (MEMS) technologies, Materials, Circuits):
  - acceleration, vibration, gyroscope, tilt, magnetic, heat, motion, pressure, temp, light, moisture, humidity, barometric
  - chemical (CO, CO_2, radon), biological, micro-radar
  - actuators too (mirrors, motors, smart surfaces, micro-robots)
- Communication:
  - short range, low bit-rate, CMOS radios

Technology Push

- Power
  - batteries remain primary storage, fuel cells 10x
  - solar, vibration, flow
- Smaller battery powered devices
  - 1 cm^3 vibrational micro-generators can be expected to yield up to 800 μW/cm^3 from machine-induced stimuli. This is orders of magnitude higher than what provided by currently available micro-generators

I.F. Akyildiz, W. Y. Lee, M.C. Vuran and S. Mohanty,
"NeXt Generation/Dynamic Spectrum Access/Cognitive Radio Wireless Networks: A Survey," Computer Networks (Elsevier) Journal, Vol. 50, pp.2127-2159, Sept. 2006.

Design Space

- Resource constraints
  - ✓ Cost (few to thousands of Euros)
  - ✓ Size (Brick, Matchbox, Grain, Dust)
  - ✓ Energy (Power, Battery, Solar)
- Communications Modality
  - ✓ Satellite (GPS)
  - ✓ Radio
  - ✓ Defuse light
  - ✓ Laser
  - ✓ Inductive Coupling (RFID: Radio Frequency Identification)
  - ✓ Capacitive Coupling
  - ✓ Sound (ultrasound is used under water)

Design Space

- Deployment
  - ✓ Random
  - ✓ Manual
    - One-time activity
    - Iterative activity
- Mobility
  - ✓ Immobile
    - Partly
    - All
  - ✓ Occasional
  - ✓ Continuous
    - Active or Passive

Design Space

- Heterogeneity
  - ✓ Homogeneity
  - ✓ Heterogeneity
- Infrastructure
  - ✓ Infrastructure
  - ✓ Ad-hoc
- Network Topology
  - ✓ Single-hop
  - ✓ Multi-hop
  - ✓ Cluster (Star) or network of clusters
  - ✓ Tree
  - ✓ Graph (mesh)

Design Space

- Coverage
  - ✓ Redundant vs Sparse vs Dense
- Connectivity
  - ✓ Connected vs Intermittent vs Sporadic
- Network Size
  - ✓ (few to thousands; 10 vs 100 vs 1,000 vs 10,000 vs 100,000)
    Determines the scalability requirements in terms to protocols and algorithms
- Lifetime
  - ✓ (hours to years; day vs month vs year vs decade)
    It has high impact on the required degree of energy efficiency and robustness of the nodes

Challenges in Sensor Nets

Energy constraint:	Nodes are battery powered
Unreliable communication:	Radio broadcast, limited bandwidth, bursty traffic
Unreliable sensors:	False positives
Ad hoc deployment:	Pre-configuration inapplicable
Large scale networks:	Algorithms should scale well
Limited computation power:	Centralized algorithms inapplicable
Distributed execution:	Difficult to debug & get it right

Design Space

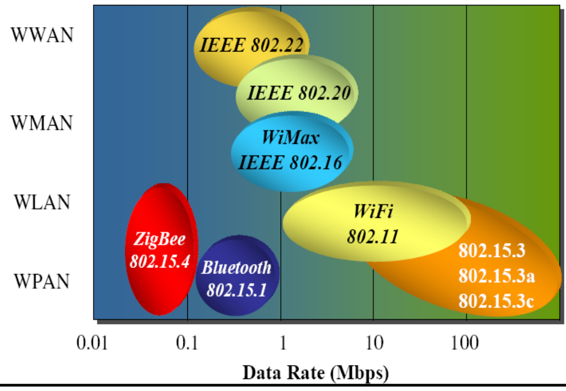
- Other QoS Requirements
  - ✓ Real-time (within certain period) reports
  - ✓ Remain operational after well-defined failures (Robustness).
  - ✓ Remain operational after deliberate attacks (Tamper-resistance).
  - ✓ External entities cannot eavesdrop on data traffic (Eavesdropping-resistance).
  - ✓ Presence of network is hard to detect (Unobtrusiveness or stealth).

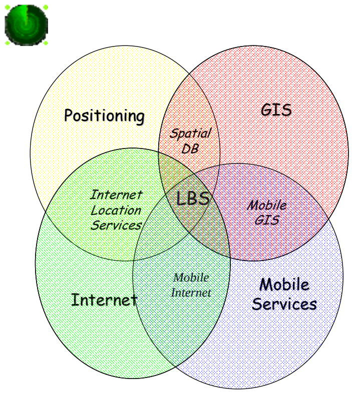
  The above requirements may impact on other dimensions on the design space, like coverage and resources.

Challenges in Environmental Sensor Nets (ESNs)

- Micro and Nano Sensors
- Distributed Sensor Networks
- Surveillance and Monitoring
- Sensor Fusion and Tracking
- Scheduling and Optimisation
- Machine Intelligence

Wireless Standards





- Characteristics of LBSs:
  - -Scalability: Ability of a location-aware server to provide real-time responses to a large number of continuous, concurrent spatio-temporal queries of different types.
  - -Complexity: Spatial comparisons may require complex geometric algorithms. Efficient algorithms are required to avoid unnecessary complex computations.

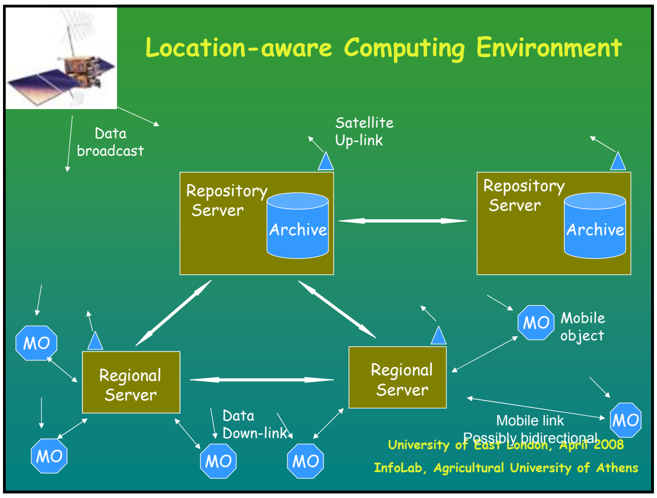
Convergence of mobile technologies location aware technologies (positioning) with the Internet and GIS to create LBSs.

Location Based Services

- LBSs integrate information related to geographic position of a mobile device with other information such as
  - mapping,
  - routing,
  - searching,
  - multimedia content and
  - address location functionalities

  to provide added value to a user with specified profile and content.
- LBSs applications approaches are:
  - ✓ person/device oriented
  - ✓ push/pull services.

Location-aware Computing Environment



Location Based Services

- Location-aware context:
  - A key point in the design of a location-aware services is to provide fast query responses.

    Queries

    - Snapshots: Queries that can be answered using data that is already collected, either in one of the fixed regional servers or in a large repository serer.
    - Continuous: Queries whose responses depend on data progressively accumulating into servers.
      - A report of accumulated results at a regular time interval.
      - A report about the results when a certain event happens.

    To a large number of continuous, concurrent spatio-temporal queries of different types it is required to provide:

    - ✓Efficient data structures.
    - ✓Query optimization techniques.

Location Based Services

- Classification of Spatio-temporal queries:
  - Queries based on the time of the query
    - ✓ Current (one-time) spatio-temporal queries.

      Queries interested only on the current location of moving objects.

      This type of queries provide the instantaneous view of the network.

      Continuous version:

      "Based on my current location, where is the nearest gas station?"

      "What is the humidity in a certain region now?"

      - To answer "now" queries, a location-aware server keeps track of the latest location of all moving objects.
      - The query triggers a single query response, (data traffic generated by one time queries is the least).
      - A warning message that informs the user of some unusual activity in the network (one-time query response that is time-critical).
      - These are usually time critical as user wants to be notified immediately about the current situation of the network.
      - Access methods: Hashing, VCI-index, Q-index, and the LUR-tree.

