IFIP Open Conference on Metropolitan Area Networks
Architectures, Protocols, Control, and Management
MAN 2005 – Ho Chi Minh City, Vietnam, April 11-13

Wireless Sensor Networks

Architecture, Protocols, Applications

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Work developed with support of Sensornet Project – CNPq Brazil
http://www.sensornet.dcc.ufmg.br

Outline

Wireless Sensor Networks (WSN)

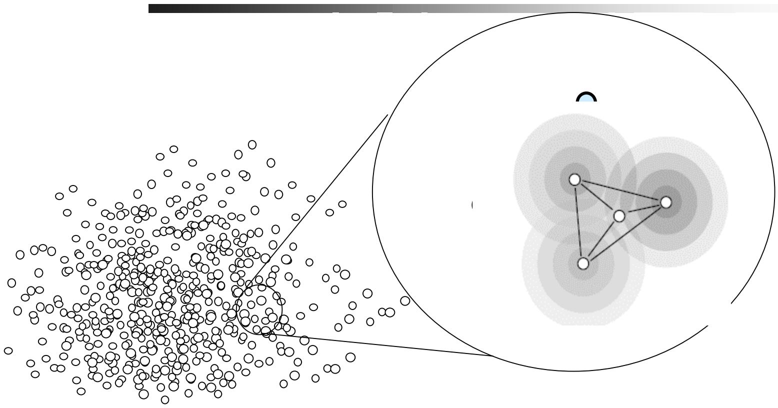
- Introduction
- Application fields and application examples
- Characterization
- Networking sensors and protocols
- Performance comparison and metrics
- Technical challenges
- Taxonomy
- Case study
- Conclusion

Wireless Sensor Networks

- Network of computational elements called **sensor nodes**
- Sensors are equipped with one or more elements capable of capturing (*input*) data from one or many phenomena occurring in a pre-defined physical environment area
- Sensor node has
  - Sensing
  - Processing
  - Wireless communication capabilities

JPL SensorWeb

Wireless Sensors Networks



Wireless Sensors Networks

- Research and commercial interest
  - Web pages hits (Google) by Jan 2005:
    - 220.000 for sensor networks
    - 60.000 for wireless sensor networks
  - A number of dedicated annual workshops (IPSN, EWSN, WSNA,etc) and sessions in conferences (IST, ICC, Globecom, Infocom, VTC, MobiCom, MobiHoc, etc)
  - Research projects funded by north american and others countries agencies
  - NSF workshop on *fundamental research in networking* elected "**sensorized universe**" one out of six grand challenges (2003)

Wireless Sensors Networks

- Today, 99 percent of the sensors are wired
  - Costs
  - Delay in deployment
  - Estimated cost of wiring: $ 40 - $ 2000 per linear foot of wire

Motivation:

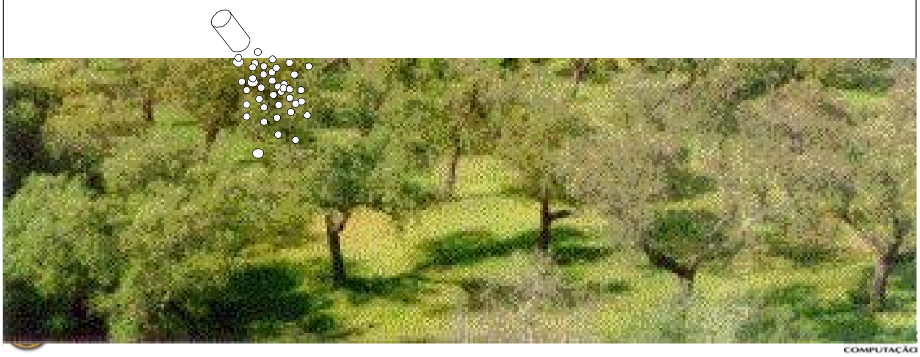
Applications for WSN

Current technology allows sensing parameters such as

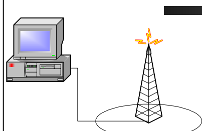
- Temperature
- Pressure
- Humidity
- Luminosity
- Infrared light
- Chemical agents
- Soil composition
- Displacement
- Movement
- Sound
- Images
- Presence
- Electromagnetic field
- Mechanical stress

Wireless Sensors Networks
Applications

Dozens of sensor nodes tied in tree branchs forming a new type of scientific tool: macroscope.

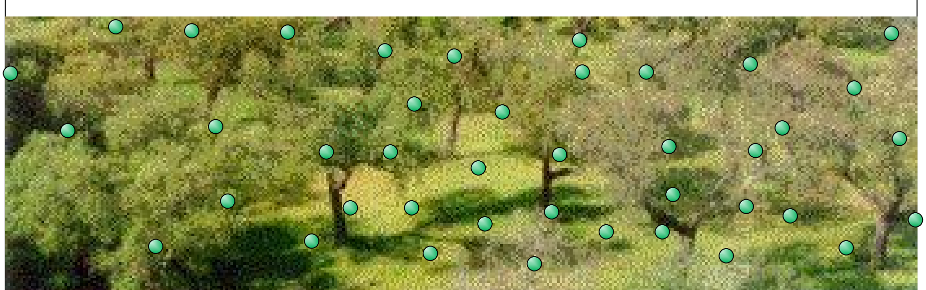


Wireless Sensors Networks
Applications



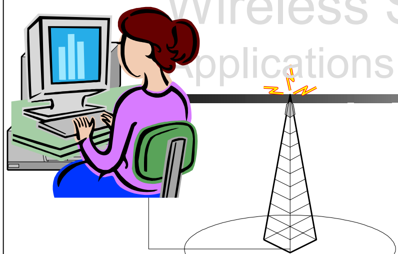
Ability to register microclimate around certains areas.

