MONASH University

Information Technology

FIT5183: Mobile and Distributed Computing Systems (MDCS)

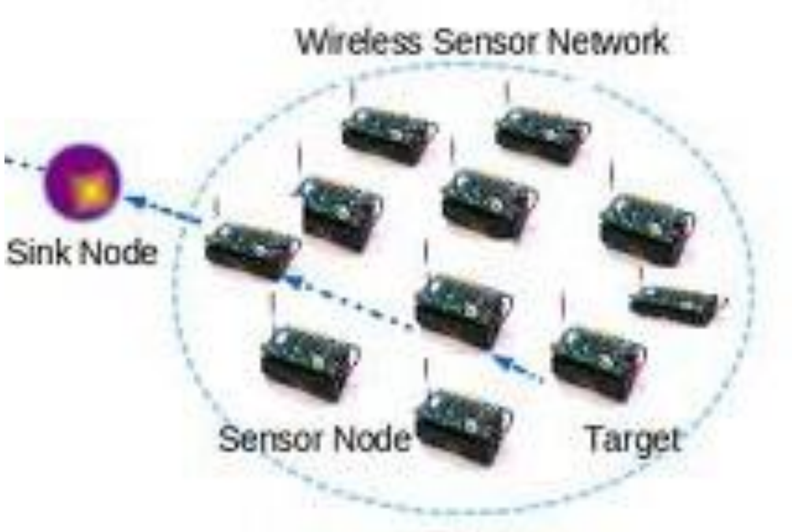
Lecture 9
Wireless Sensor Networks (WSNs)

Overview

- Sensor nodes
- WSN classification and architectures
- Querying sensor nodes and routing
- Applications

Wireless Sensor Networks (WSNs)

- A wireless sensor network is composed of a large number of sensor nodes, which are densely deployed either inside the phenomenon or very close to it
- Sensor networks **allow remote monitoring** of the physical world and are significant for a number of application



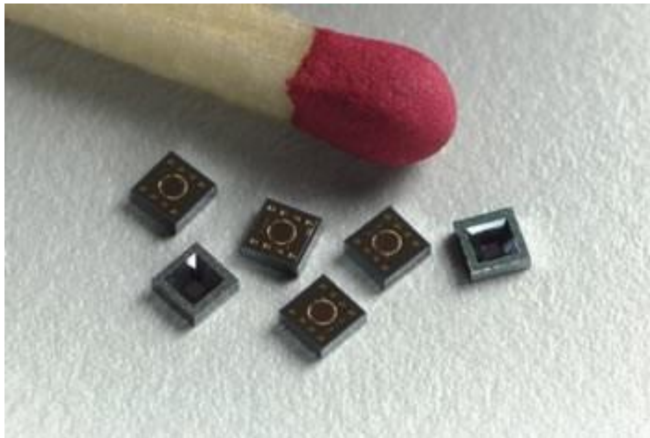
US NRC Definition

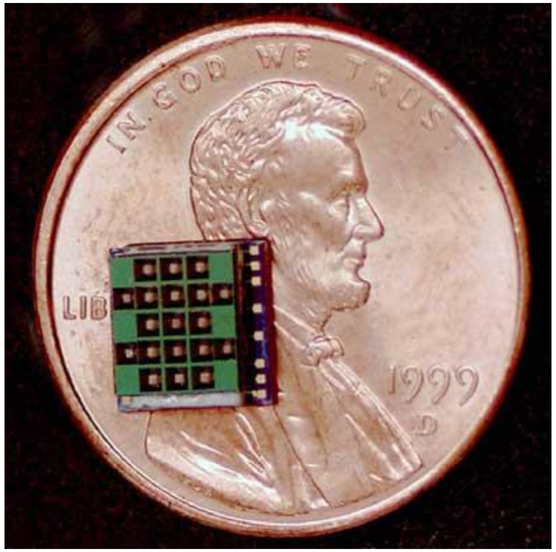
The National Research Council expanded the DARPA definition:

Sensor networks are massive numbers of small, inexpensive, self-powered devices pervasive throughout electrical and mechanical systems and ubiquitous throughout the environment that monitor (i.e., sense) and control (i.e., effect) most aspects of our physical world

Sensor Nodes

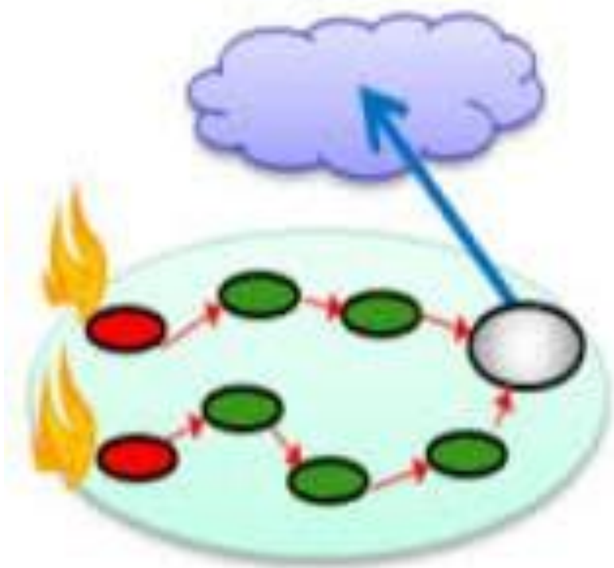
- **Sensor**: converts a physical parameter (i.e. temp) into an electrical or digital output (analogue vs. digital sensors)
- **Actuator**: converts electrical or digital signals into non- electrical output (mechanical/physical motion)





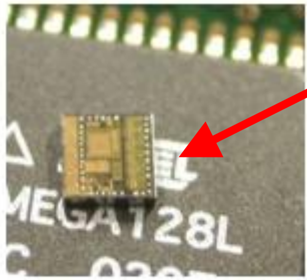
Sensor Nodes

- In WSNs, nodes sense the environment and observe the physical phenomenon
- Nodes communicate the collected information through wireless links (radio)
- Each sensor has the ability to collect and route data
- Nodes have minimal CPU, memory and extremely low power
- Nodes can be stationary or moving
- Nodes can be aware of their location
- Nodes can be homogeneous or not

