Wireless Sensor Networks: Introduction and Applications

Lecture #2
Prof. Raj Rajkumar

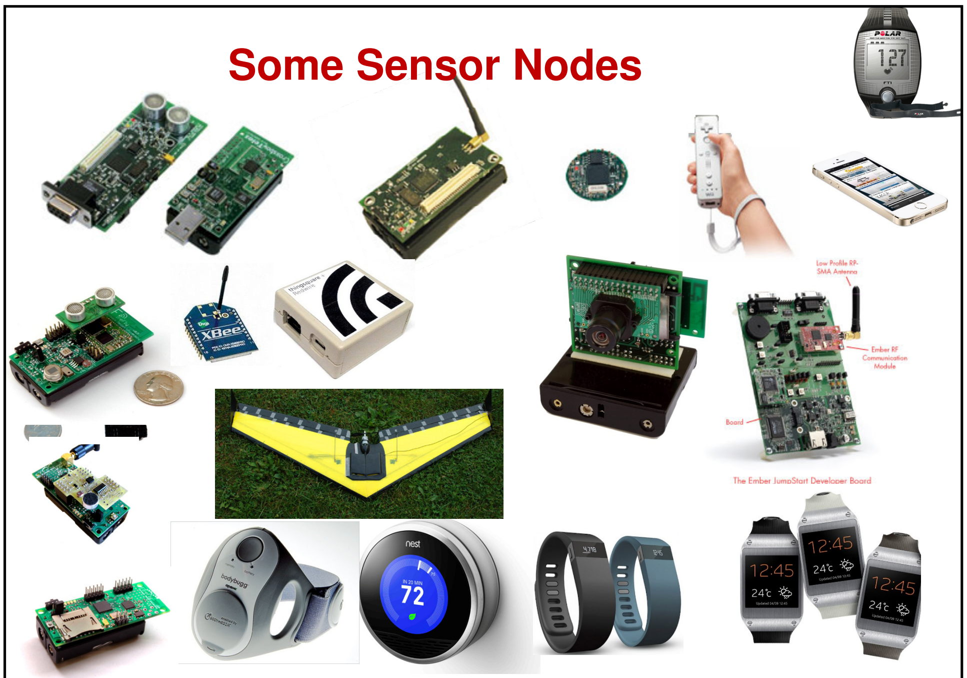
Previous Lecture

- Course Objectives
- Course Personnel
- Grading Criteria
- Course Elements
- Course Logistics

Outline of This Lecture

- Some Sensor Nodes
- Application Domains for WSNs
- Advantages of WSNs
- Taxonomy of WSNs
- Batteries and Energy
- Challenges and Metrics
- Summary

Some Sensor Nodes



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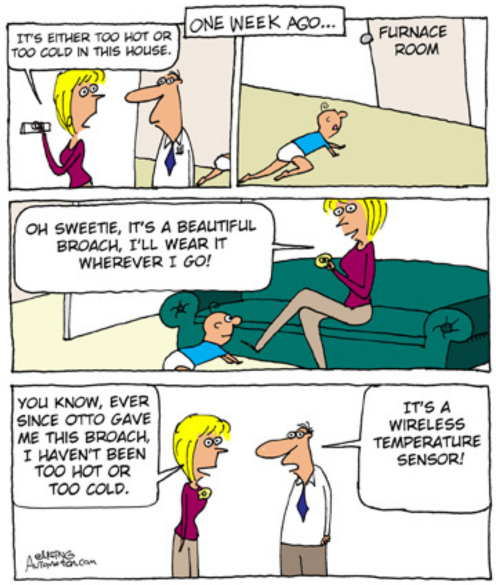
An Opinion Piece on IOE

- "Internet of Everything —A $19 Trillion Opportunity"