Location Based Services

- Classification of Spatio-temporal queries:
  - Queries based on the time of the query
    - ✓ Historical spatio-temporal queries.

      Queries that ask about past data (stored at the repository servers).

      "Find the locations of a certain object between 10 - 11 am today."

      "What was the humidity 2 hours back in a certain region of the farm?"

      Continuous version:

      "Continuously, find the locations of a certain object in the last hour."

      - A location-aware server stores only the locations of the moving objects at different times.
      - Once a location of moving object is updated the old location is sent to the repository server along with the time the old location was reported.
      - Access methods include: TB-tree, MV3R-tree, and SETI.

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Location Based Services

- Classification of Spatio-temporal queries:
  - Queries based on the time of the query
    - ✓ Future spatio-temporal queries.

      Queries interested in predicting the locations of moving objects (additional information, e.g., velocity, or destination, need to be set from the moving objects to the servers.)

      Continuous version:

      "What is going to be the temperature for the next 2 hours in a certain region?

      "Alert me if a moving object is going to cross a certain region in the next 30 minutes?"

      The "alert" is sent before the actual event happens.

      - A persistent query generates maximum query responses in the network depending on it's duration.
      - The purpose of the persistent query is to perform periodic background monitoring.
      - Access methods: R-tree (e.g., TPR-tree, RExP-tree, TPR*- tree, and quadtree-based structures.

Location Based Services

- Classification of Spatio-temporal queries:
  - Queries based on the mutuality of both objects and queries.
    - ✓ Stationary queries on moving objects.

      Query regions are stationary while objects are moving.

      Continuous version:

      "How many tracks are within the city boundary?"

      "Find the nearest 5 taxes to a certain home."

      - The query regions (city boundary and home neighborhood) are fixed, while the objects of interest (trucks and cars) are moving.
      - To support continuous fixed queries the following approaches may be used:
        - ➢ Index the moving object with R-tree based structures (e.g., TPR-tree, R^{ExP}-tree, TPR*-tree) access methods.
        - ➢ Index the fixed queries with Q-index and Q+Rtree access methods

Location Based Services

- Classification of Spatio-temporal queries:
  - Queries based on the mutuality of both objects and queries.
    - ✓ Moving queries on moving objects.

      Both query regions and objects are moving.

      Continuous version:

      "As a farmer is moving in a certain trajectory, make sure that the number of collecting trucks within 3 kms of his location is more than a certain threshold."

      - The query region is moving.
      - The objects of interest (collecting trucks) are moving.
      - To support moving queries in a location aware server, moving objects need to be indexed using a TPR-tree like structure (e.g., TPR-tree, R^{ExP}-tree, TPR*-tree) access methods. Then, special algorithms are developed to process moving queries in TPR-tree like structure.

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Location Based Services

- Classification of Spatio-temporal queries:
  - Queries based on the mutuality of both objects and queries.
    - ✓ Moving queries on stationary objects.

      Query regions are moving, while objects are stationary.

      Continuous version:

      "As I am moving in a certain trajectory, show me all the gas stations within 3 kms of my location."

      - To organize the fixed objects traditional methods are employed by the queries (e.g., fractals or R-trees).
      - Efficient algorithms that utilize the R-tree are proposed for the continuous single nearest-neighbor queries and the continuous K-nearest neighbor queries.

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Location Based Services

- Routing (Directed Diffusion)
  - Protocol initiated by destination (through query)
  - Data has attributes; sink broadcasts interests
  - Nodes diffuse the interest towards producers via a sequence of local interactions
  - Nodes receiving the broadcast set up a gradient (leading towards the sink)
  - Intermediate nodes opportunistically fuse interests, aggregate, correlate or cache data
  - Reinforcement and negative reinforcement used to converge to efficient distribution

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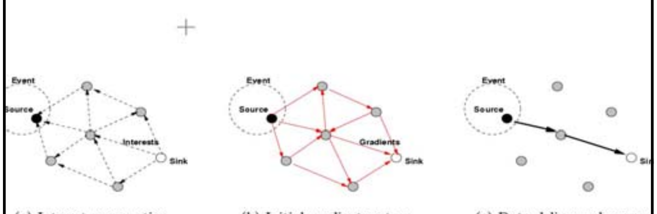
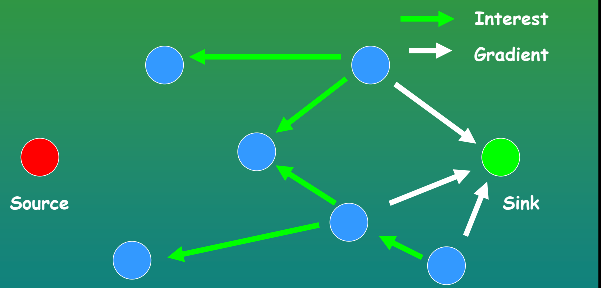
Location Based Services
Routing (Directed diffusion)



(a) Interest propagation (b) Initial gradients set up (c) Data delivery along re-inforced path

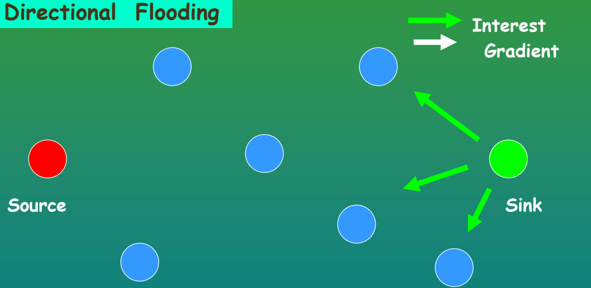
Intanagonwiwat, Govindan and Estrin,
"Directed diffusion: a scalable and robust communication paradigm for sensor networks"
6th conf. on Mobile computing and networking, 2000.

Location Based Services
Routing (Directed diffusion)

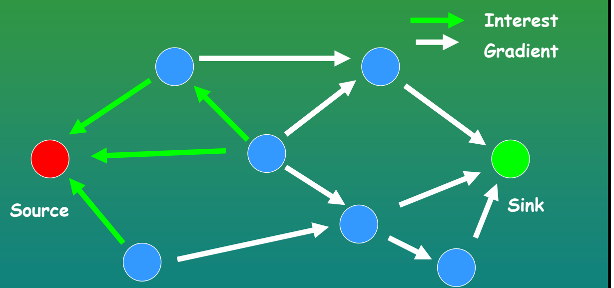


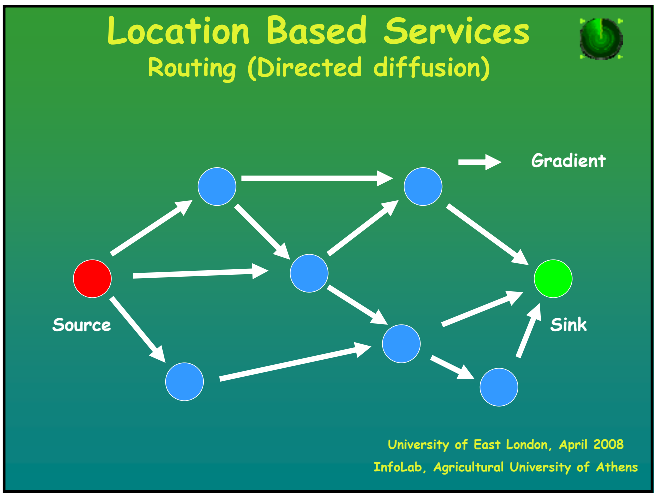
Location Based Services
Routing (Directed diffusion)