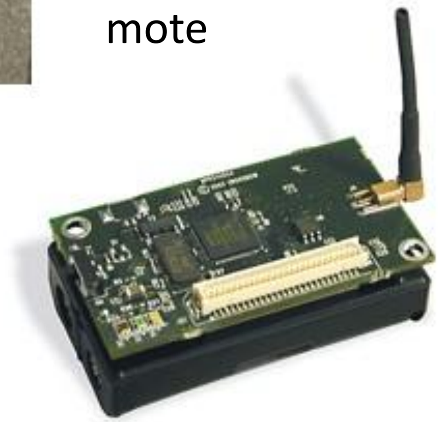


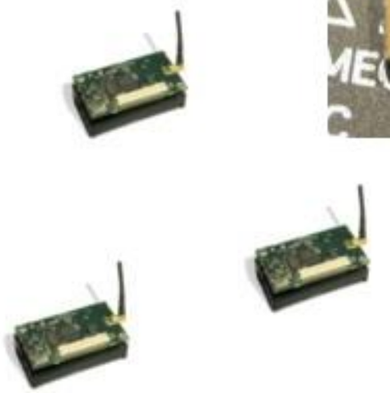
Examples of Sensors

- ❑ Sun SPOT
- ❑ Mica Motes
- ❑ Mulle
- ❑ BTNode



Miniaturised 'Spec' mote sitting on top of previous generation Mica mote





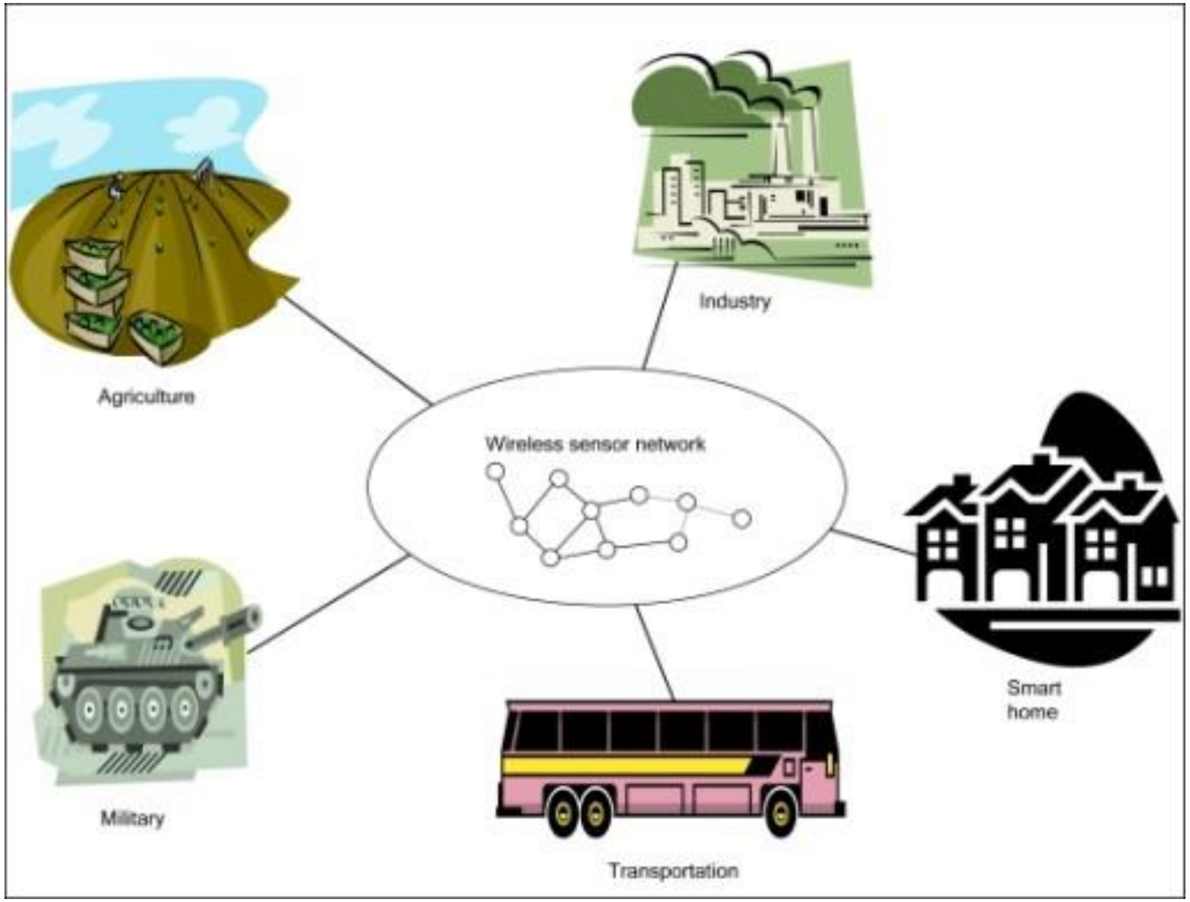
CrossBow MicaZ motes

Sensors

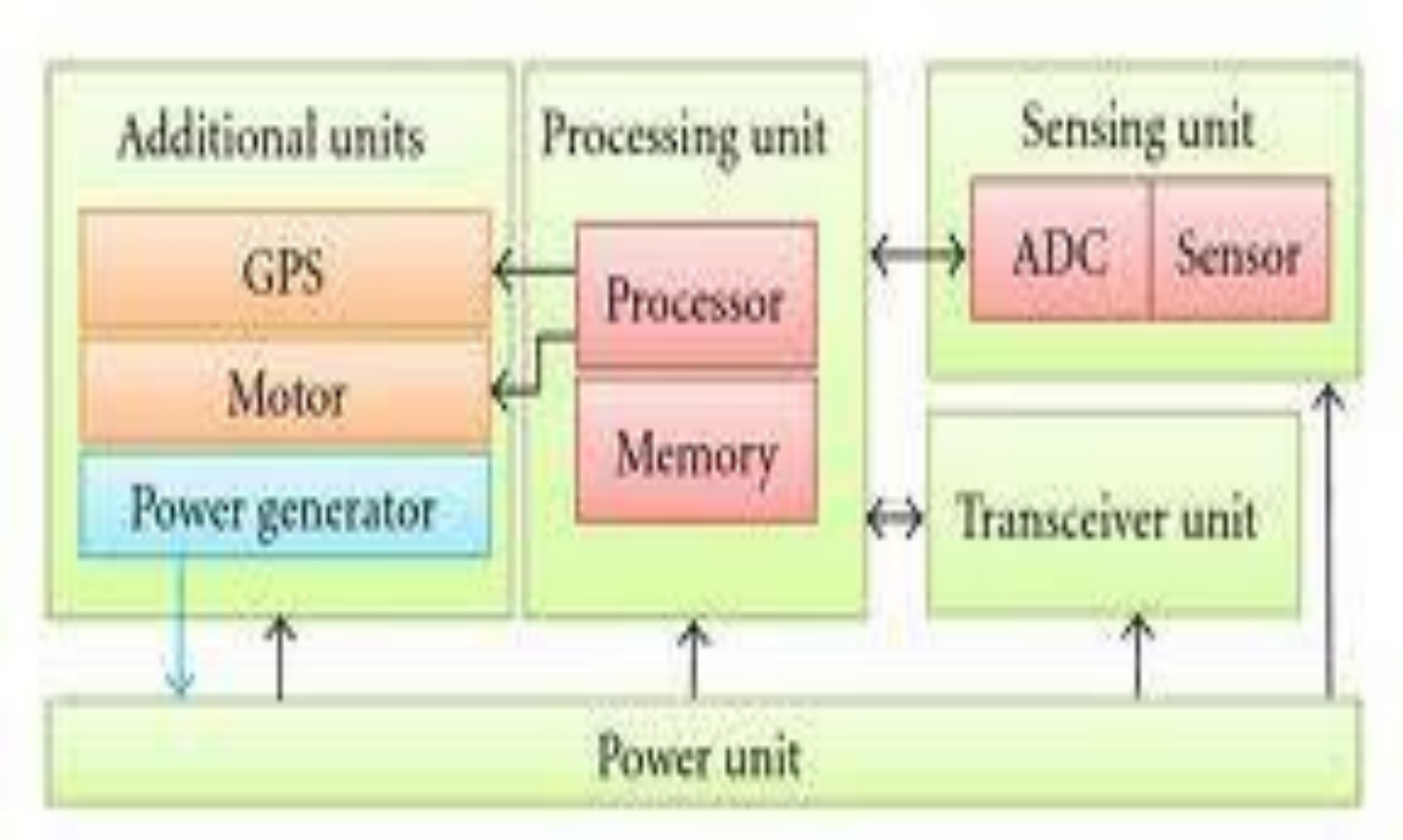
Sensor names	Microcontroller	Memory	Programming	Operating System
Tinynode	Texas Instruments MSP430 microcontroller	8 KB RAM	C	TinyOS
Sun SPOT	ARM 920T 802.15.4	512 KB RAM	Java	Squawk, Java ME Virtual Machine
Mulle	Atmel AT86RF230 802.15.4 / Bluetooth 2.0	32 KB RAM	nesC, C	Contiki, TinyOS
MicaZ	ATMEGA 128 802.15.4/ZigBee	4 KB RAM	nesC	TinyOS, SOS, MantisOS

Types of Sensors

- Light
- Sound
- Temperature
- Humidity
- Pressure
- Wind speed
- Acceleration
- Soil moisture
- Air/water quality
- Seismic



Sensor Node Components



Sensor Components

- A sensing unit:
  - produces a measurable response to a change in a physical condition like temperature
- ADCs (analog-to-digital converter)
- A communication unit (Transceiver):
  - Used to send and receive short range

    radio signals
- Additional components:
  - A global positioning system (GPS) in location aware sensors
  - A motor to move mobile sensor nodes
  - SD cards for storage

Energy Sources

- ❑ Power unit: responsible for supplying energy
- ❑ Battery-powered
  - – Eventually need for battery replacement but difficult in places hard to reach
  - – Require energy management to reduce battery consumption
  - – Battery types: Alkaline, Lithium (AA batteries can last for years)
- ❑ Energy-Harvesting
  - – Extracting energy from the environment and other sources
    - Solar energy
    - Mechanical energy: wind power, water flow, or vibrations
    - Thermal energy

Sensor Operation Modes

- The sensor processor, radio, memory and ADC converter can be in different modes of operations, for example: *Active*, *Hibernate*, *Sleep* and *Deep Sleep*
  - By putting the sensor to sleep you can save battery
  - However, in lowest-energy states processor inactive and will not detect changes (for example temperature sensing for fire-threat monitoring)
  - Sensor **duty cycles** can be varied according to needs and conditions

Sleep States	Processor	Memory	Sensor/ADC	Transceiver
S_0	Active	Active	On	Tx/Rx
S_1	Sleep	Sleep	On	Rx
S_2	Sleep	Sleep	On	Off
S_3	Sleep	Sleep	Off	Off

State Transition

- In WSNs, the transition time for entering and exiting sleep modes differs
- Nodes in deeper sleep consume less energy but it requires higher energy to wake them up