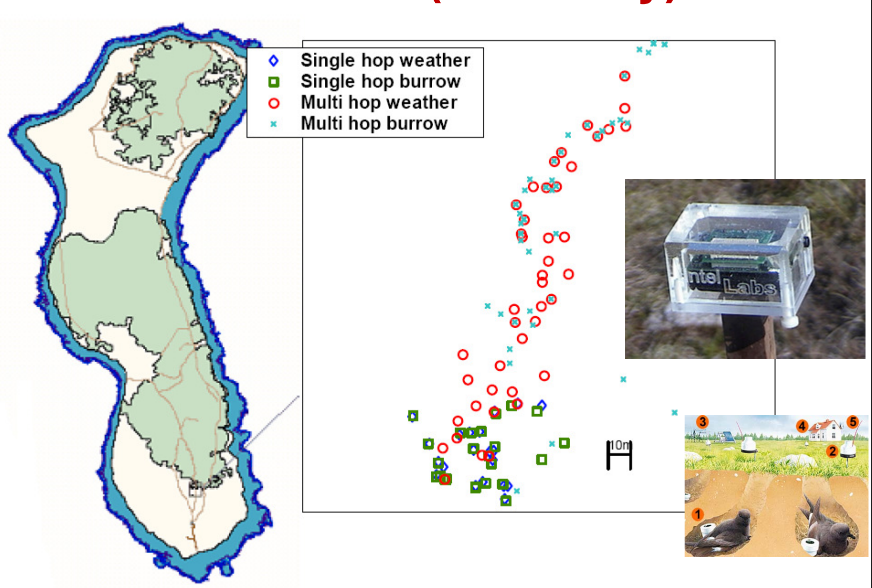
http://www.cisco.com/c/dam/en_us/services/portfolio/consulting-services/documents/consulting-services-capturing-ioe-value-aag.pdf

Thought of the Day



SAMPLE APPLICATIONS

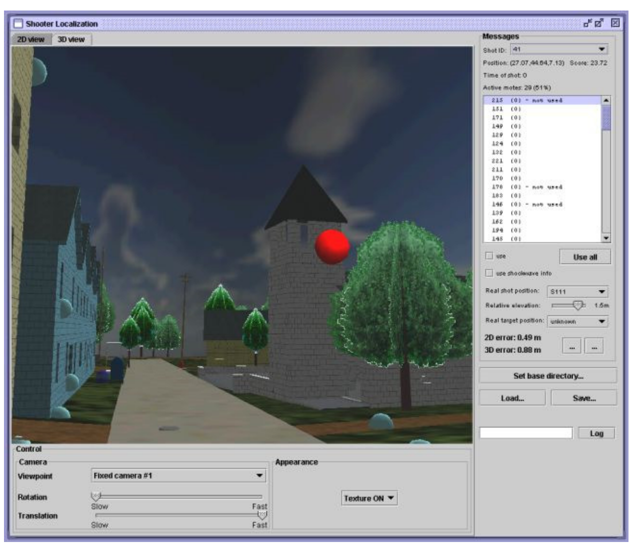
Duck Island (Berkeley)



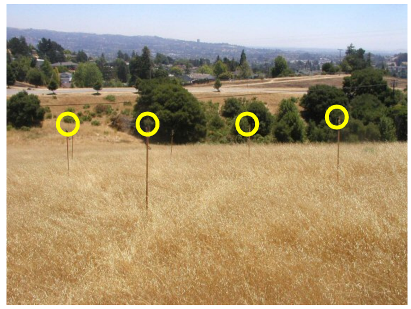
Preventive Maintenance on an Oil Tanker in the North Sea: The BP Experiment

- Collaboration of Intel & BP.
- Sensor networks offer preventive maintenance on board an oil tanker in the North Sea.
- A sensor network deployment onboard the ship.
- System gathered data reliably and recovered from errors when they occurred.
- Recognized as a top 100 IT project.