Wildlife computing.



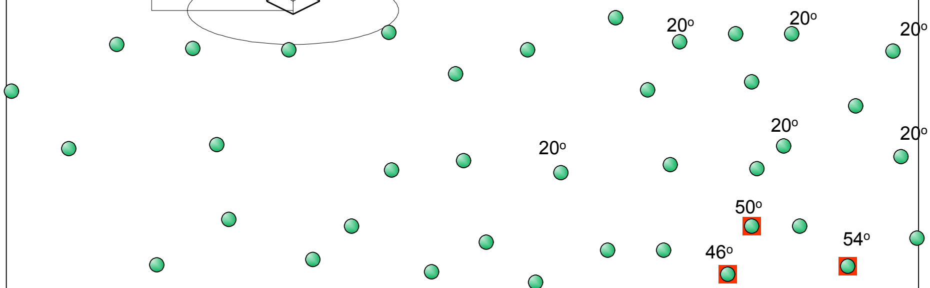
Sensing: temperature, radiation, CO, humidity, aeolian activity ...

Wireless Sensors Networks Applications

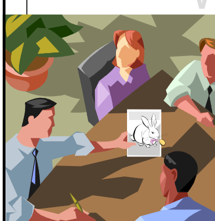


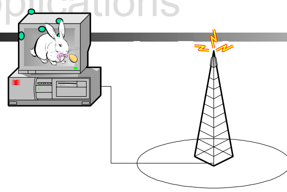
Fire prevention and detection.

Deforestation and invasion prevention.

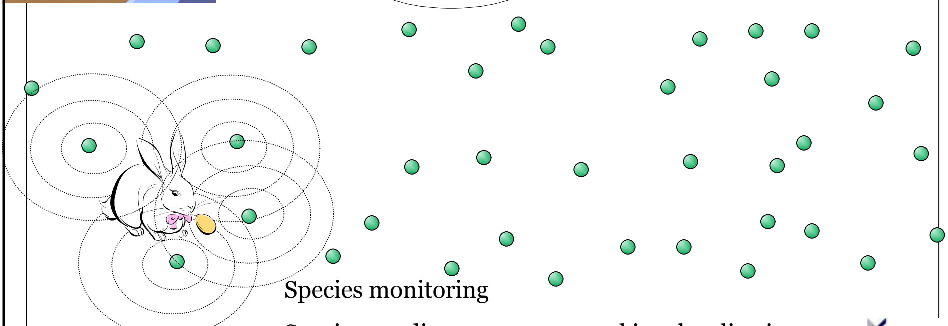


Wireless Sensors Networks Applications





Help biologists and ecologists understand fauna and flora behavior in certain region.



Species monitoring

Sensing: audio, movement, tracking, localization

Wireless Sensors Networks

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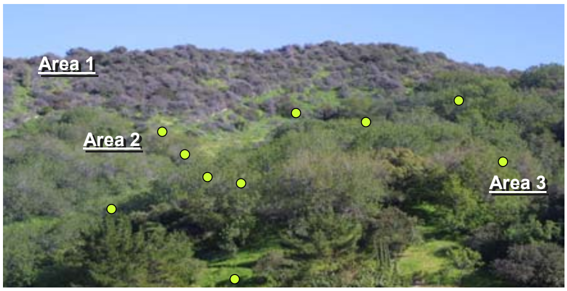


Difficult access areas monitoring

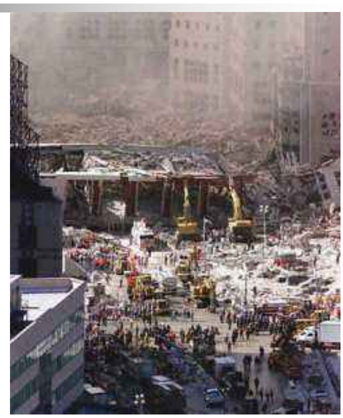
Wireless Sensors Networks

Applications

Air quality monitoring in urban areas.

Noise and traffic monitoring.