Directional Flooding



Location Based Services
Directed diffusion




Location Based Services
Routing (Directed diffusion)
Gradient
Source
Sink
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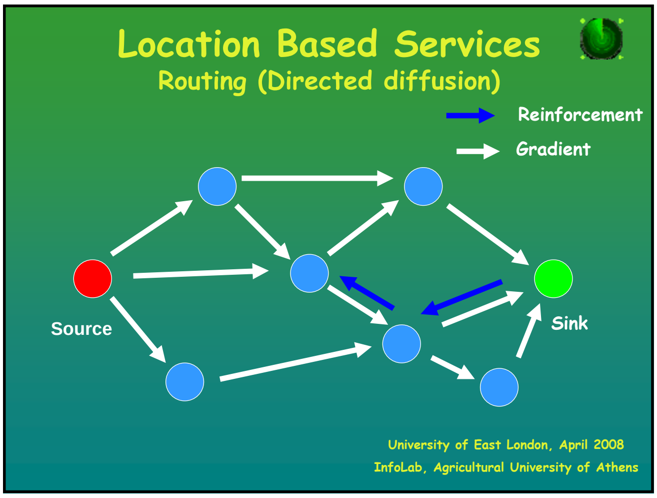
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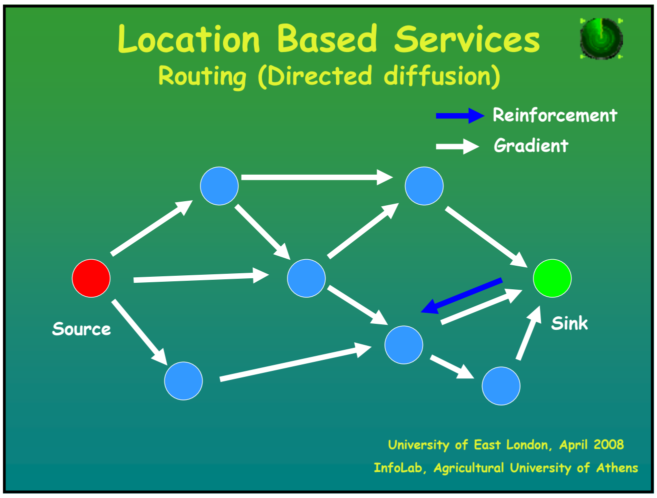
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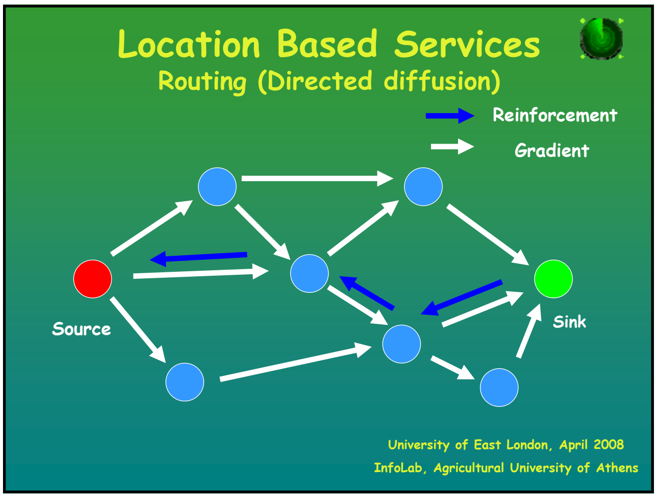
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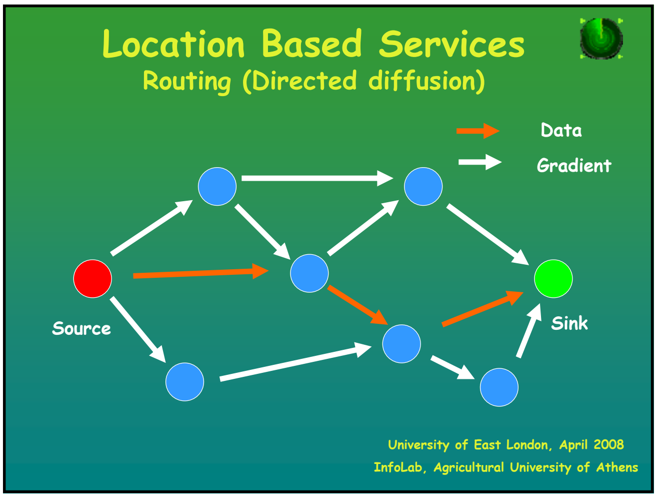
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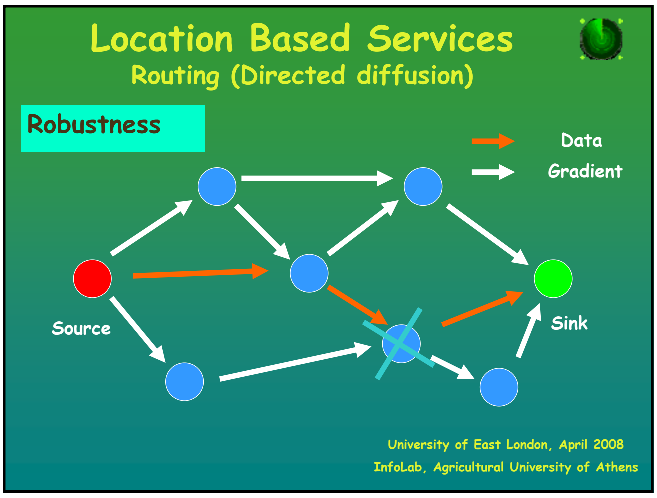
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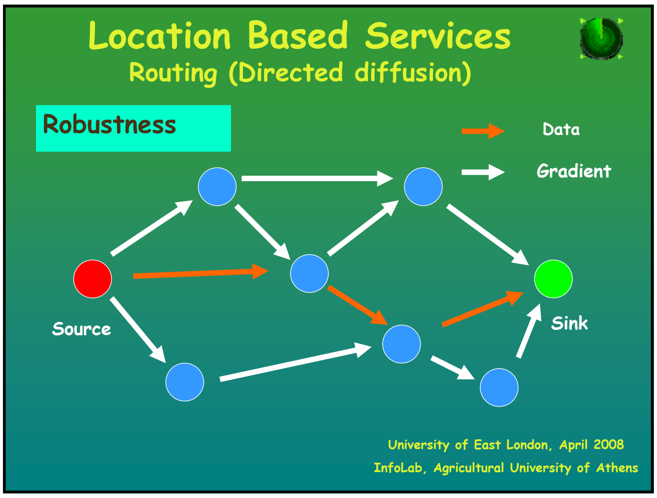
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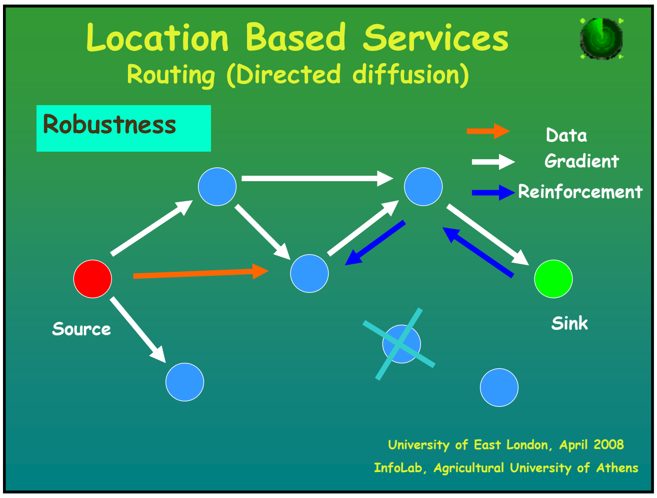
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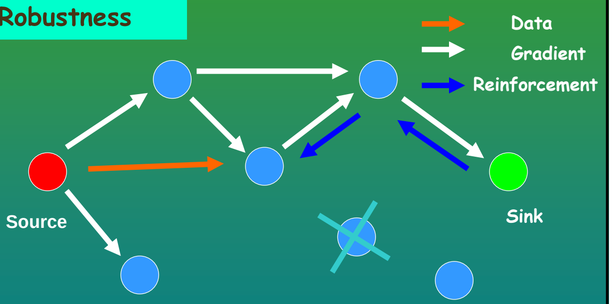
Location Based Services
Routing (Directed diffusion)

Robustness



Location Based Services
Routing (Directed diffusion)