Shooter Localization (Vanderbilt)

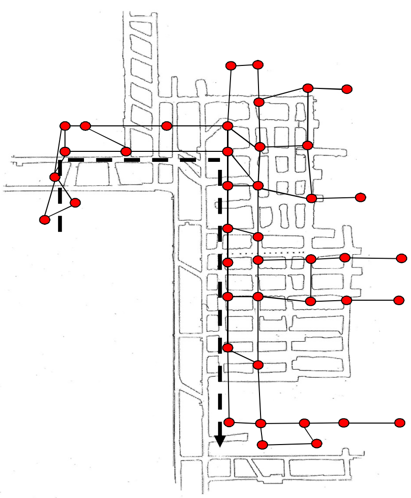


FireBug (Berkeley)

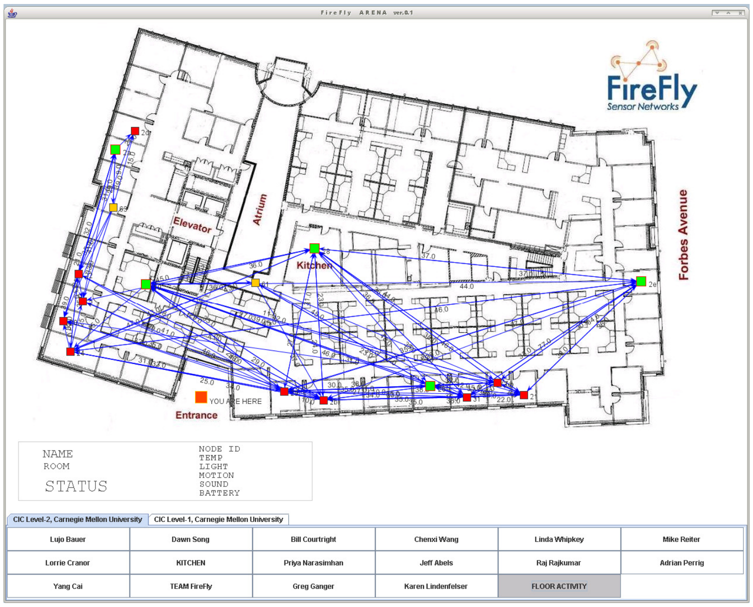


- Wildfire Instrumentation
- Predict evolving fire behavior

CMU: Miner Tracking in Mines



Coal Mine in South Hills Test Deployment

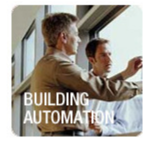


Video

http://www.nsf.gov/news/special_reports/science_nation/eyeonhome.jsp

Sensor Network Applications

- Infrastructure Security
- Environment and Habitat Monitoring
  - Monitoring of hostile work environments
- Industrial Automation
- Building automation
  - HVAC control
  - Energy management
  - Security systems
- Traffic Control
- Health Monitoring
- Waste Monitoring
- Smart Farming and Irrigation
- Asset Management
- Civil Infrastructure Monitoring
- Assisted Living
- Military and aerospace



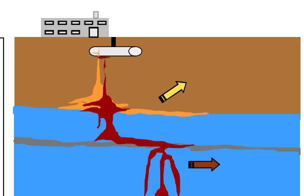
Embedded Networked Sensing Apps

Seismic Structure response

Micro-sensors, on-board processing, wireless interfaces feasible at very small scale--can monitor phenomena “up close”

Enables spatially and temporally dense environmental monitoring

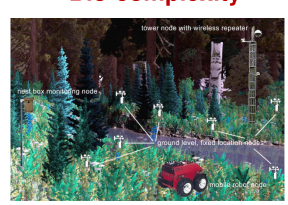
Embedded Networked Sensing will reveal previously unobservable phenomena



Contaminant Transport

Marine Microorganisms

Ecosystems, Bio-complexity



Advantages

- Small size
- (Relatively) low cost of nodes
- Reduce (eliminate?) cost of wiring
- Self-configuring and self-optimizing
- Self-healing
  - Redundancy and fault-tolerance
- Long lifetimes (?)
- Interfacing with the physical world

SENSORS & ACTUATORS

What Can We Sense?