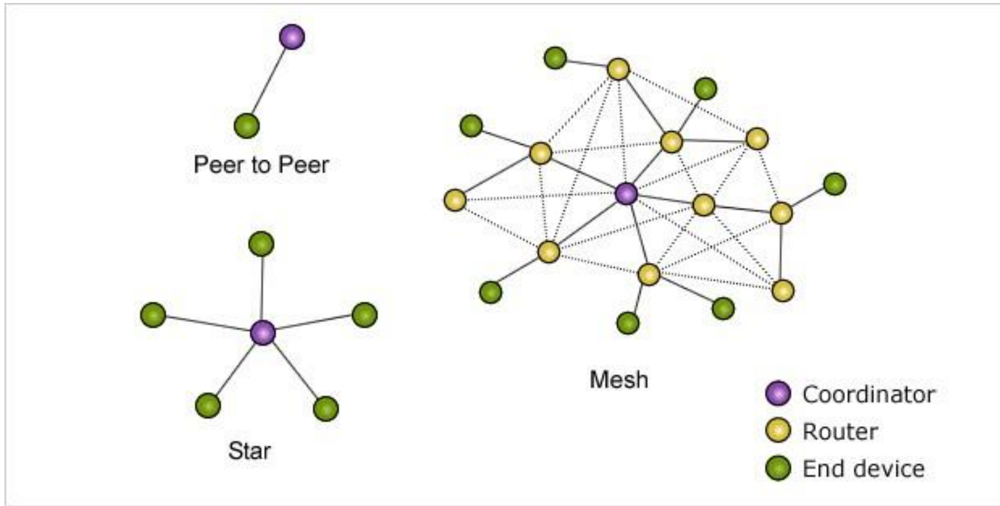
- *The total energy costs = the state energy consumption*

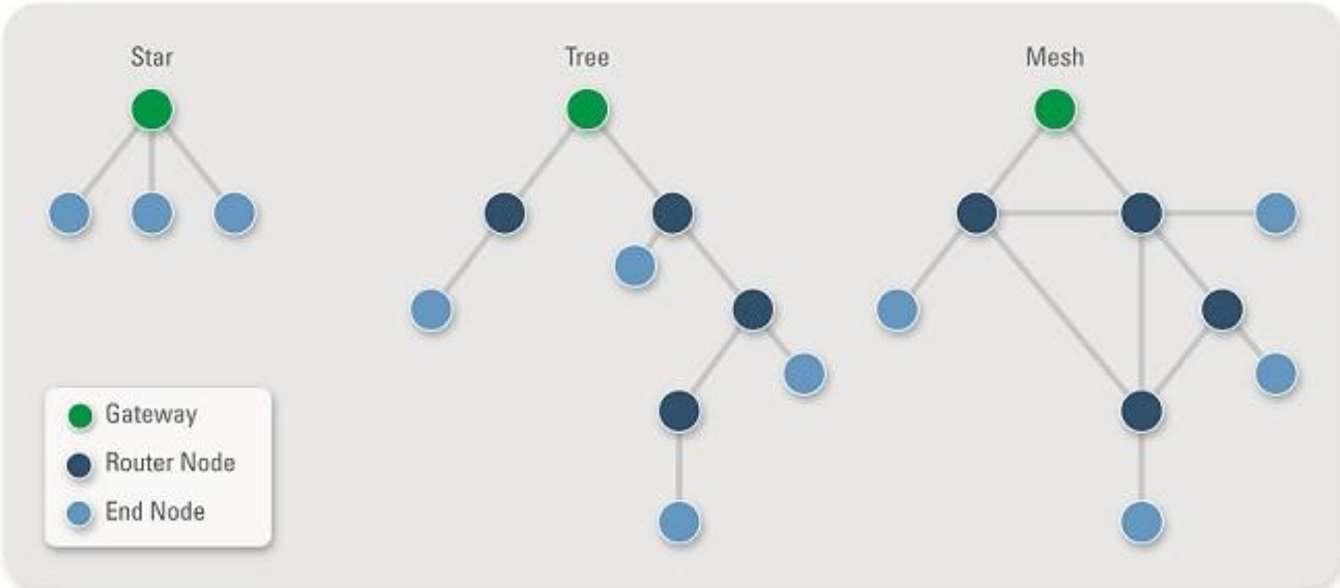
  \+

  *the state **transition** energy consumption*

WSNs Topologies

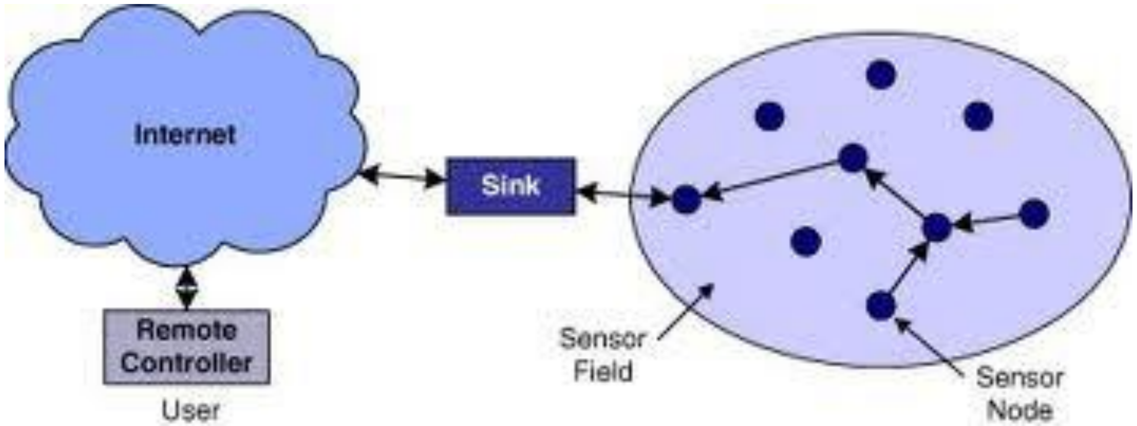
- ➢ Point to Point Topology
- ➢ Star Topology
- ➢ Mesh Topology
- ➢ Tree Topology





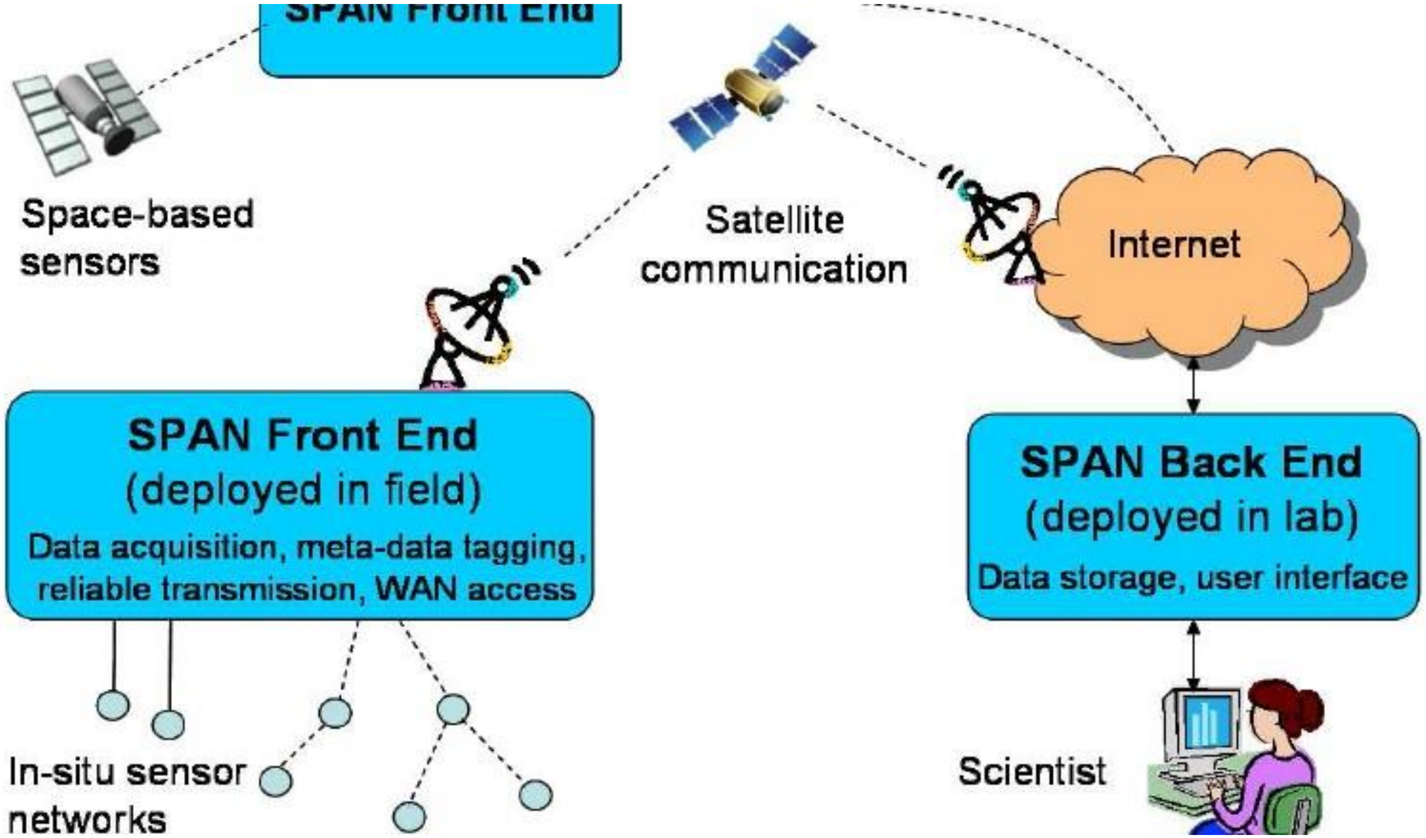
Sink

- Data collected by sensors usually forwarded to a sink
- Unlike sensors, a sink has high resources (memory, CPU, storage, power source)
- A sink can use data locally, **performing simple data processing** OR it can serve as a ***gateway*** for connecting to the Internet (remote sensing)
- It can send queries or commands to nodes while sensors collaborate to accomplish the sensing task and send the sensed data to the sink