- **Data Naming**
  - Expressing an Interest
    - Using attribute-value pairs

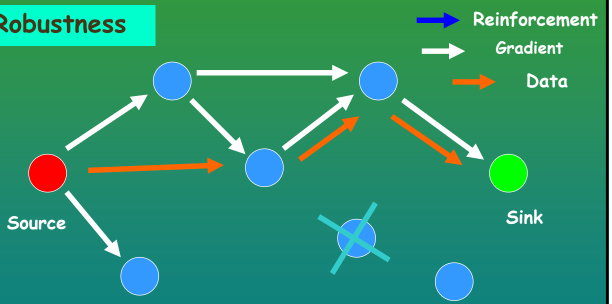
      Examples

```
Type = Wheeled vehicle // detect vehicle location
Interval = 20 ms       // send events every 20ms
Duration = 10 s        // Send for next 10 s
Field = [x1, y1, x2, y2]// from sensors in this area
```

```
Select Vehicle.ID                // select vehicle
From Vehicles V                  // select from a set V
Where Vehicle.speed > speed      //query condition Send AND
Vehicle.location inside R
```


Location Based Services
Routing (Directed diffusion)

Robustness



Enabling Technologies

- Considerable attention within LBS technology has been placed to its constituent technologies, like wireless Web, mobile Internet-enabled devices and mobile positioning.
- The heart of the whole system represents Internet-enabled GIS technology.
- LBSs will benefit from real-time information acquisition at the client side.
- Client will be equipped with sensors to collect information automatically and send it back to Server.

Sensors Everywhere - Applications

- Visions
  - Ubiquitous [pervasive | proactive] computing
  - Design space - Challenges
- Applications
  - Food Industry
  - Environmental monitoring (Crop yield, Cattle herding, Ocean water, fishing, power, construction, etc.)
  - Crop acreage (fertilization, harvest, contaminations, diseases, pests).
  - Water management
  - Precision agriculture
  - Chemical spraying
  - Livestock and wild animals tracking
  - Transportation of goods
  - Integrated electronic market
  - Management of Forest Industry
  - Surveillance
  - Emergency calls (E-112/E-911), finding – rescue of missing persons

Applications

Application	Description
Bird observation on Great Duck Island • WSN, immobile • Buttery, solar • Whether stations, burrow nodes, gateways • Radio –Infrared • Star of clusters • Dense (every burrow) • Tens of hundreds (~100 deployed) • 7 months breeding period	Observe the breeding behaviour of small bird (Leach's Storm Petrel) on Maine, USA. Biologists are interested in • Usage pattern of their nesting burrows, • Changes in the environmental conditions outside and inside the burrows during the breeding season, • Parameters of preferred breeding sites • Sensors measure pressure, temperature, humidity, and ambient light. • Borrow nodes are equipped with infrared sensors to detect the presence of the birds

Applications

Application	Description
Grape Monitoring • WSN, immobile • Sensor-gateway-BS, • Cable-Radio • Tree topology (two-tiered, multi-hop) • Sparse (20m apart), • Several hundreds (up to 65 deployed)	Monitor the conditions that influence plant growth across a vineyard in Oregon, USA. Support precision harvesting, precision plant care, frost protection, predicting insect, pest, fungi development. •Measure of temperature, soil, moisture, light and humidity.
Bathymetry • Self-organized, ad-hoc Homogeneous, • Radio, GPS, • Graph, sparse (0,5-1km) • 4-5 years life, • 6-50 hundreds	Monitor the impact on the surrounding environment of a wind farm off the coast of England (UK). •Formation of sand banks, tidal activities •Measure of pressure, temperature, conductivity, current, and turbidity.

Applications

Application	Description
Cattle Herding • WSN multi-hop, ad hoc • Homogeneous • Radio • BS-GPS, (BS transmits fence coordinates to the nodes) • Graph • Dense (every cow) • Up to hundreds (~10 deployed) • Days to weeks	Supports the implementation of virtual fences using acoustic stimulus being given to animals that cross a virtual fence line. A sensor is attached to the neck of the cows and consists of • PDA with GPS receiver, • WLAN card and • loud-speaker for providing acoustic stimuli to the cattle.

Applications

Application	Description
Cold Chain Management • WSN multi-hop, ad hoc • Sensors-relays-access boxes-BS (warehoue) • Radio • Relays, Access boxes • Tree (two-tired) • Sparse • Up to hundreds(55 sensors, 4 relays, deployed) • years	The commercial Securifood System monitors the temperature compliance of cold chains from production, via distribution centers and stores, to consumer. Clients receive an early warning of possible breaks in the cold chain. • Sensors are transported with the products and collect temperature data. • Relays collect and store temperature data from sensors. They also form a multi-hop network. • Access boxes act as gateways between the relay net and the Internet. There is one access box per production site. • Internet hosted data warehouse acts as a central server, collecting data from all the access boxes. It provides an on-line image of all the sensor data in he system and acts as a central repository for applications.

Applications

Application	Description
Rescue of Avalanche Victims	Assist rescue teams in saving people buried in avalanches. The goal is to better locate buried people and to limit the overall damage.
Parts Assembly	Assist people during the assembly of complex composite objects such as "do-it-yourself" constructions.
Tracking Military Vehicles	Track the path of military vehicle
Sniper Localization	Locate snipers and the trajectory of bullets providing valuable clues for low enforcement.

Applications

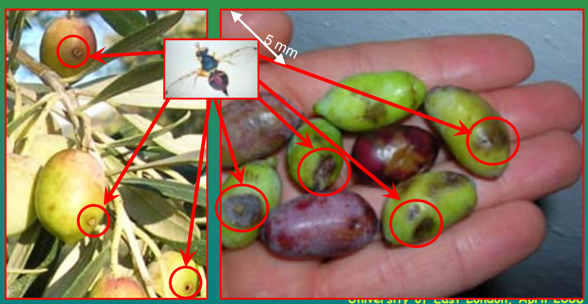
Application	Description
ZebraNet	Behavior of wild animals
Glacier Monitoring	Earth' s climate
Ocean Water Monitoring	Observe the temperature, salinity, and current profile of the upper ocean. ARGO progect:
Vital Sign Monitoring	Monitor vital signals of patients in a hospital environment.
Power Monitoring	Monitor power consumptions in large and dispersed office buildings.

The FruitFlyNet application

- The OliveFlyNet project aims to develop a complete insect pest management system that provides real-time information to managers in order to monitor the olive fly population and control the spray application of olive trees.
- Extension includes other important species of the Tephritid fruit fly family:
  - Mediterranean fruit fly
  - Cherry fruit fly
  - The Ethiopian fruit fly

Olive fly

The olive fly (*Bactrocera* (*Dacus*) *oleae*) (Gmelin)
(Diptera: Tephritidae)



Agro-environmental Information Systems

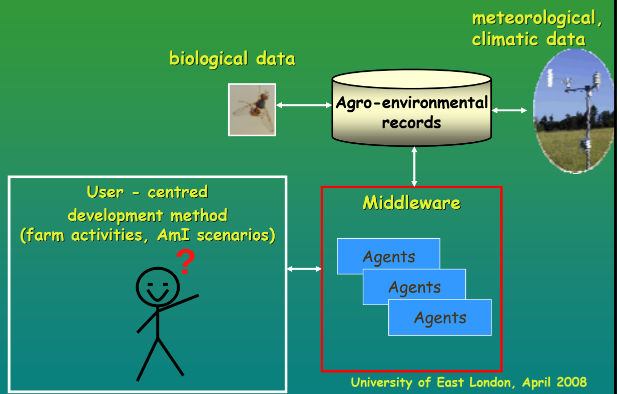
- Provide access to electronic agro - environmental (e.g biological, climatic, meteorological, etc.) records
- Provide accurate and timely information to farmers in support of decision - making.
- Autonomous agents can cope with the complexities associated with implementing AmI environments for precision farming settings.
- Farms are distinguished from
  - the distributed nature of the information,
  - the intensive collaboration and mobility of their personnel,
  - the need to access agro - environmental information occasionally.