- Sound
  - includes ultrasound, hearing range and sub-sonic
- Motion
- Strain
- Vibration
- Temperature
- Light
- Moisture
- Pressure
- Radio
- Magnetic
- Image
- Video
- …

- Biological agents
- Chemical agents
- Gases
- Fluids
- Solids/metals
- …

Often using
Analog-To-Digital Converters (ADCs)

More on Sensors

- Passive elements: seismic, acoustic, infrared, strain, salinity, humidity, temperature, etc.
- Passive arrays: imagers (visible, IR), bio-chemical
- Active sensors: radar, sonar
  - High energy, in contrast to passive elements
- Technology trend: use of IC, MEMS and (later nano) technologies for increased robustness, lower cost & smaller size
  - COTS adequate in many domains; much to be done for bio-chemical sensing.

What Can We Actuate?

- Turn on/off valves
- Turn on/off switches
- Motor control
- Lights
- Buzzers/Speakers
- Alarms
- E-M radiation
- Chemical triggers
- …

Often using
Digital-to-Analog Converters (DACs)

Think
Wireless Sensor/Actuator Networks

Sensor Network Attributes

Sensors	Size: small (MEMS etc.), large (radars, satellite) Type: passive (seismic) or active (lidar) Coverage: sparse, dense Deployment: stationary, mobile
Sensed Variables	Extent: distributed or localized Mobility: static, dynamic Nature: cooperative (air-traffic) or non-cooperative (military)
Operating Environment	Benign (factory floor) or adverse (battlefield)
Communication	Networking: wired or wireless, single or multi-hop Bandwidth: high or low
Architecture	Centralized, distributed or hybrid
Energy	Very constrained (e.g. in small sensors) or rich source (e.g. radars)

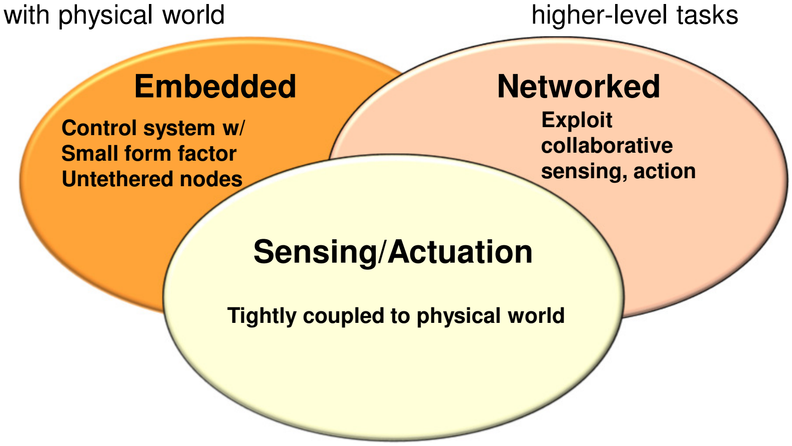
Sensor Network Generations

	Gen 1 (80s-90s)	Gen 2 (1999-2006)	Gen 3 (2010 and beyond)
Manufacturer	Custom contractors, special vendors	Crossbow, Sensoria, Ember	Dust, Inc. …
Size	Large shoe-box ↑	Pack of cards to small shoe box	Dust particle??
Weight	Kilograms	Grams	Negligible??
Node architecture	Separate sensing, processing and communication	Semi-integrated sensing, processing and communication	Fully integrated sensing, processing and communication
Topology	Point-to-point, star	Client-server, peer-to-peer	P2P
(Energy) Lifetime	Large batteries; hours/ days/weeks	AA batteries; days to weeks (months?)	Solar, energy-harvesting, years
Deployment	Vehicle-placed or air-drop single sensors	Hand-emplaced (generally)	Embedded, "sprinkled" or "scattered" leave-behind

WSNs: Enabling Technologies

Embed numerous distributed devices to monitor and interact with physical world

Network devices to coordinate and perform higher-level tasks



Exploit spatial/temporal density, in situ/remote operation, sensing/actuation

ENERGY

What is Energy?