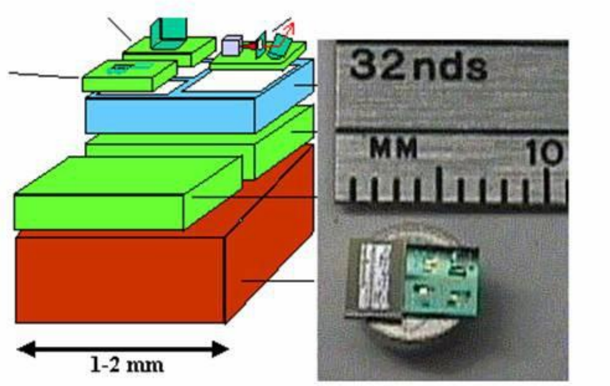
Remote Sensing

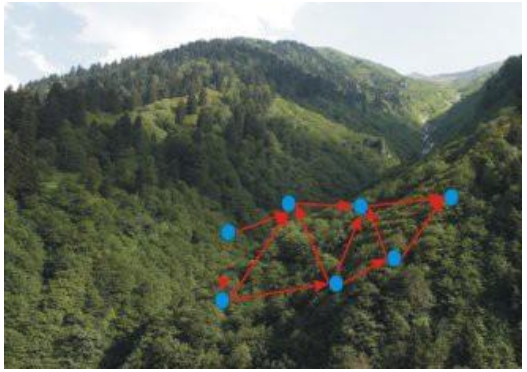
- When there is no cellular coverage or WiMAX in an area, satellite communications would be required



Berkeley’s Smart dust

- One of the pioneering projects in WSNs
- Started in 1990s by University of California, Berkeley and funded by DARPA
- Smart dust refers to a complete sensor/communication system integrated into a **cubic millimeter** package
- Primarily motivation for a military application
- It uses tiny micro electromechanicalsystems (MEMS)
  - MEMs are very small devices with components between 1-100 micrometres with a central processing unit (the microprocessor)





Possible Applications for "Smart Dust"

Defense-related sensor networks

battlefield surveillance, treaty monitoring, transportation monitoring, scud hunting, ...

Virtual Keyboard

Glue a dust mote on each of your fingernails. Accelerometers will sense the orientation and motion of each of your fingertips, and talk to the computer in your watch. QWERTY is the first step to proving the concept, but you can imagine much more useful and creative ways to interface to your computer if it knows where your fingers are: sculpt 3D shapes in virtual clay, play the piano, gesture in sign language and have to computer translate, ...

Combined with a MEMS augmented-reality heads-up display, your entire computer I/O would be invisible to the people around you. Couple that with wireless access and you need never be bored in a meeting again! Surf the web while the boss rambles on and on.

Inventory Control

The carton talks to the box, the box talks to the palette, the palette talks to the truck, and the truck talks to the warehouse, and the truck and the warehouse talk to the internet. Know where your products are and what shape they're in any time, anywhere. Sort of like FedEx tracking on steroids for all products in your production stream from raw materials to delivered goods.

http://robotics.eecs.berkeley.edu/~pister/SmartDust/

Possible Applications for “Smart Dust”

Product quality monitoring

temperature, humidity monitoring of meat, produce, dairy products. Mom, don't buy those Frosted Sugar Bombs, they sat in 80% humidity for two days, they won't be crunchy!

impact, vibration, temp monitoring of consumer electronics.

failure analysis and diagnostic information, e.g. monitoring vibration of bearings for frequency signatures indicating imminent failure (back up that hard drive now!)

Smart office spaces

The Center for the Built Environment has fabulous plans for the office of the future in which environmental conditions are tailored to the desires of every individual. Maybe soon we'll all be wearing temperature, humidity, and environmental comfort sensors sewn into our clothes, continuously talking to our workspaces which will deliver conditions tailored to our needs. No more fighting with your office mates over the thermostat.

The dark side

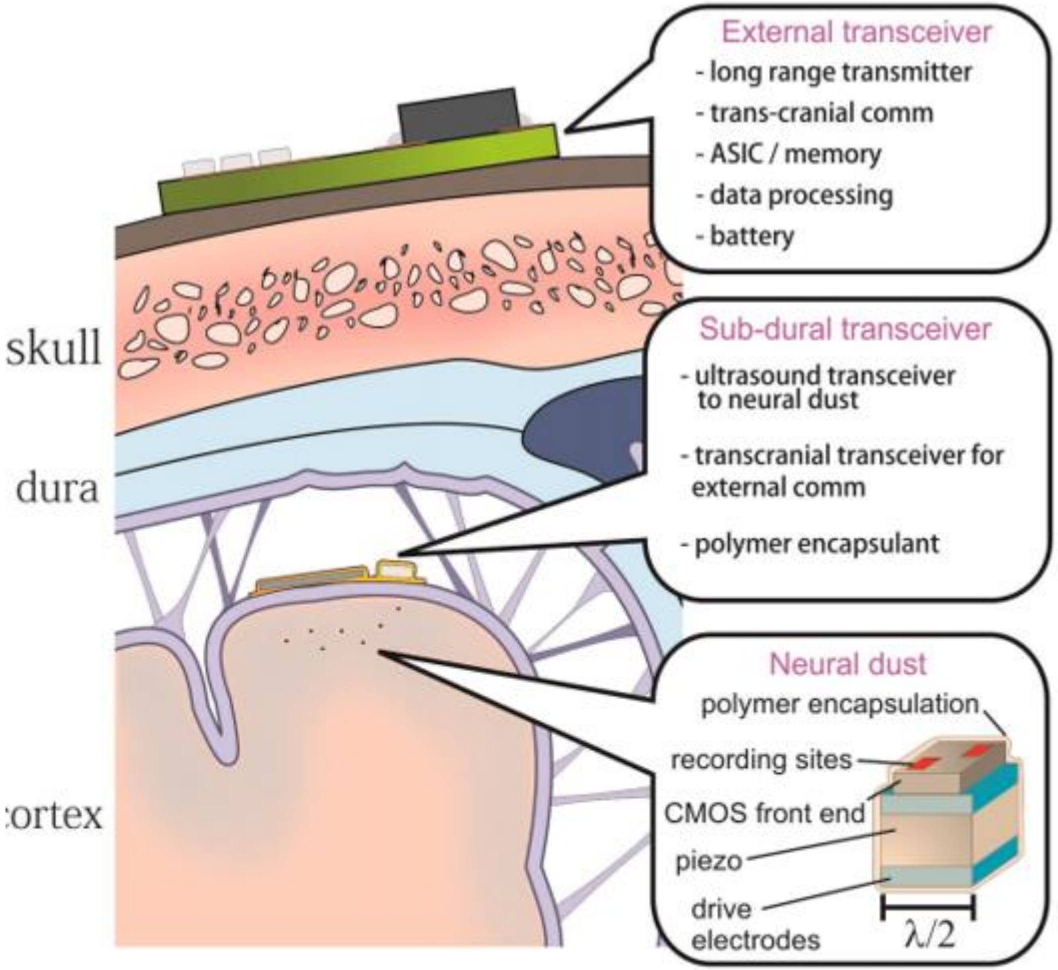
Yes, personal privacy is getting harder and harder to come by. Yes, you can hype Smart Dust as being great for big brother (thank you, New Scientist). Yawn. Every technology has a dark side - deal with it. [this was my original comment on "dark side" issues, but it made a lot of people think that we weren't thinking about these issues at all. Not true.]

As an engineer, or a scientist, or a hair stylist, everyone needs to evaluate what they do in terms of its positive and negative effect. If I thought that the negatives of working on this project were larger than or even comparable to the positives, I wouldn't be working on it. As it turns out, I think that the potential benefits of this technology far far outweigh the risks to personal privacy.

http://robotics.eecs.berkeley.edu/~pister/SmartDust/

Where is this heading: *Neural* Smart Dust?