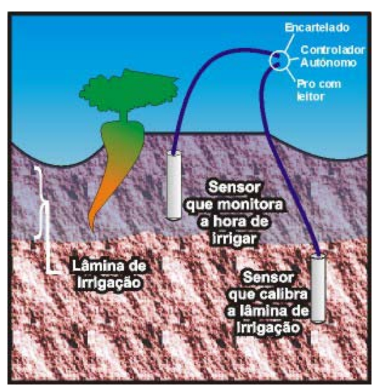
Wireless Sensors Networks
Applications



Wreckage areas

Wireless Sensors Networks
Applications

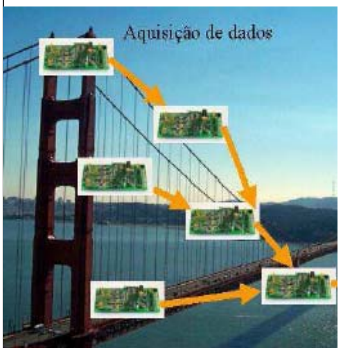
Precision agriculture



Irrigation control – Irrigás Project - Embrapa

Wireless Sensors Networks

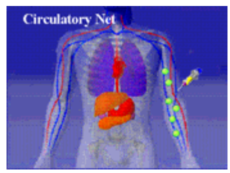
Infra-structure monitoring



Oil platforms

Cable replacement in airplanes and cars

Medicin



Wireless Sensors Networks
Applications

Interplanetary

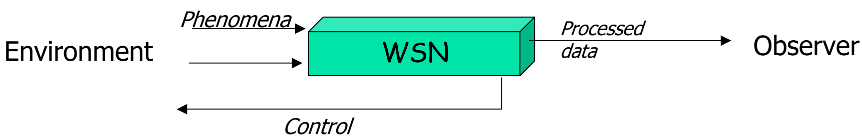
Mobile robotics

Wireless Sensors Networks
Characterization

- A WSN can be composed by sensor nodes only

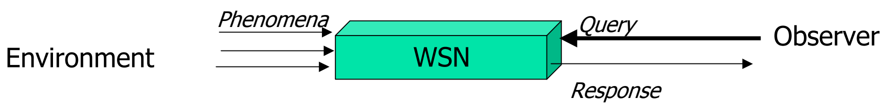
Wireless Sensors Networks

- Sensors + actuators



Wireless Sensors Networks

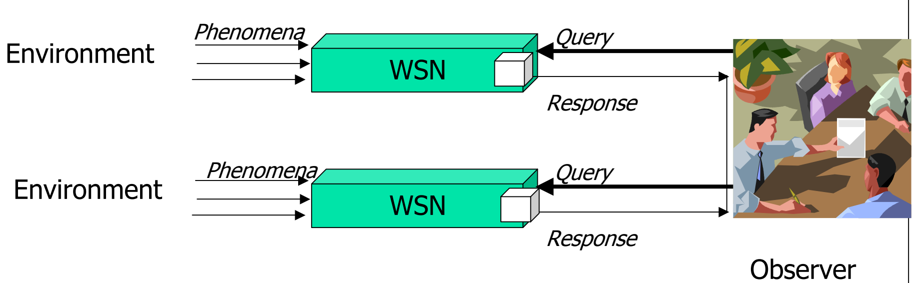
- A WSN can answer to observer's queries.



- The outcome of a WSN can be evaluated by a precision metric
- The input can use fidelity parameters

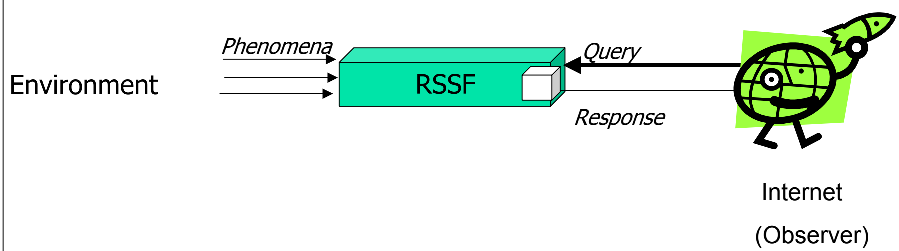
Wireless Sensors Networks

- A WSN can exchange data/information with other WSN



Wireless Sensors Networks

- A WSN can exchange data/information with other networks



Wireless Sensors Networks

- A WSN aims to monitor and, sometimes, to control an environment
- WSNs are expected to operate for periods of time varying from weeks to years in an autonomous way
- WSNs are application dependent

Wireless Sensors Networks

- Some basic features
  - Self-organizing capabilities
  - Short-range broadcast communication and multi-hop routing
  - Dense deployment and cooperative effort of sensor nodes
    - Hundreds or thousands of small dimension devices
  - Frequently changing topology due to fading and node failures
  - Severe limitations in energy capacity, computing power, memory, transmit power

Wireless Sensors Networks
Sensor node hardware - Categories

1. Augmented general-purpose computers
2. Dedicated embedded sensor nodes
3. System-on-chip nodes

Wireless Sensors Networks
Sensor node hardware - Categories

1. Augmented general-purpose computers 1/2

- Low power PCs
- Embedded PCs (e.g.: PC104)
- Custom designed PCs (e.g.: Sensoria Wins NG nodes)
- Various personal digital assitants (PDA)
- Run off-the-shelf operating systems: Win CE, Linux, etc
- Standard communic. Protocols, e.g.: IEEE 802.11, BlueTooth
- Wide variety of sensors
- More power hungry

Wireless Sensors Networks
Sensor node hardware - Categories

1. Augmented general-purpose computers 2/2

- More availability of
  - Networking protocols
  - Popular programming languages
  - Middleware
  - Other off-the-shelf software

Wireless Sensors Networks
Sensor node hardware - Categories

2. Dedicated embedded sensor nodes 1/2

- Commercial off-the-shelf (COTS) chip sets
- Small form factor
- Low power processing and communication
- Simple sensor interfaces