- Energy: A measure of being able to do work.
  - Forms of energy: heat, mechanical, electrical, radiant, chemical, nuclear, …
- Energy is measured in such units as
  - joule (J),
  - erg,
  - kilowatt-hour (kW-hr),
  - kilo-calorie (kcal),
  - foot-pound (ft-lb.),
  - electron-volt (ev), and
  - British thermal unit (BTU).

1 Joule = one watt per second
= 0.737 foot-pounds
= 0.2389 calories
= (1 / 1055) BTU

Energy: State of the Practice

A cubic millimeter of battery space has enough energy to

- send and receive 10 million (10^9) bits of data,
- take 100 million (10^{11}) sensor samples, or
- perform 1 billion (10^{12}) 32-bit computations.

Communication is <u>very</u> expensive.

Energy Consumption Example

For Chipcon 2420 and Atmel32 processor

Power Parameter	Symbol	Current (mA)	Power (mW)
Radio Transmitter	P_{radio_TX}	17.4	52.2
Radio Receiver	P_{radio_RX}	19.7	59.1
Radio Idle	P_{radio_idle}	0.426	1.28
Radio Sleep	P_{radio_sleep}	1e-6	3e-3
CPU Active	P_{CPU_active}	1.1	3.3
CPU Sleep	P_{CPU_sleep}	1e-6	3e-3

Watt: a standard unit of power defined as one Joule of energy transferred or dissipated in one second.

```
Power = Voltage * Current
Power (in watts) = Voltage (in volts) * Current (in amperes)
```

Energy Stored in a AA Battery

- The specific energy ε is defined as the stored energy U per unit mass m.
- AA battery: the voltage is 1.5 V, and the Ampere-hours is (say) 2.5 AHr
- Therefore, the stored energy in the battery is

  U_{AA} = (1.5 V)(2.5 A · Hr)(3600 s) = 14000 Joules
- The diameter of the battery is about 1.5 cm and the length about 6 cm

  → the volume of the battery is roughly 1.1×10^{-5} m^3.
- Therefore, the specific energy of the battery

  ε_{AA} = (14000 J)/(1.1 × 10−5 m3)

  = 1.3×10^9 J/m^3 = 1300 J/cm^3.

Battery Ratings

- Non-rechargeable lithium: 2,880 J/cm^3
- Zinc-air: 3,780 J/cm^3 (has very high leakage)
- Alkaline: 1,190 J/cm^3
- Rechargeable lithium: 1,080 J/cm^3
- Nickel metal hydride (NiMHd): 864 J/cm^3
- Fuel cells (based on methanol): 8,900 J/cm^3
- Hydrocarbon fuels (for use in micro heat engines): 10,500 J/cm^3

More on Batteries

Quantity	Voltage	Group Size	AHr Rating	75% Of Max*	Amps Per Hour
One	12 Volt	24	40 – 85	64 AHs	2 – 4
One	12 Volt	27	85 – 105	80 AHs	4 – 5
One	12 Volt	4 D	140 – 160	120 Ahs	7 – 8
One	12 Volt	8 D	200 – 215	160 AHs	10 – 11
Two	6 Volt	T-105	200 – 225	170 AHs	10 – 11
Two	6 Volt	L-16	325 – 350	260 AHs	16 – 17
Four	6 Volt	T-105	400 – 450	340 AHs	20 - 22

*Battery performance depends on battery age, ambient temperature & state of charge

Source: Duracomm

Energy Harvesting?

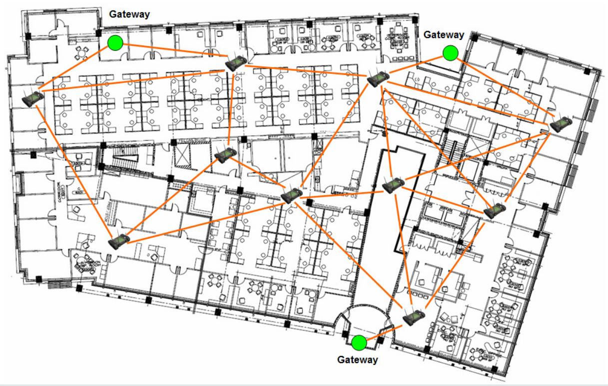
- Solar (outdoors mid-day): 15 mW/cm^2
- Solar (indoor office lighting): > 10 μW/cm^2
- Vibrations (from microwave oven casing): 200 μW/cm^3
- Temperature gradient: 15 μW/cm^3
  - from a 10°C temperature gradient