- We may well see the development of extremely sophisticated Brain Computer Interfaces (BCIs) based on this type of technology in the not too distant future.
- Less invasive concepts for Human Machine Integration (HMI) include gluing smart dust 'motes' equipped with MEMS magnetometers onto fingernails, thereby enabling contactless keyboard, mouse and other gesture based inputs to computing devices.

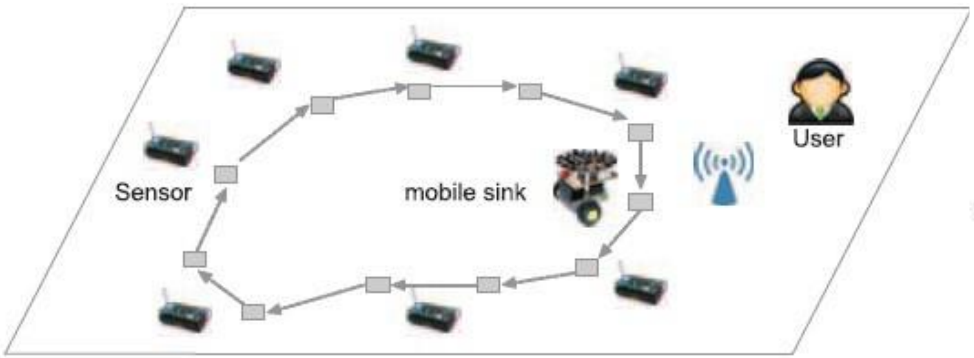


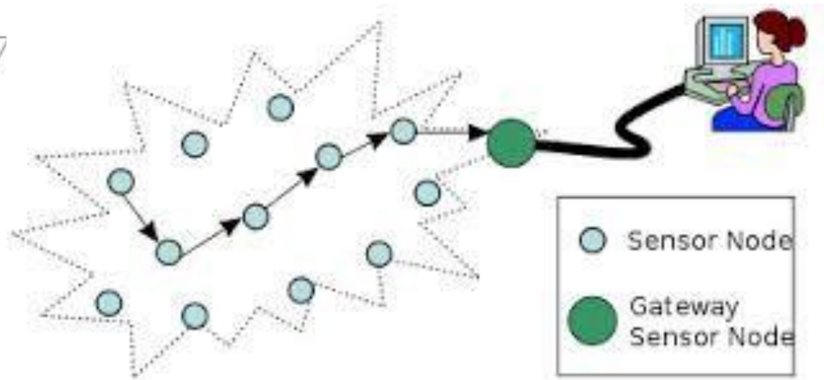
Classification of WSNs

❑ Static-sink and mobile-sink network

– A sink with a fixed position close to the sensing region can cause a **bottleneck** situation, and also closer nodes can die soon

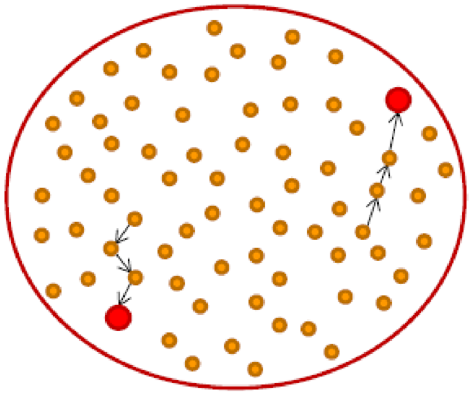
– In the mobile-sink network, the sink moves around the region





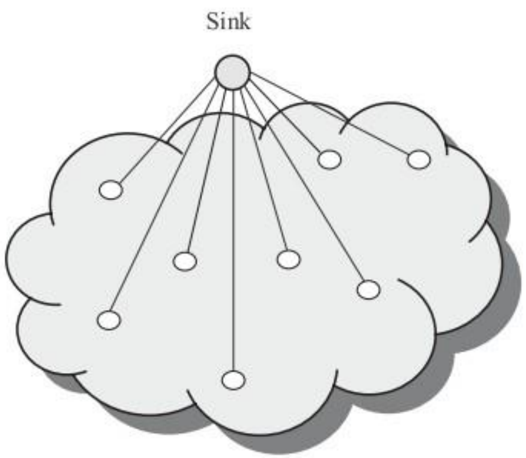
Classification of WSNs

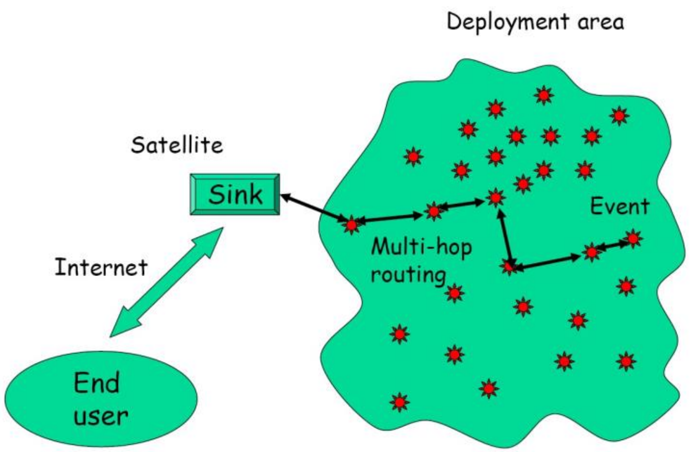
- ❑ Deterministic or non-deterministic network
  - – In deterministic networks, the positions of sensors are preplanned
- ❑ Homogeneous or heterogeneous network
  - – Whether sensors have the same capabilities (energy, computation and storage) or not
- ❑ Single-sink or multi-sink network
  - – In multiple sinks, sensors can send data to the closest sink
  - – Increases complexity and cost but improves performance



Classification of WSNs

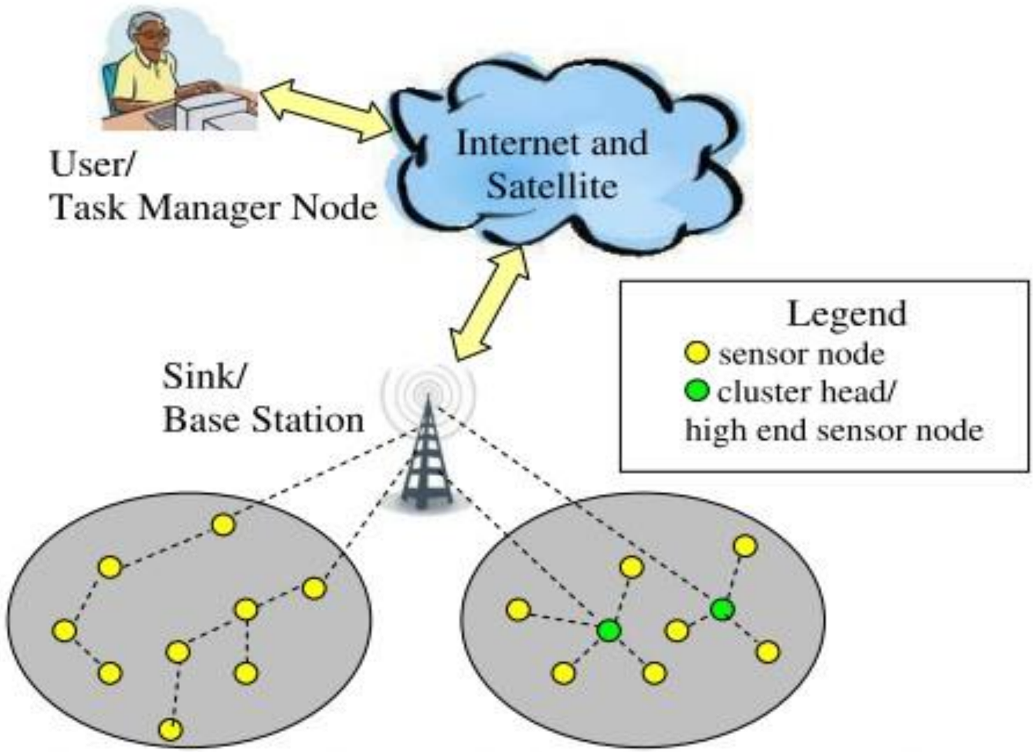
- Single-hop or multi-hop network
  - **Single-hop** transmission: long distance, very expensive in terms of energy (suitable for short coverage) but simpler to control
  - **Multiple hops**: the sensor node transmits its data to the sink via one or more intermediate nodes
    - Short distance, more energy efficient





WSN architectures

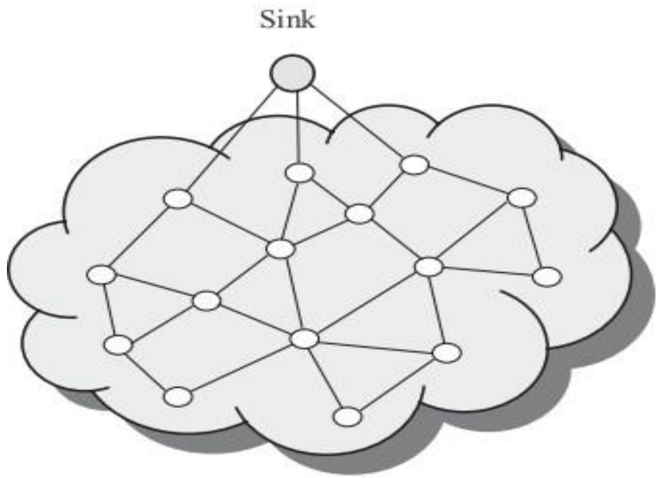
- The multi-hop sensor networks can be divided into two types:
  - Flat sensor network
  - Hierarchical/clustered architecture



(a) Flat sensor network; (b) Clustered sensor network.