Socio-economic Motivation

IOBC wprs Bulletin Vol. 25, 2002

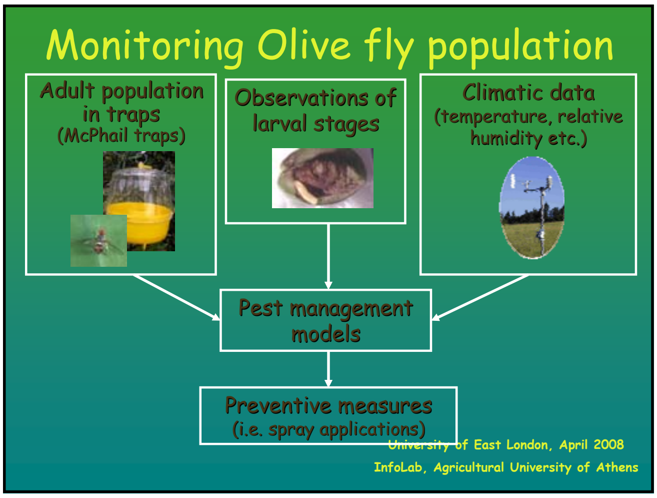
- Mediterranean basin has 98% of the world's cultivated olive trees
- Number of olive trees: About 800 million
- Surface area: Approximately 10 million hectares.
- Production:
  - About 1.6 million metric tonnes per annum of olive oil
  - About 750,000 metric tonnes of table olives (about 9% of the area's production of olives).
- Losses (insect pests, fungi and weeds):
  - About 30% of production.
- Estimated damage caused to harvested fruits by insect pests is at least 15% of production.
  - This equates to 800 million US dollars per annum.
  - This comes despite the fact that olive growers spend annually more than 100 million US dollars combating these pests and of which 50% corresponds to pesticides.

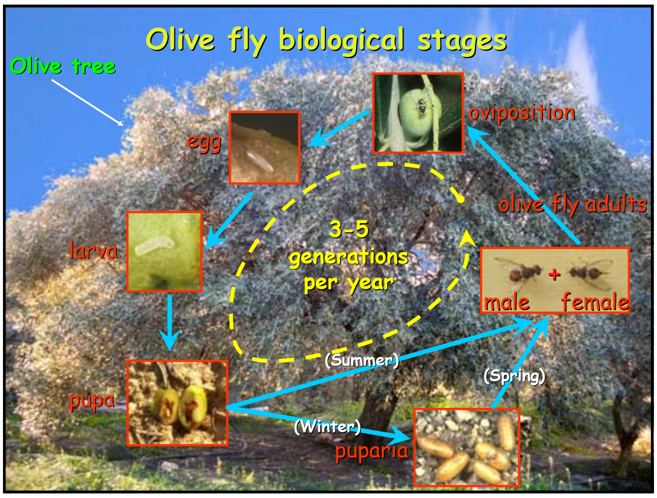
Agro-environmental Information Systems

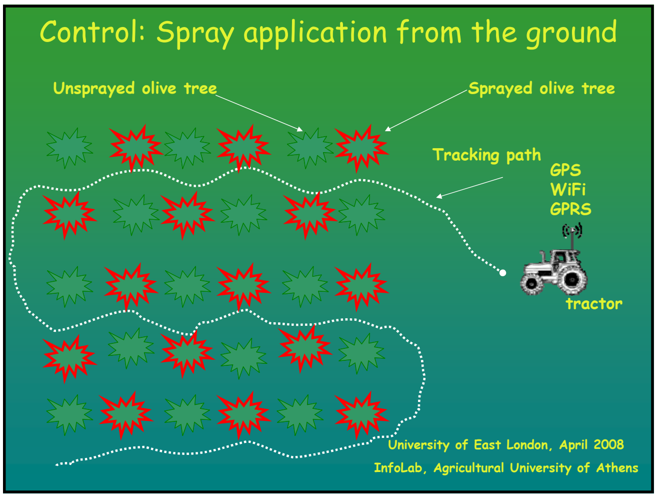


Agro-environmental Information Systems

- An AmI scenarios in PFarming - The olive fly case
  - The Dacus_oleae middleware for spray control of olive trees is based on:
    - ✓ an envisioned scenarios and
    - ✓ the easy integration of components represented by autonomous agents.
  - Building Blocks used for sensory information management
    - ✓ Data gather
    - ✓ Event handler
    - ✓ Communications module
  - The communication aspects of the middleware architecture, allows different context-aware applications to query, retrieve and use sensor data in a way that will be decoupled from the mechanisms used for acquiring the raw sensor data.



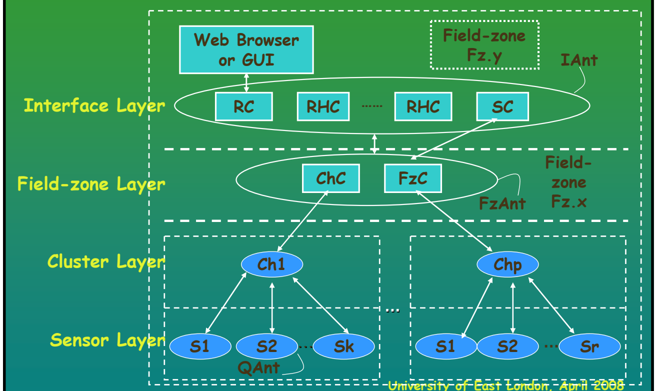




Spray application from the ground

- To avoid failures in the spray treatment, there is a need to ensure that:
  - The experimental plants of olive trees are large enough.
  - The population of olive flies tend to increase significantly.
  - The olives must be in an advanced stage.
  - The female to male insect ratio should be greater than one.
  - The female insects must be in a mature stage
  - The temperature and the humidity levels should exceed a threshold.

Communication Module



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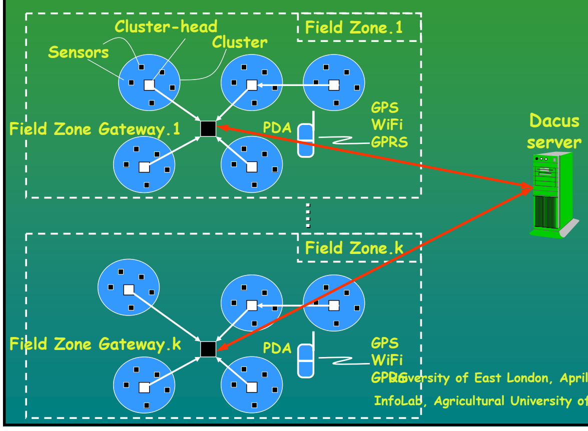
Optimal Design of the *Dacus oleae* Wireless Sensor Network



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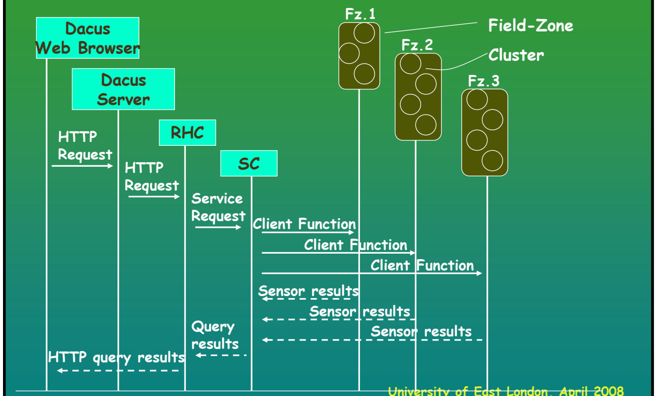
Simulation and Results



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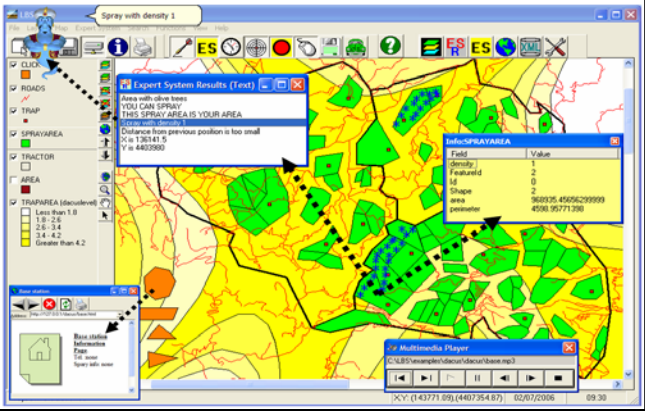
Problems to be solved [1]

- the air temperature and air speed values are unknown to the spraying attendant. In this case, the spraying could continue even when the meteorological conditions have been violated.
- the spraying areas cannot be memorized by the attendant and, therefore, over or under spraying may occur.
- the spray volume is dependent on the coverage of olive trees and, as a result, the spraying attendant cannot easily determine if the number of the olive trees per area unit is low, medium, or high.