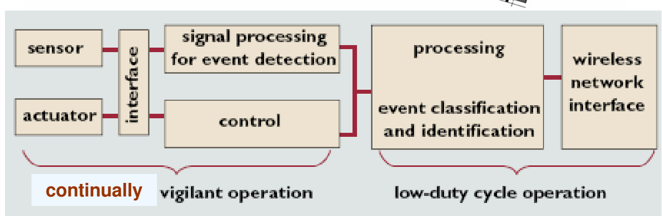
CORE PRINCIPLES

Laws and Principles to Follow

- Propagation laws for communications
  - Think volume:
    - surface area of a sphere of radius $r = 4\pi r^2$
  - Think signal quality
    - **Multipath** effects result from radio signals reaching a receiver by two or more paths (Rayleigh fading)
    - **Attenuation** results from dissipation of energy
    - Frequency shifts from Doppler effect?
  - Think noise
    - Ambient white noise
    - Interference from other electro-magnetic sources
- Physical distribution
- Estimation theory for detection
  - A branch of statistics and signal processing that studies estimating the values of parameters based on measured/empirical data
- Control and hybrid systems theory for control

Example Configuration





Challenges

- Scale
  – Network Control and Routing
  – Collaborative Signal and Information Processing
- Limited access
  – Security
  – Limited energy
- Extreme dynamics
  – Ad-Hoc Network Discovery
  – Tasking and Querying

From Embedded Sensing to Embedded Control

- Embedded in unattended "control systems"
  - control network, and act in environment
- Critical apps extend beyond sensing to control and actuation
  - transportation, precision agriculture, medical monitoring and drug delivery, battlefield apps
  - concerns extend beyond traditional networked systems and apps: usability, reliability, safety
- Need systems architecture to manage interactions
  - current system development: one-off, incrementally tuned, stove-piped
  - repercussions for piece-meal uncoordinated design: insufficient longevity, interoperability, safety, robustness, scaling

Why can we not simply adapt "end-to-end" Internet protocols?

- Internet routes data using IP Addresses in Packets and Lookup tables in routers
  - humans get data by "naming data" to a search engine
  - many levels of indirection between name and IP address
  - embedded, energy-constrained (un-tethered, small-form-factor), unattended systems cannot tolerate communication overhead of indirection
- Special-purpose system function(s): do not want general-purpose functionality designed for elastic applications.

Example Layered Architecture

Resource constraints call for more tightly integrated layers

Open Question:

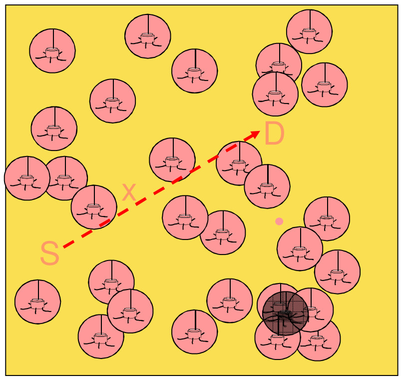
What are defining Architectural Principles?

- User Queries, External Database
- In-network: Application processing, data aggregation, query processing
- Data dissemination, storage, caching
- Adaptive topology, Geo-Routing
- MAC, Time, Location
- Phy: comm, sensing, actuation, SP

Fine-Grained Time and Location

- Unlike the Internet, node time/space location essential for local/collaborative detection
  - fine-grained localization and time synchronization needed to detect events in 3-D space and improve estimation across nodes
- GPS provides solution where available (with differential GPS providing finer granularity)
  - GPS not always available, too “costly,” too bulky
- Localization of sensor nodes has many uses
  - beam-forming for localization of targets and events
  - geographical forwarding
  - geographical addressing