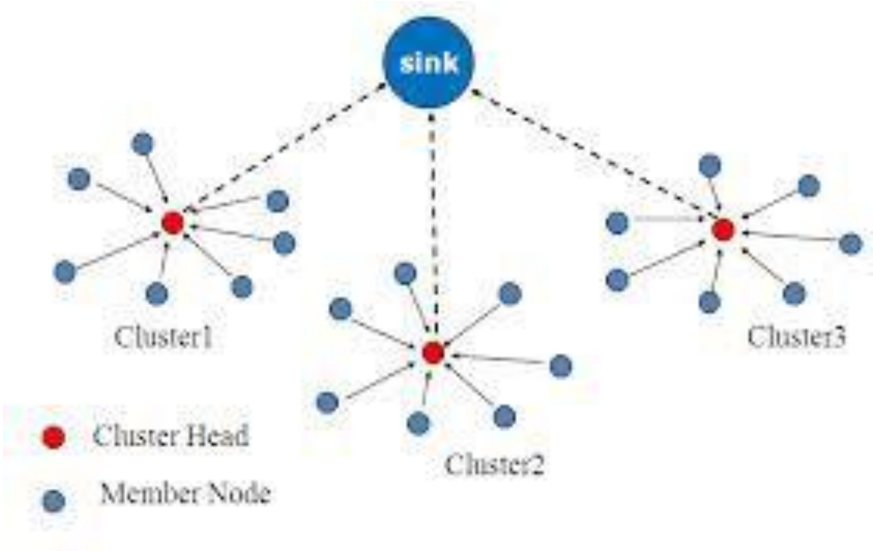
Flat Architecture

- All sensor node have the same role and act as peers
- In such network, the sink usually sends a query to all the nodes and only the nodes that have the data satisfying the query will respond
- In this architecture, the sensor node can act as a router and transfer data to a sink through **multi-hop routing**, using their peers to relay the data



Hierarchical Architecture

- ❑ Sensor nodes are grouped into clusters
- ❑ Each cluster has a **cluster head** (CH)
- ❑ Sensor nodes in each cluster send data to its CH
- ❑ CH performs simple processing and sends processed data to the sink
- ❑ Reduces energy consumption for communication
- ❑ Improves scalability for larger networks and balances traffic load

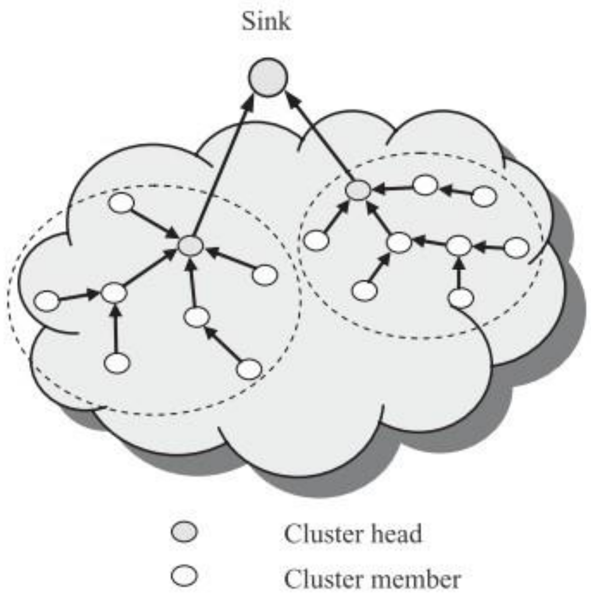


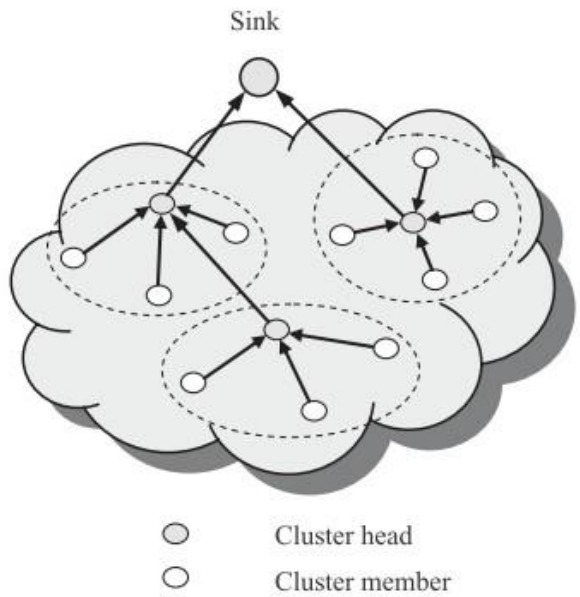
MDCS - WSNs

Clustering

❑ Questions:

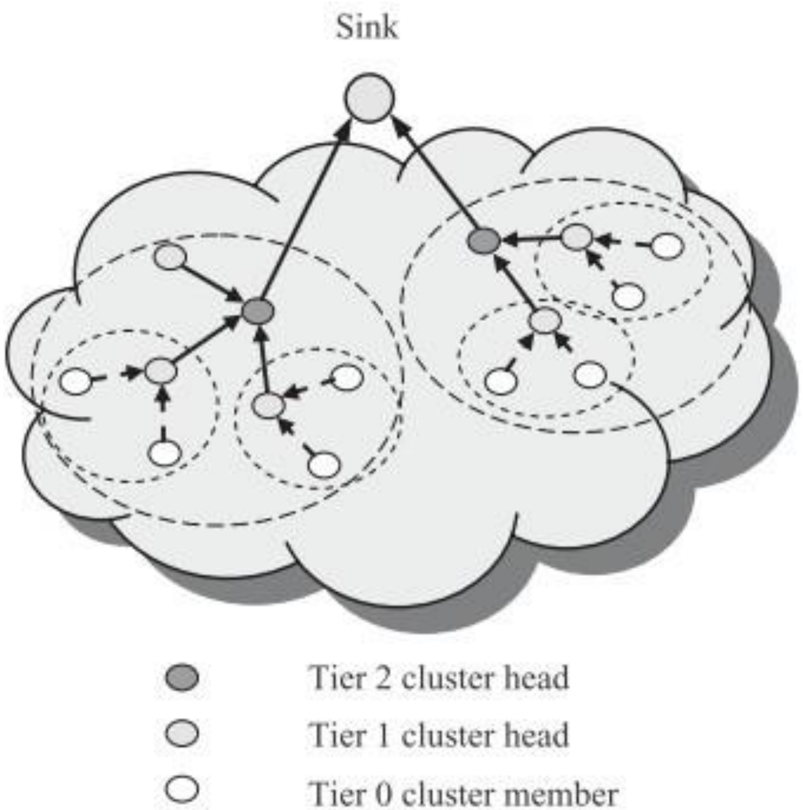
- Single or Multi-hop clustering?
- How to arrange clusters? E.g. based on the distance
- How to select CH? E.g. based on its energy level





Multi-tier clustering architecture

- ❑ A clustered sensor network can be also established as a Multi-tier clustering architecture