The *Dacus oleae* application



Problems to be solved [2]

- the existing areas inside the spraying area which must not be sprayed for some reason (i.e. domestic areas).
- the olive fly population of the spraying area is not known to the attendant and therefore the spray volume per area cannot be determined at all.
- the lack of communication between the supervisor and the attendants.

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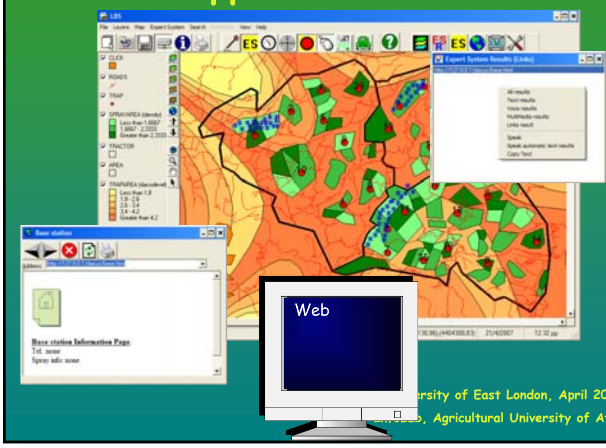
An application scenario



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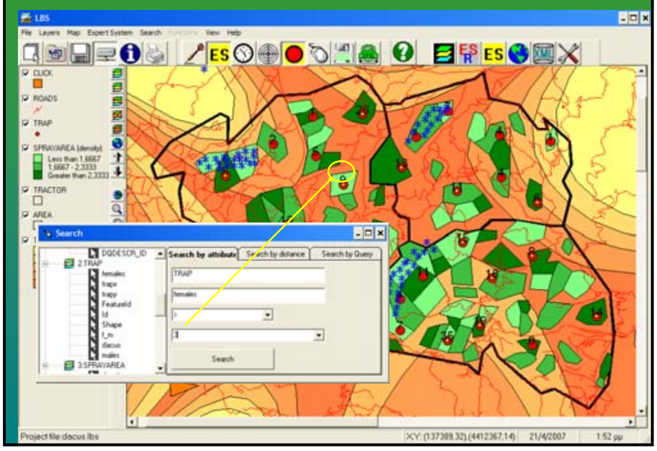
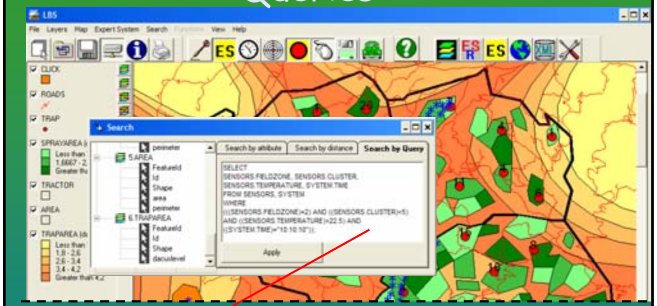
Queries (1)

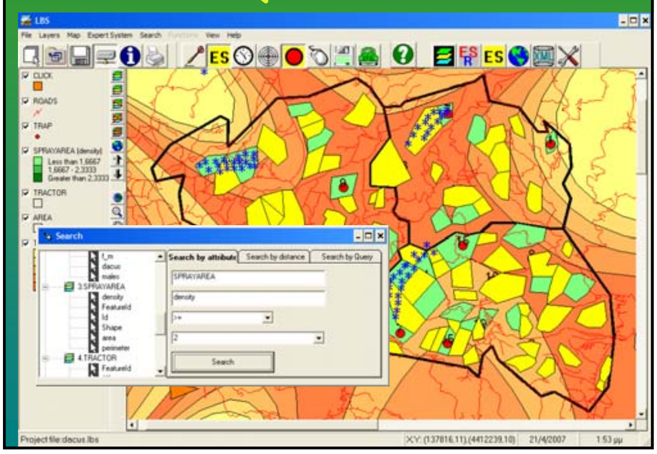


Queries (3)



FIELDZONE	CLUSTER	TEMPERATURE
2	1	23.2
2	2	24.5
2	3	26.7
2	4	24.1

Queries (2)



Testing and Evaluation (1)

- Critical questions
  - ✓Testing and evaluating the proposed application in its target environment with a suitable infrastructure and a volunteer user community is costly and usually does not scale well to large number of users or applications.
  - ✓To proceed with a different approach we created a test environment that supports the evaluation of key aspects of the *Dacus oleae* application, without extensive resource investments necessary for a full application implementation and deployment.

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Testing and Evaluation (2)

- A complete evaluation requires many different aspects to be examined, such as:
  - user interface issues,
  - system and network related issues,
  - physical device considerations,
  - new embedded sensing devices
- Our concern here is:
  - to improve the test environment
  - to use it as part of the test and evaluation process for this and other, similar applications.

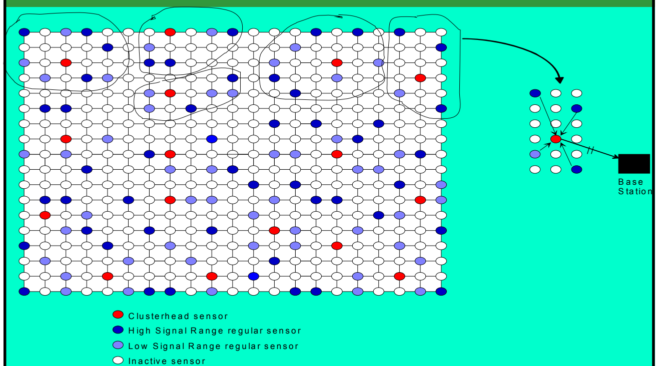
WSN characteristics (2/2)

- Regular sensors communicate with closest clusterhead
- CHs communicate with *base station* (BS)
- Single-hop transmission in both cases
- Range of CHs: capable of reaching the BS
- Range of HSR sensors: radius = 10 length units
- Range of LSR sensors: radius = 5 length units

WSN characteristics (1/2)

- Open field cultivation at an area of 30 by 30 length units
- 900 sensors on a 30x30 grid deployment
- Sensors are identical, either *active* or *inactive*
- Active sensors can operate as:
  - clusterheads (CHs)
  - high signal range (HSR) regular sensors
  - low signal range (LSR) regular sensors

Example WSN architecture



GA-system objectives

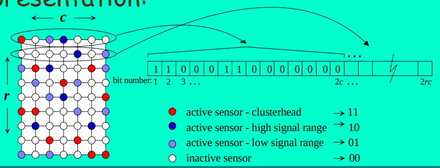
1. Discover optimal topologies of sensor operating modes (CHs, HSR, LSR, inactive) so that energy consumption is minimized and application-specific requirements are met (network characteristics are optimized).

2. Dynamically adapt optimal topologies according to remaining battery levels of sensors.

3. Investigate the performance of dynamic design algorithm in both network's life duration extension and measurements' quality according to precision agriculture (PA) requirements.