- Examples:
  - Berkeley Mote family
  - UCLA Medusa family
  - MIT μAMP

Wireless Sensors Networks
Sensor node hardware - Categories

2. Dedicated embedded sensor nodes 2/2

- Support of at least one programming language such as C
- Programmers are given full access to the hardware
  - Almost no operating system support
- Example: TinyOS platform and nesC prog. language

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Sensor node hardware - Categories

3. System-on-chip nodes 1/2

- At hardware limits
- Hardware architecture rethougth for sensor nodes at chip design levels
- Examples:
  - Smart dust,
  - BWRC picoradio

Wireless Sensors Networks

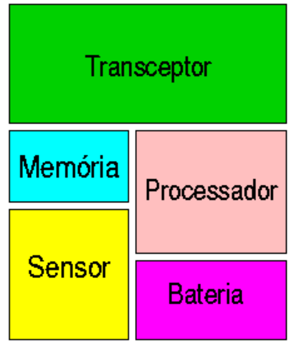
Sensor node hardware - Categories

3. System-on-chip nodes 2/2

- Design goals
  - New ways of integrating CMOS, MEMS, RF technologies
  - Extremely low power and small footprint sensor nodes
  - Providing certain sensing, computational, and communication capabilities
- Research domain, no platforms available

Wireless Sensors Networks
Sensor nodes

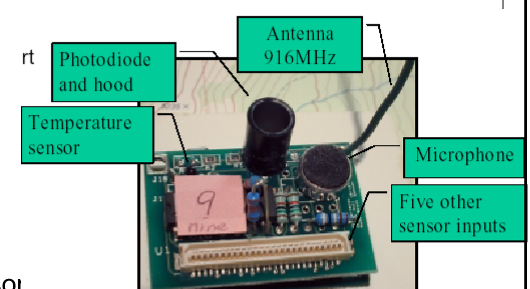
- Transceptor
  - bandwidth 1 to 100 kbps
- Battery
- Processor
  - 8 bits, 4MHz
- Memory
  - ~128 KB
- Sensor
  - pressure, temperature, chemical, image,etc



Wireless Sensors Networks
Sensor nodes

Example: Mica Mote

- CPU:
  - • 8-bit, 4 MHz Atmel processor
  - • No floating-point arithmetic support
- Radio:
  - • 916 MHz RFM @10Kbps
  - • Distance 10-300m
  - • Adjustable strength for RF transmission & reception
- Storage:
  - • 8 KB instruction flash
  - • 512 bytes data RAM
  - • 512 bytes EEPROM (on processor)
- OS:
  - • TinyOS, event driven (3.5KB code space)



- Sensors:
  - • Sensing: light, sound, temperature, cceleration, magnetic field, pressure, humidity, RF signal strength
  - • 10-bit ADC mux'd over 7 analog input channels

Wireless Sensors Networks

- Riding on Moore's law, smart sensors get smaller

Easy to use

HP iPAQ w/802.11

CPU: 240 MIPS
32MB Flash
64MB RAM
Both integrated and off-board sensors

Inexpensive & simple

Crossbow MICA mote

4 MIPS CPU (integer only)
8KB Flash
512B RAM
Sensors: on board stack

Super-cheap & tiny

Smart Dust (in progress)

CPU, Memory: TBD (LESS!)
Sensors: integrated

Wireless Sensors Networks
Sensor nodes

Node	Origin	Radio	CPU	OS
WINS	UCLA	Connexant RDSSS9M 100m	StrongARM SA-1100	microC/OS-II
µAMPS	MIT	LMX3162	StrongARM SA-1100	Red Hat eCos
Mica 2 Mote	Berkeley	CC1000, 300m	ATMEGA128L	TinyOs
BEAN	UFMG	CC1000, 300m	MSP430F169	YATOS

Chipcom, FSK modulation, 300m
Different operating modes

16-bit, 8 MIPS, Texas Instruments
Different operating modes

Table 1.1 Comparison of the four sensor platforms shown in Figure 1.2.

	WINS NG 2.0 Node	iPAQ with 802.11 and A/D Cards in Sleeve	Berkeley MICA Mote*	Smart Dust**
Parts cost*** (quantity 1000+)	$100s	$100s	$10s	<$1
Size (*cm*^{3})	5300	600	40	.002
Weight (*g*) (including battery)	5400	350	70	.002
Battery capacity (*kJ*)	300	35	15	(Less)
Sensors	Off-board	Microphone & light sensors integrated, others off-board	Integrated on PCB: Acceleration, temperature, light, sound	MEMS sensors to be integrated
Memory	32 MB RAM, 32 MB flash	64 MB RAM, 32 MB flash	4 KB RAM, 128 KB flash	(Less)
CPU	Hitachi SH4	StrongARM or XScale	ATmega 103L	(Less powerful)
Operating system	Linux	WinCE or Linux	TinyOS	(smaller)
Processing capability	400 MIPS/ 1.4 GFLOPS	240 MIPS	4 MIPS	(Less)
Radio range	100 m	100 m	30 m	(Shorter)

*The MICA mote is slightly larger than the WeC mote shown in Figure 1.2(c), and is more widely used.
**Smart Dust is not yet fully operational, but the size goal and power sources are known, and cost and weight are estimated.
***Note that the parts cost is based on large-quantity production.

Source: Zhao & Guibas: Wireless Sensor Networks: an information processing approach. Elsevier 2004.