Coverage measures



Given: sensor field (either known sensor locations, or spatial density)

- *Area coverage:* fraction of area covered by sensors
- Detectability: probability that sensors detect moving objects
- Node coverage: fraction of sensors covered by other sensors
- Control:
  - where to add new nodes for max coverage
  - how to move existing nodes for max coverage

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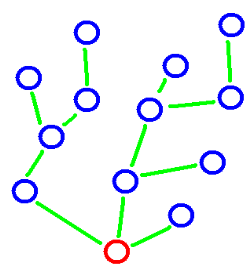
In-Network Processing

- Communication expensive when
  - Limited power
  - Limited bandwidth
- Perform (data) processing in network
  - close to (at) data sources
  - forward fused/synthesized results
  - e.g., find max. of data
- Distributed data, distributed computation



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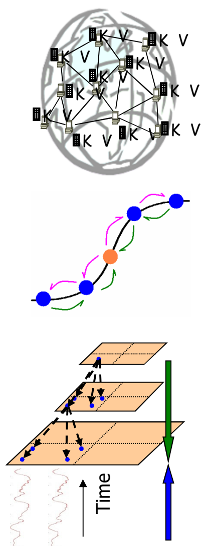
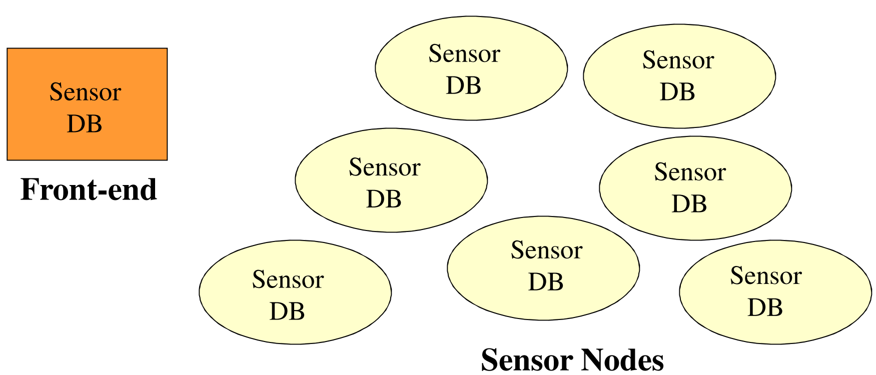
Distributed Representation and Storage



- Data-Centric Protocols, In-network Processing
  - Interpretation of spatially distributed data
    - per-node processing alone is not enough
  - Network does in-network processing based on distribution of data
  - Queries automatically directed towards nodes that maintain relevant/matching data
- Pattern-triggered data collection
  - Multi-resolution data storage and retrieval
  - Distributed edge/feature detection
  - Index data for easy temporal and spatial searching
  - Finding global statistics (e.g., distribution)

Sensor Database System

- Sensor Database System supports distributed query processing over sensor network



Sensor Database System

Characteristics of a Sensor Network:

- Streams of data
- Uncertain data
- Large number of nodes
- Multi-hop network
- No global knowledge about the network
- Node failure and interference is common
- Energy is the scarce resource
- Limited memory
- No administration
- …

Can existing database techniques be reused?

What are the new problems and solutions?

- Representing sensor data
- Representing sensor queries
- Processing query fragments on sensor nodes
- Distributing query fragments
- Adapting to changing network conditions
- Dealing with site and communication failures
- Deploying and Managing a sensor database system

New WSN Paradigms

- Self-configuring systems that adapt to unpredictable environment
  - dynamic, messy (hard to model), environments preclude pre-configured behavior
- Leverage data processing inside the network
  - exploit computation near data to reduce communication
  - collaborative signal processing
  - achieve desired global behavior with localized algorithms (distributed control)
- Long-lived, unattended, un-tethered, low duty-cycle systems
  - energy is a central concern
  - communication primary consumer of scarce energy resource

Summary

- WSNs enable a wide range of new application domains
- Unique features and challenges
- Energy is a <u>big</u> constraint