Genetic Algorithms

- GAs were used for the optimization of WSN design
- GA characteristics:
  - Binary representation (bit-strings)
  - One-point & two-point crossover
  - Bit-swapping mutation
  - Roulette-wheel selection
  - Elitism
- WSN Representation:



WSN design parameters

- Application-specific parameters:
  - Measurements uniformity
  - Measurements spatial density
- Connectivity parameters:
  - Sensors-per-clusterhead limit
  - Sensors in range to some clusterhead
- Energy related parameters:
  - Operational energy consumption
  - Communication energy
  - Battery life

GA Fitness function

- *Goal of fitness function*:
  to depict all optimization parameters of the problem (i.e., the factors that affect performance)
- Application-specific parameters
- Connectivity parameters
- Energy related parameters
- All parameters have to be expressed mathematically.
- Their weighted combination forms the final fitness function of the GA

Application-specific parameters

- Measurements Uniformity
  MRD (Mean Relative Deviation)

$$MRD=\frac{\sum_{i=1}^{N}\left|\rho_{S_i}-\rho_S\right|}{N\cdot\rho_S}$$

- Measurements Spatial Density
  Spatial Density Error (*SDE*)

$$SDE=\begin{cases}\frac{\rho_s-\rho_d}{\rho_d} & if\ \rho_s<\rho_d\\ 0 & otherwise\end{cases}$$

where:
ρ_{S_i} - spatial density of measurements in sub-area S_i
ρ_S - spatial density of entire area
ρ_d - desired spatial density
N - number of overlapping sub-areas the entire area was divided into

Energy related parameters

- Operational energy consumption (*OE*)

$$OE=20\cdot\frac{nch}{n}+2\cdot\frac{nhs}{n}+\frac{nls}{n}$$

where: *nch, nhs, nls* - the number of CHs, HSR and LSR sensors in the network, respectively.

- Communication energy (*CE*)

$$CE=\sum_{i=1}^{c}\sum_{j=1}^{n_i}\mu\cdot d_{ji}^{k}$$

where:
c - the number of clusters in the network;
n_i - the number of sensors in the i-th cluster
d_{ji} - the Euclidean distance from sensor j to its CH (of cluster i)
μ, k - constants; characteristic of the topology and application site of the WSN (μ = 1, k = 3)

Connectivity parameters

- Sensors per CH limit
  Sensors-per-CH error (*SCE*)

$$SCE=\begin{cases}\frac{\sum_{i=1}^{nfull}n_i}{nfull} & if\ nfull>0\\ 0 & otherwise\end{cases}$$

- Sensors in range to some CH
  Sensors out-of-range error (*SORE*)

$$SORE=\frac{nout}{n}$$

where:
nfull: the number of CHs with more than 15 active sensors in their cluster
n_i: the number of sensors in the i-th of those clusters.
nout: the number of active sensors that cannot communicate with their CH
n: the total number of active sensors in the network.

Energy related parameters

- Battery life

Battery Capacity Penalty (*BCP*)

$$BCP^{[t]}=\sum_{i=1}^{ngrid}PF_i^{[t]}\cdot\left(\frac{1}{BC_i^{[t]}}-1\right)$$

where:
$BCP^{[t]}$: The battery capacity penalty of the WSN at measuring cycle t
$PF_i^{[t]}$: A penalty factor of sensor i that takes different values according to the operation mode of sensor i [values: 20 / 2 / 1 / 0]
$BC_i^{[t]}$: The battery capacity of sensor i at measuring cycle t (0-1):
where:

$$BC_i^{[t]}=BC_i^{[t-1]}-BRR_i^{[t-1]}$$

$BRR_i^{[t-1]}$: A battery reduction rate term (depends on operation mode of sensor i during the previous time step) [values: 0.2 / 0.02 / 0.01 / 0]

Evolutionary approach
Final fitness function

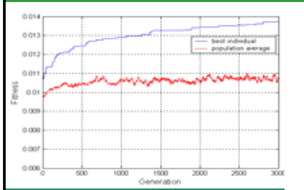
$$f = 1/(\alpha_1 \cdot MRD + \alpha_2 \cdot SDE + \alpha_3 \cdot SCE + \alpha_4 \cdot SORE + \alpha_5 \cdot OE + \alpha_6 \cdot CE + \alpha_7 \cdot BCP)$$

- Values of weighting coefficients:

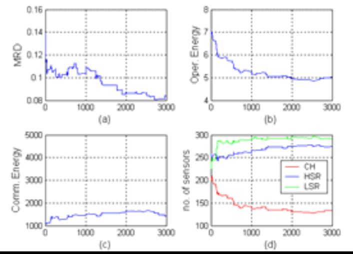
Weighting coefficient	"Equal importance" values	Final values
α_1	10^2	10^2
α_2	10^4	10^4
α_3	2	10^6
α_4	10^3	10^5
α_5	10	10
α_6	$5 \cdot 10^{-3}$	10^{-2}

- α_7: trade-off between energy management optimization and network characteristics optimization

Evolution process - Results



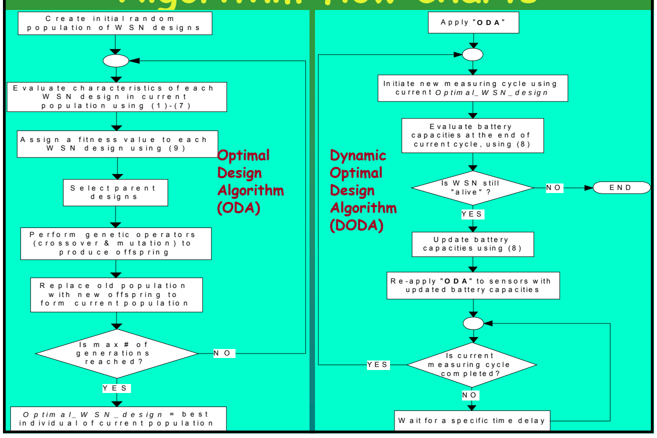
Evolution of fitness values



Evolution of network characteristics

Optimal design algorithm

Algorithm flow charts



WSN designs comparison

	"GA1"	"GA2"	"GA3"	Rand1	Rand2	Rand3	Rand4
MRD (uniformity)	0.0840	0.1018	0.1141	0.5513	0.3333	0.1815	0.1541
SDE (spat. dens. error)	0	0	0	0.0944	0	0	0
OE (operational energy)	5.0086	4.6827	4.9711	2.5276	3.4021	6.5550	8.2474
CE · 10^3 (comm. energy)	1.4323	1.6422	1.4965	1.3882	8.8816	1.7896	0.9610
Out-of-range sensors	0	0	0	29	5	0	0
Over-connected clusters	0	0	0	4	2	0	0
Active sensors	699	602	622	163	378	591	679
CHs	133	105	117	9	39	161	248
HSR sensors	275	222	247	78	167	224	209
LSR sensors	291	275	258	76	172	206	222
CHs / Active	0.19	0.17	0.19	0.05	0.10	0.27	0.36
HSR / Active	0.39	0.37	0.40	0.48	0.44	0.38	0.31
LSR / Active	0.42	0.46	0.41	0.47	0.46	0.35	0.33
Fitness value	0.0137	0.0136	0.0131	-	-	-	-

Results – Initial WSN design

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MA-system objective(*)

- Explore ways to hybridize the GA-system
- Improve the performance of the GA-system by guiding the population formulation of the GA towards more intelligent decisions.

MA – an example

Say that we have a network of only 4 sensors and we are at measuring cycle "x".

The 4 sensors have the following battery levels at this point:

| 0.67 | 0.08 | 0.45 | 0.83 |

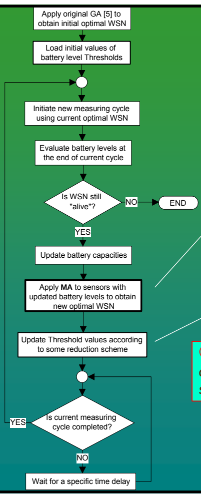
During GA optimization, after *crossover and mutation*, an individual of the population may give the following operating modes for these sensors:

| CH | HSR | inactive | CH |

At this measuring cycle ("x"), the MA-thresholds for the 3 operating modes are:

$T^x_{CH} = 0.8$, $T^x_{HSR} = 0.5$, $T^x_{LSR} = 0.1$

Instead of using the original GA-assignments for these sensors, we check with these thresholds in the following way:



Memetic algorithm – GA hybridization

for each sensor node
if its battery < some threshold (*)
"reduce" its operation mode
end for

Thresholds' update scheme:

$$T^{[t+1]} = (1 - RR) \cdot T^{[t]}$$

(*) Thresholds are different for each operating mode and are reduced at each measuring cycle according to some specific update scheme.