Wireless Sensors Networks

Sensor node software platforms

- Node-centric design methodologies (usually)
  - How a node should behave in the environment
  - Platforms
    - Node-centric operating systems
      - Hardware abstraction of a sensor node to programmers
      - Ex.: TinyOS
    - Language platforms
      - Provide library of components
      - nesC – imperative language, extension of C

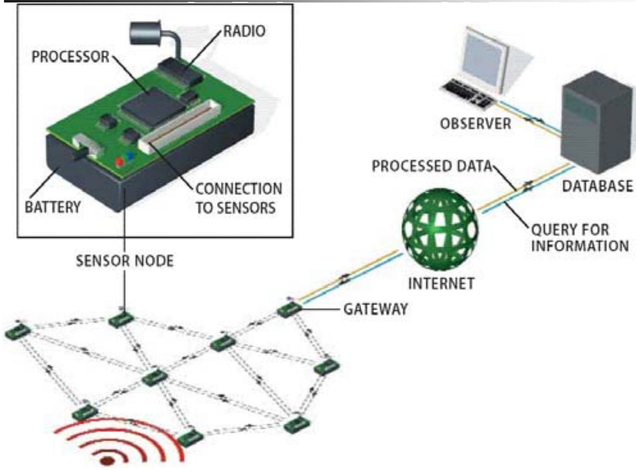
Wireless Sensors Networks
Node-level simulators

- Node-level design methodologies are usally associated with simulation of the behavior of sensor nodes
- Study of the performance
  - timing, power, bandwidth, and scalability
- Components
  - Sensor node model
  - Communication model
  - Physical environment model
  - Statistics and visualization

Wireless Sensors Networks
Node-level simulators

- Types of execution (how the time is advanced)
  - Cycle-drive simulation – CD
  - Discrete-event simulation – DE
- Examples:
  - NS 2 simulator and sensor network extension
  - TOSSIM - dedicated for TinyOS
  - Mannasim – ns 2 extension

Wireless Sensors Networks
Networking



Wireless Sensors Networks
Networking

- Allows geographical distribution of nodes and placement close to signal source
- Effective internode communication is essential for
  - Aggregating data collected,
  - time syncronization,
  - node localization,
  - sensor tasking, etc
- Radio communication: the most expensive operation
- Reality:
  - unstable links,
  - nodes failures,
  - network disconnections

Wireless Sensors Networks
Networking

- Some common assumptions
  - Wireless communication w/ radio links
  - Node talk directly to neighbors within radio range, broadcast
  - Ad hoc deployment, no particular geometry or topology
  - Nodes untethered, limited power resources
  - Mostly with limited or no mobility

Wireless Sensors Networks
Networking

- Distributed sensor net: multi-hop RF advantages

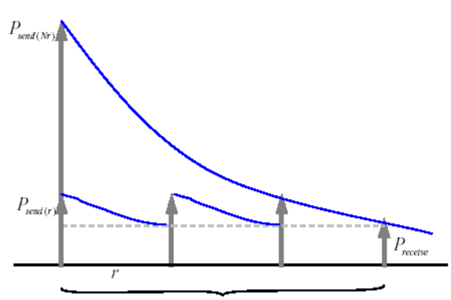
RF power attenuation near ground:

$$P_{receive} \propto \frac{P_{send}}{r^{\alpha}}, \qquad \alpha : 3-5$$

Or equivalently, $P_{send} \propto r^{\alpha} P_{receive}$

Power advantage:

$$\frac{P_{send(Nr)}}{N \cdot P_{send(r)}} = \frac{(Nr)^{\alpha} P_{receive}}{N \cdot r^{\alpha} P_{receive}} = N^{\alpha-1}$$



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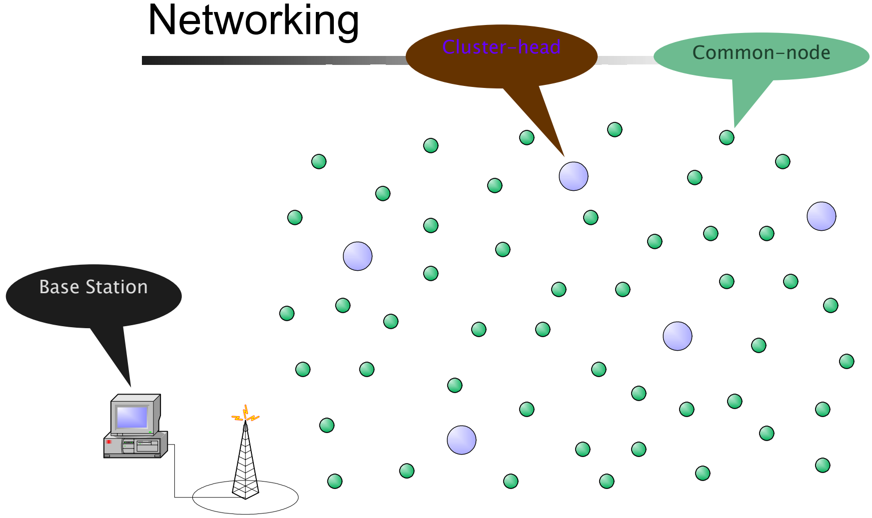
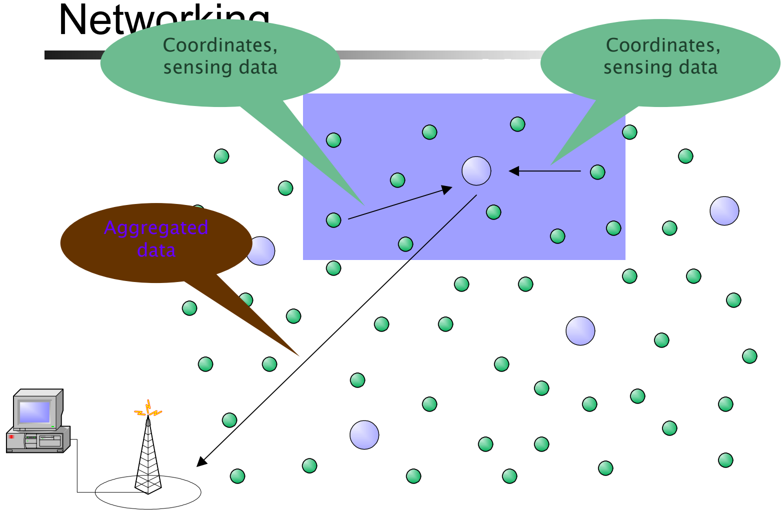
Wireless Sensors Networks