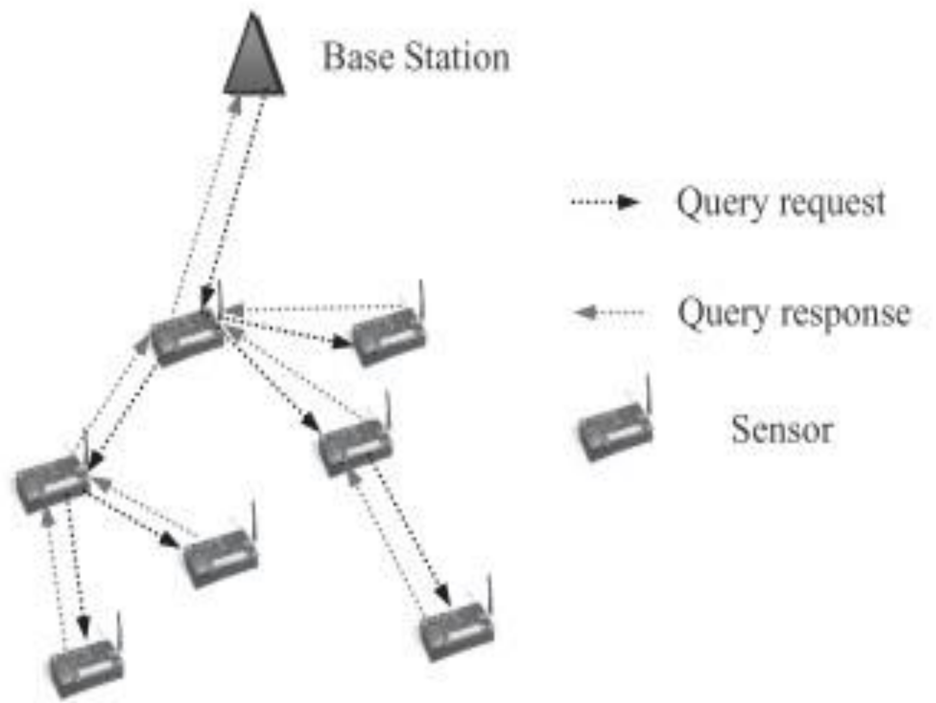
Communication

- Wireless technologies for WSN:
    - IEEE 802.15.4 ZigBee
    - 802.15.1 (Bluetooth)
    - WiFi

- Other communication options for remote monitoring:
    - 3G and 4G
    - Satellite communication

Querying Sensor Nodes

- ❑ Query Request: includes a query from the BS to the sensor nodes in a region of interest
- ❑ Query Response: carries a query answer back to the BS

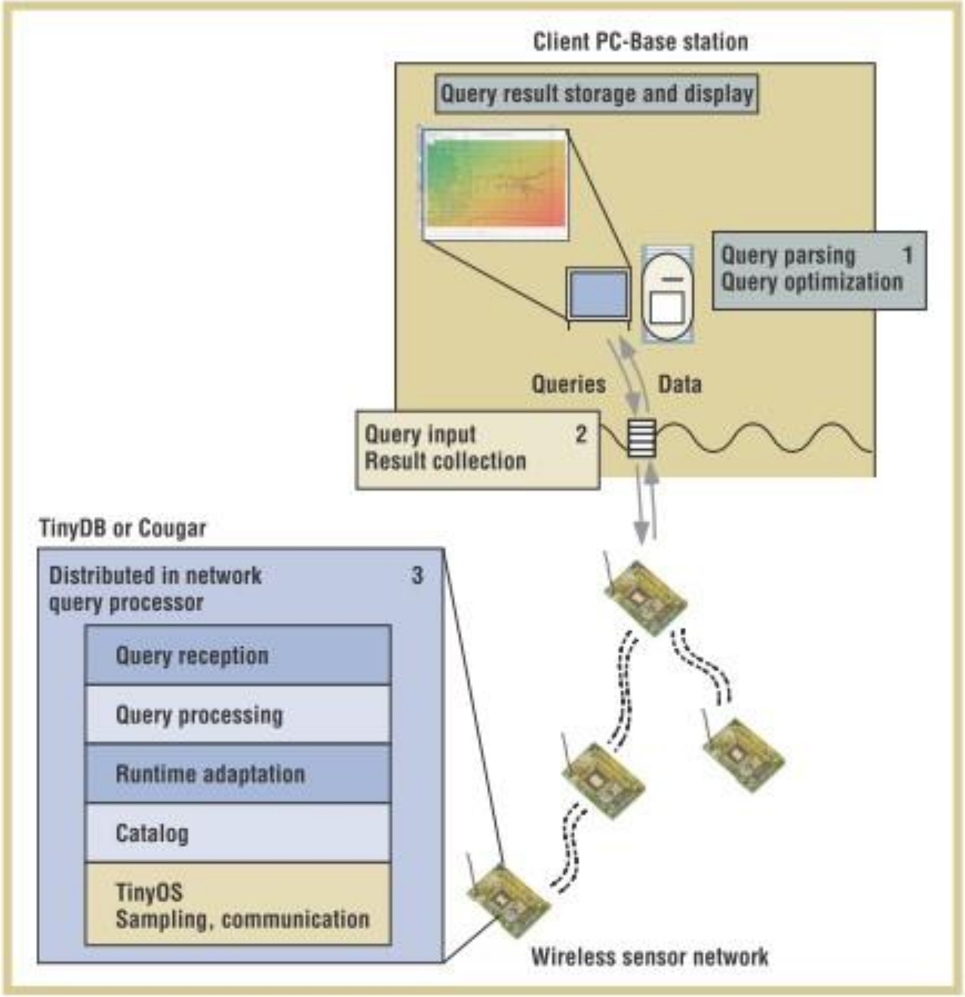


Query Processing Systems

- Queries can support operations like join, projection, aggregation, and grouping
- Queries in Cougar and TinyDB similar to an SQL query:
  - SELECT - FROM - WHERE – GROUP BY HAVING
- Queries in Corona (a query processing system for Sun SPOT)
  - E.g. SELECT temperature FROM sensors WHERE light > 100 FRESHNESS 10s

TinyDB

- ❑ TinyDB is a query processing system for managing data from TinyOS sensors
- ❑ It provides a simple, SQL-like interface
- ❑ E.g. SELECT nodeid, light, temp, FROM sensors, SAMPLE PERIOD 1s (interval) FOR 10s (duration)



Query Categories: Classifying queries based on frequency of responses

- **Historical query**: used for analysis of historical data stored at a remote BS or any specific node
  - What was the temperature 24 hours ago?
- **One-Time/snapshot Query**: provides an instantaneous view of the network
  - What is the temperature now?
- **Persistent/continuous Query**: used to monitor a network for a continuous period of time
  - Collect the temperature for the next 2 hours with 1 sec interval
- **Event-driven Query**: data is transmitted when event occurs
  - On Event (wind>5m/s) around boundary (80,40) collect temperature

Spatial and Temporal Queries

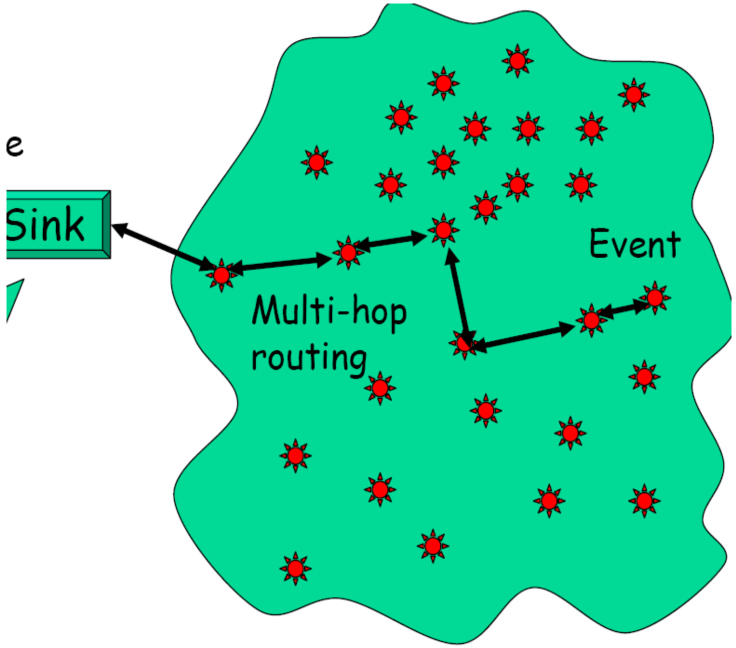
- **Spatial Query**: for a particular attribute value occurring in a given space of interest.
  - E.g. SELECT attr_val FROM sensor WHERE loc=[−200,200,400,600]

- **Temporal Query**: for a particular attribute value occurring during a specified period of time.
  - E.g. SELECT attr_val FROM sensor WHERE time=6:50am – 2:30 am

- **Spatio-Temporal Query**: combines both spatial and temporal queries

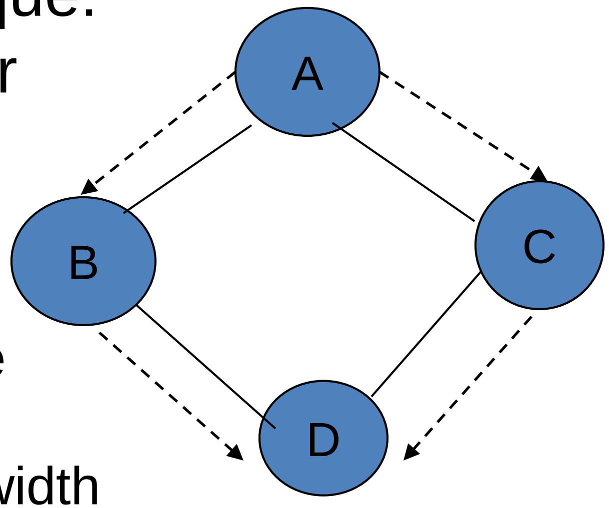
Routing Protocols

- ❑ Nodes need to collaborate to ensure that leaf nodes communicate with the sink
- ❑ A route with possible multiple hops to the sink needs to be established to transmit data through intermediate sensor nodes
- ❑ Importance of routing protocols:
  - To determine the 'best' path
  - 'Best' can be application-specific (the most efficient, with minimum 'hop', or else)
  - Generally to improve energy consumption and extend network lifetime