MA – an example

Sensors batteries: | 0.67 | 0.08 | 0.45 | 0.83 |

Original GA assignments: | CH | HSR | inactive | CH |

Thresholds: $T^x_{CH} = 0.8$, $T^x_{HSR} = 0.5$, $T^x_{LSR} = 0.1$

For sensor 1: CH → Is battery (0.67) ≥ T^x_{CH} (0.8) ? → NO → Reduce to HSR
HSR → Is battery (0.67) ≥ T^x_{HSR} (0.5) ? → YES → Keep it a HSR

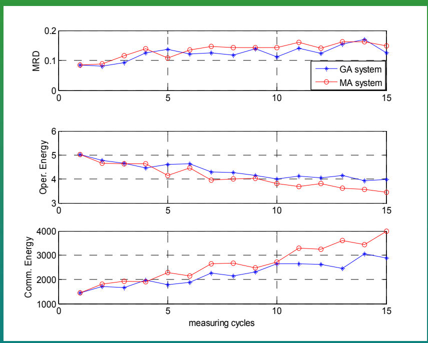
For sensor 2: HSR → Is battery (0.08) ≥ T^x_{HSR} (0.5) ? → NO → Reduce to LSR
LSR → Is battery (0.08) ≥ T^x_{LSR} (0.1) ? → NO → Reduce to inactive.
Inactive → No more checks.

For sensor 3: It's inactive → No check

For sensor 4: CH → Is battery (0.83) ≥ T^x_{CH} (0.8) ? → YES → Keep it a CH

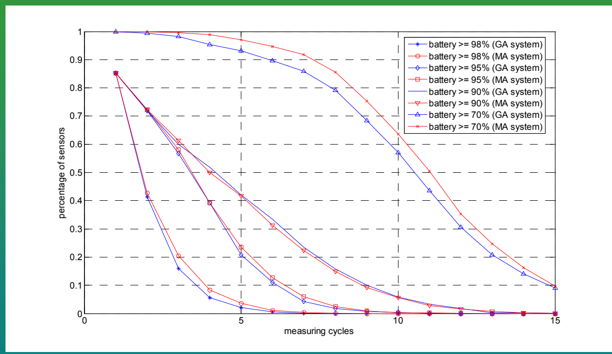
Thus, the **modified individual** of the GA population will be:
| HSR | inactive | inactive | CH |

Network characteristics



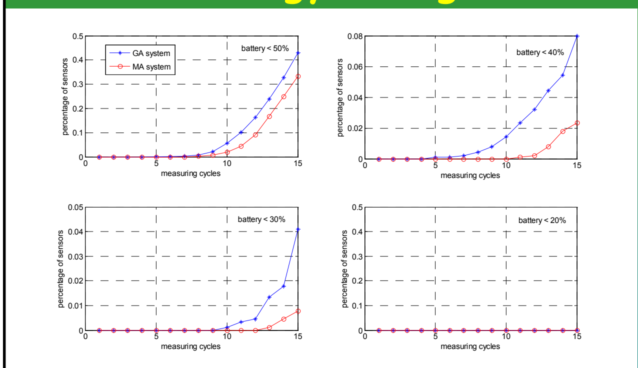
Results: GA vs. MA

Energy saving



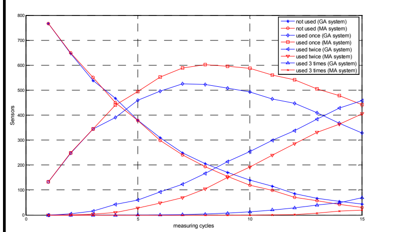
RESULTS: Sensors above specific battery levels

Energy saving

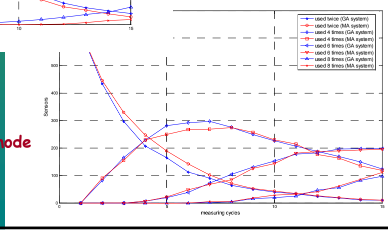


RESULTS: Sensors below specific battery levels

Energy saving



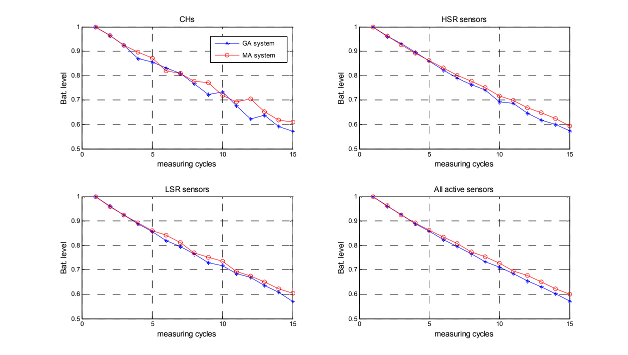
# of sensors used as CHs



# of sensors used in HSR mode

RESULTS:
Usage of available sensors

Energy saving



Conclusions (1) - Middleware

- We proposed the design of a multi-agent middleware to support a novel application for spray control and treatment of the olive fly pest problem.
- The multi-agent design architecture allows agents to cooperate and communicate among themselves, disseminating and/or gathering the sensory data on the WSN.
- The architecture consists of four layers with different types of functionalities. It is open and may adapt future technologies, encapsulating and integrating various modules as agents, by means of communication, with a clearly defined XML schema.

Conclusions (2) - Middleware

- The application integrates many interesting characteristics, such as:
  - the independence of the positioning system,
  - the location model support,
  - the capability of the decision support system,
  - the user friendly environment with multimedia capabilities of the GUI,
  - the flexibility in the development of a new location aware application and services.
- The system provides efficient data dissemination, in cases where sensors are deployed in large areas with limited power.

Conclusions(3) - Optimization

- **The original GA-system managed to:**
  - intelligently decide on sensors' activity/inactivity schedule and rotation of operating modes (CH, HSR, LSR)
  - extend network's life duration
  - keep application-specific properties of the WSN close to optimal values
- **The hybridized MA-system managed to:**
  - perform better exploration of possible solutions during the optimization process
  - achieve better energy conservation of the WSN in comparison with the GA-system
  - keep similar performance with the GA-system as far as the application-specific properties of the WSN are concerned

Future Work (4) - Optimization

- Experimentation and fine tuning of the parameters that could improve even more the performance of the MA:
- Initial values of the battery-level thresholds for each operating mode of the sensors
- The nature of the reduction schemes of those thresholds.

See you all in Athens, Greece

Call for papers

4th HAICTA Conference on ICT in Bio and Earth Sciences

September 18-20, 2008.

Paper submission deadline: April 21, 2008

http://infolab.aua.gr/haicta

Bio-geo-sensing

Publications

- Costas Pontikakos and Theodore A. Tsiligiridis
  A Multi-agent Middleware for Building Location-Aware Services, IEEE Transactions on Network and Service Managements, to appear.
- Costas Pontikakos and Theodore A. Tsiligiridis
  A Middleware for Managing Sensory Information in Pervasive Environments
  in Proceedings of NTMS 2007 Conference, May 2007, Paris (Springer & Verlang publication)
- Konstantinos P. Ferentinos & Theodore A. Tsiligiridis
  A Memetic Algorithm for Dynamic Design of WSNs
  IEEE CEC 2007, 25-28 September 2007, Singapore
- Konstantinos P. Ferentinos & Theodore A. Tsiligiridis
  Evolutionary Design and Energy Optimization of WSNs
  Computer Networks, 51(4): 1031-1051 (2007)
- Konstantinos P. Ferentinos & Theodore A. Tsiligiridis
  Evolutionary Energy Management and Design of WSN
  in Proceedings of IEEE SECON 2005, CA UCLA.