Networking



Wireless Sensors Networks

Networking



Wireless Sensors Networks
Networking

Medium Access Control layer - MAC

- A specialized MAC protocol?
  - Most nodes idle most of the time
  - Occurence of events → concentration of activities → episodic and sporadic processing → potentially large latency
  - In network processing can improve bandwidth utilization
  - Lack of mobility and relatively fixed neighborhood → to be exploited by protocol design
  - Energy efficiency, scalabilitiy, robustness → paramount importance → prolonging network life time
- WSN specific MAC protocols
  - S-MAC (UCLA)
  - IEEE 802.15.4 (low rate personal wireless)

Wireless Sensors Networks
Networking

S-MAC protocol

- Main goal
  - Reduce energy waste caused by listening, collisions, overhearing, control overhead
- Components
  - Periodic listening and sleep
  - Collision avoidance
  - Overhearing avoidance
  - Message passing

Wireless Sensors Networks Networking

- Periodic listening and sleep
  - To reduce consumption, radio off
  - Syncronization of sleep schedules by periodic exchanges of node schedules
- Collision avoidance
  - Similar to DCF for IEEE 802.11 ad hoc mode
  - RTS/CTS
  - Contention: transmisson or sleep
  - Duration field in packets
- Overhearing avoidance
  - Put node to sleep while neighbors are talking
- Message passing
  - Long message fragmented in packets
  - One CTS/RTS exchange

Wireless Sensors Networks Networking

IEEE 802.15.4 and ZigBee

- 802.15.4
  - Physical and MAC layers protocols for remote monitoring/control and WSN applications
- ZigBee
  - Industry consortium to promote IEEE 802.15.4
  - Ensures interoperability
  - High network layers and application interfaces
- Low power, low cost → years on standard batteries
- Low data throughput → up to 115.2 kbps
- Low duty cycle → expected 1% only → very low avg. power consumption

Network layer

- Provides routing and forwarding service
- Many ways to do routing in WSN → efficiency
- Communication typically from source nodes to sink node - *inverted multicast*
- Data related to a common event
  - Potencial data redundancy
- Data fusion and/or aggregation
  - Towards WSN operation optimization
  - In network pre-processing of data

Network layer

- Data centric view and routing
- The big difference!
- Classical separation of content and address no more viable
- What matters is the information and not the nodes themselves
- Nodes are fragile objects that can be destroyed
- Nearby nodes can sense the same information, usually
- Routing decisions based on destination attributes and their relation to attributes of the packet content
  - Node's location, node's type of sensors, certain range of values in a certain type of sensed data

Wireless Sensors Networks
Networking

- Routing modes
  - Geographical
  - Plain
  - Hierarchical
- Addressing modes
  - Spatial
  - Attribute based
  - Transaction based

Wireless Sensors Networks
Networking

Summary of WSN protocols		
Layer	Physical	Radio frequency, optical, infra-red
	Link	S-MAC, 802.15.4, ARC T-MAC, B-MAC,TRAMA
	Network	DD, SPIN, TinyBeaconing, LEACH, GPSR, TBF, etc
	Transport	PFQS, ESRT,RMTS

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Wireless Sensors Networks
Performance comparison and metrics

Since sensor networks are designed for tasks such as detection, tracking, or classification, comparison or measure of performance is only meaningful when it is discussed in the context of these tasks.

Wireless Sensors Networks
Performance comparison and metrics

Detectability:

- How reliably and timely can the system detect a physical stimulus?
  - Measured by sensing coverage, response latency, detection resolution, dynamic range

Accuracy:

- How well does the system detect, localize or track physical stimuli?
  - Typically characterized in terms of
    - tracking errors (e.g., deviation, continuity, smoothness) or
    - detection and classification errors (e.g., false alarms or misses)

Scalability:

- How does a specific property of the system vary as the size of the network, the number of physical stimuli, or the number of active queries increases?

Wireless Sensors Networks
Performance comparison and metrics

Survivability:

- How does the system perform in the presence of node or link failures as wels as malicious attacks?
  - Sometimes also called as robustness
  - Related to fault tolerance

Wireless Sensors Networks
Performance comparison and metrics

Resource usage:

- What is the amount of resource that each task consumes?
  - The resources include energy and bandwidth
  - Related to transport capacity and througput
  - Related to energy efficiency

Wireless Sensors Networks
Technical challenges

Reviewing the fields of application for WSN

General Engineering

- Automotive telematics
- Sensing and maintenance in industrial plants
- Fingertip accelerometer virtual keyboards
- Aircraft drag reduction
- Smart office spaces
- Tracking of goods in retail stores
- Tracking of containers and boxes
- Social studies
- Comm. and res. security

Wireless Sensors Networks
Technical challenges

Agriculture and Environmental Monitoring

- Precision agriculture
- Planetary exploration
- Geophysical monitoring
- Fresh water quality monitoring
- Animal mobility tracking (Zebranet)
- Habitat monitoring (Great Duck Island project)
- Disaster detection

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Wireless Sensors Networks
Technical challenges

- Civil engineering
  - Monitoring of infrastructure
  - Urban planning
  - Disaster recovery
- Health Monitoring and Surgery
  - Medical sensing
  - Micro-surgery
- Military
  - Asset monitoring and management
  - Surveillance and battle-space monitoring
  - Urban warfare
  - Protection (of sensitive objects)
  - Self-healing minefields

Wireless Sensors Networks
Technical challenges

Applications provide ubiquitous opportunities

however

Formidable challenges must be solved before these applications become reality

Wireless Sensors Networks
Technical challenges

- Dense deployment and cooperative effort of sensor nodes
- Frequently changing topology due to fading and node failures
- Limitations in energy capacity, computing power, memory, transmission power

Make sensor networks **different** from other wireless ad hoc or mesh networks

Wireless Sensors Networks
Technical challenges

Ad hoc versus WSN	
Issue	**Difference**
Energy constraints challenge	Similar
Routing challenge	Similar
Traffic patterns	Different
Lifetime requirements	Different
Mobility	Different *

* Mobile ad hoc nodes, static sensor nodes, mobile sensors w/ robots

Wireless Sensors Networks
Technical challenges

Energy consumption: data transmission, signal processing, distributed algorithms, hardware operations

Develpt. of energy-efficient processing techniques

Protocol stack --- Minimize message passing

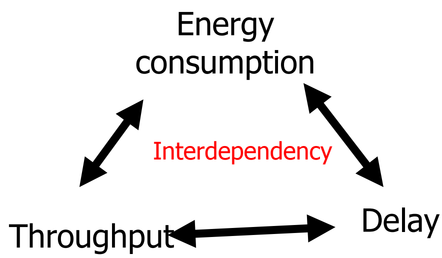
Wireless Sensors Networks
Technical challenges

Most challenging issue

Limited and unrechargeable energy provision

Reserch efforts in improving energy efficiency

Wireless Sensors Networks
Technical challenges



- Metrics tightly coupled → Design trade-offs
- Protocol stack → Cross layer approach instead of layer-by-layer

Wireless Sensors Networks
Technical challenges

- Power supply
  - Batteries (1 J/mm2), capacitors
- Design of energy-efficient protocols
  - Clustering, broadcast and multicast trees
  - Many to one traffic
  - Sleep modes of operation
- Transport capacity and throuput
  - Capability to carry traffic
- Channel access and scheduling
  - Node and system levels

Wireless Sensors Networks
Technical challenges

- Routing
  - In ad hoc: determining and detecting topology changes; maintaining network connectivity; calculating and finding proper rules
  - In WSN: protocols such as
    - *destination sequence distant vector* (DSDV),
    - *temporally-ordered routing algorithm* (TORA),
    - *dynamic source routing* (DSR),
    - and *ad hoc on demand distance vector* (AODV)
    - are not well suited
      - The main type of traffic is "*many-to-one*"
      - Too much control overhead
  - Routing may be associated with data compression to enhance scalability
  - Routing may be associated with security

Wireless Sensors Networks
Technical challenges

- Modeling
  - Tractable models: the basis for analysis and simulation and analytical approaches
    - Number of nodes and relative distribution
    - Degree and type of mobility
    - Characteristics of wireless link
    - Volume of traffic injected
    - Detailed energy consumption
  - Wireless link
  - Energy consumption
  - Node distribution
  - Node mobility
  - Traffic

Wireless Sensors Networks
Technical challenges

- Connectivity
- Quality of service
- Security
- Management
- Implementation
- Etc

Wireless Sensors Networks
Taxonomy

- Classification of WSN depends on its objective and area of application. The application influences directly:
  - Functions executed by network nodes
  - Node architecture
  - Number, disposition and deployment of nodes
  - Protocol stack
  - Routing, addressing
  - Data types
  - Query types
  - Expected network lifetime, etc

Wireless Sensors Networks
Taxonomy

- WSN can be classified based on
  - Configuration
  - Sensing
  - Communication
  - Processing

Wireless Sensors Networks

WSN Configuration		
Composition	Homogeneous	Nodes w/ same hardware capacity. May execute different software.
	Heterogeneous	Nodes w/ different hardware capacity.
Organization	Hierarchical	Nodes organized in clusters. A cluster-head election. Clusters may define hierarchies among themselves.
	Plain	There is no cluster organization.
Mobility	Stationary	Nodes stay where they have been placed initially.
	Mobile	Nodes can move from the place they where deployed.
Density	Balanced	Ideal per unit area node concentration and distribution in accordance to network objective function
	Dense	High node concentration per unit area
	Sparse	Low node concentration per unit area
Distribution	Irregular	Non-uniform node distribution in the monitored area
	Regular	Uniform node distribution in the monitored area

Wireless Sensors Networks

WSN Sensing		
Data acquisition	Periodical	Data acquisition about phenonema at regular intervals. E.g., bird chant sensing only in daylight.
	Continuous	Nodes collect data continuously. E.g., security applications.
	Reative	Nodes collect data when stimuli of interest occur or when queried by an external observer. E.g., object detection.
	Real time	Nodes collect data as much as possible in the less time interval. E.g., applications that involve risk of life such as disaster recovery or wreckage areas.

Wireless Sensors Networks

WSN: Node Communication – part A		
Data dissemination	Programmed	Nodes disseminate data at regular intervals.
	Continuous	Nodes disseminate data continuously.
	On demmand	Nodes disseminate data in response to observer queries or ocurrency of stimuli.
Connection symmetry	Symmetric	The same communication reach for all nodes, except sink node.
	Asymmetric	Different comm. reach for common nodes.
Transmission - duplexity	Simplex	Nodes only transmit .
	Half-duplex	Transmission and reception in different times.
	Full-duplex	Transmission and reception in the same time.

Wireless Sensors Networks

WSN: Node Communication – part B		
Channel allocation	Static	Bandwidth divided in equal parts among "n" nodes – frequency, time, etc
	Dynamic	No fixed division of bandwidth. Nodes contend for the channel.
Inform-ation flow	Flooding	Nodes broadcast data to neighbors that do the same to its neighbors until data reach access point. High overhead but good to dynamic topology changes.
	Multicast	Nodes send data to a selected group of nodes.
	Unicast	Nodes comm. directly with access point but can use multi-hop routing protocols.
	Gossiping	Sensor nodes select nodes to send data.
	Bargaining	Data sent only if is an interest, following a negotiation process.

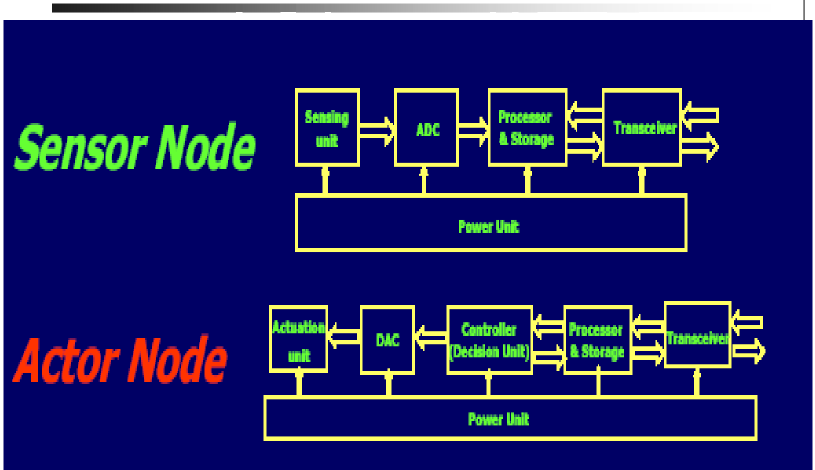
Wireless Sensors Networks

WSN Processing		
Cooperation	Infrastructure centralized	
	Localized or isolated	
	Distributed	

Wireless Sensor and Actor Networks (WSANs)

- Sensors:
  - Passive elements sensing from the environment
  - Limited energy, processing and communication capabilities
- Actors:
  - Active elements acting on the environment
  - Higher processing and communication capabilities
  - Less constrained energy resources (Longer battery life or constant power source)
- Sensors + Actors → WSAN

Wireless Sensor and Actor Networks (WSANs)



WSAN Applications

- Environmental Applications
  - Detecting and extinguishing forest fire
- Microclimate control in buildings
  - In case of very high or low temperature values, trigger the audio alarm actors in that area
- Distributed Robotics & Sensor Network
  - (Mobile) robots dispersed throughout a sensor network
- Battlefield Applications
  - Sensors detect mines or explosive substances
  - Actors annihilate them or function as tanks

Conclusions

- Ubiquitous networked sensors provide a dense spatial and temporal sensing of the physical world
- They potentially provide low-latency access to information that is highly localized in time and space, and thus provide a way to sense and act on the physical world beyond what has been possible up to now

Conclusions

- It is necessary to put togheter tools from a variety of disparate disciplines
  - Signal processing
  - Networking and protocols
  - Database and information management
  - Distributed algorithms

Conclusions

Sensor networks raise many research issues at the physical node level, the system architecture level, and the algorithm deployment

- Secure embedded systems
- Programming models and embedded operating systems
- Management of collaborative groups
- Lightweight signal processing
- Networks of high-data-rate sensors
- Search engines
- Actuators, closing the loop
- Distributed information architecture

“Thank you”

Informations, articles, etc:

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