Flooding and Gossiping

- **Flooding** is the simplest routing technique: The node broadcasts the data and other nodes retransmit it to all its neighbours until it arrives at the sink
  - Flooding causes implosion and overlap because nodes and the network will receive multiple copies of the same data messages
  - The network also wastes energy and bandwidth



- **Gossiping:** the receiving nodes broadcast data to only randomly selected neighbours
  - It addresses the implosion
  - But energy wastage and overlapping can still occur as the network might have the same copies of data

(García Villalba et al 2009) https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3260592/

Routing Protocols Classification

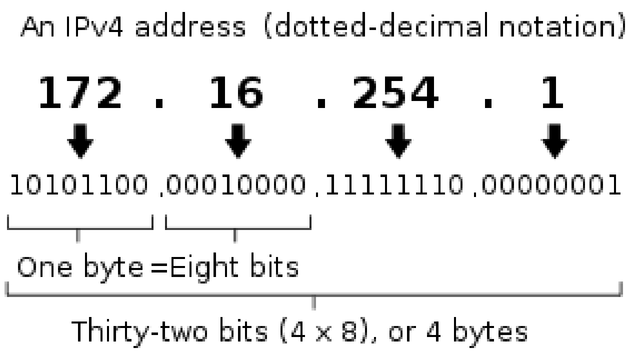
- Hierarchical (clustering) routing (already discussed)
- Attribute-based routing
  - Location-based routing
- Data-centric routing
  - Attribute-based routing
  - Directed Diffusion
- Energy-based routing
- Quality of Service (QoS) routing
- These routing approaches can sometimes overlap

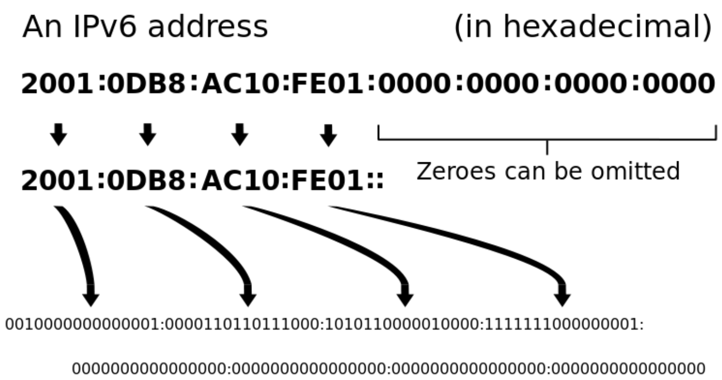
(García Villalba et al 2009) https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3260592/

Internet Protocol version 6 (IPv6) and IoT

“**Internet Protocol version 6** (**IPv6**) is the most recent version of the Internet Protocol (IP), the communications protocol that provides an identification and location system for computers on networks and routes traffic across the Internet. IPv6 was developed by the Internet Engineering Task Force (IETF) to deal with the long-anticipated problem of IPv4 address exhaustion. IPv6 is intended to replace IPv4.[1]

Every device on the Internet is assigned a unique IP address for identification and location definition. With the rapid growth of the Internet after commercialization in the 1990s, it became evident that far more addresses would be needed to connect devices than the IPv4 address space had available. By 1998, the Internet Engineering Task Force (IETF) had formalized the successor protocol. IPv6 uses a 128-bit address, theoretically allowing 2^{128}, or approximately 7038340000000000000♠3.4×10^{38} addresses. The actual number is slightly smaller, as multiple ranges are reserved for special use or completely excluded from use. The total number of possible IPv6 addresses is more than 7028790000000000000♠7.9×10^{28} times as many as IPv4, which uses 32-bit addresses and provides approximately 4.3 billion addresses. The two protocols are not designed to be interoperable, complicating the transition to IPv6. However, several IPv6 transition mechanisms have been devised to permit communication between IPv4 and IPv6 hosts.”





Source: Wikipedia

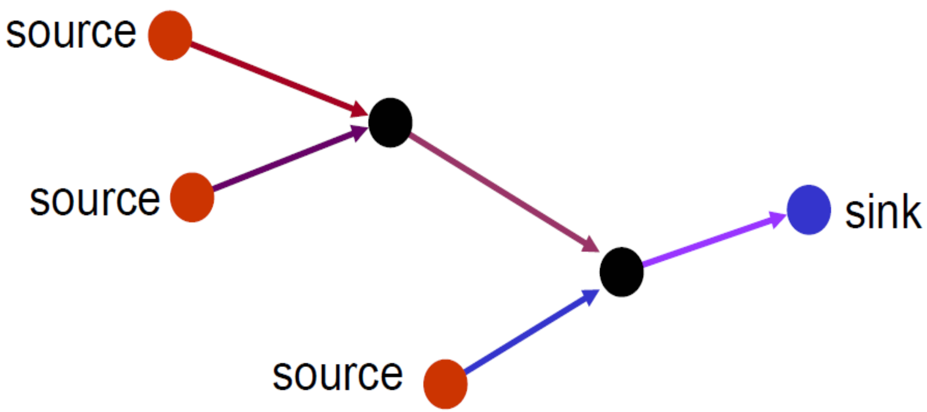
Routing Options

- Attribute-value based routing
  - Sensed data includes attribute-value pairs
  - Attributes are application-specific, relying on sensing type
  - The sink can send a query expressing its ‘interest’
  - Data that matches the ‘interest’ will be retrieved and sent back to the sink
  - In each hop, intermediate nodes route data based on attributes
- Location-based routing
  - It uses location information to select routes
  - Location can be an attribute of the query
  - Restricts routing according to the location of the nodes
  - Nodes can maintain a routing table to identify next hops

(García Villalba et al 2009) https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3260592/

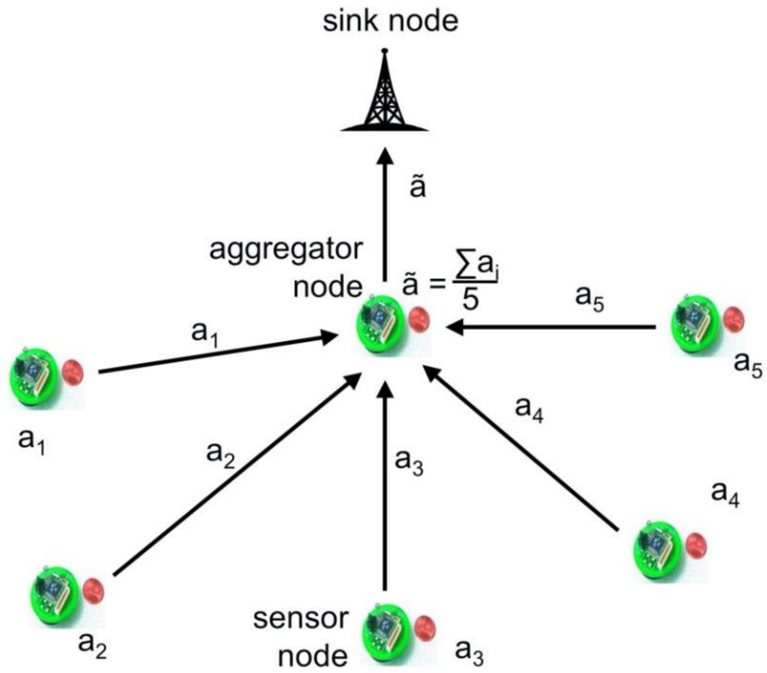
Data-Centric Routing

- Data-Centric Routing
  - Intermediate sensors perform data aggregation to prevent data redundancy and also reduce energy consumption
  - It involves in-network processing



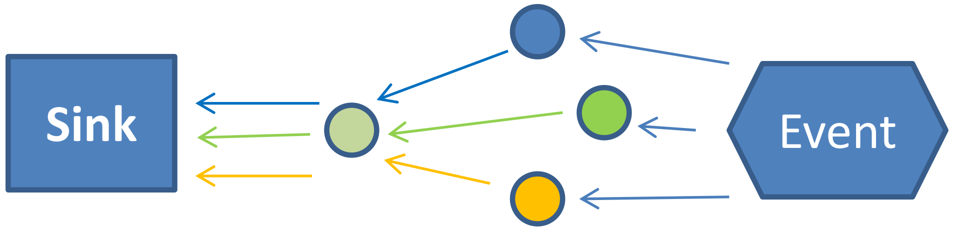
In-network Processing

- Some data processing taking place within the network on sensors
- Intermediate sensor nodes can perform:
  - Aggregation or averaging
  - Filtering out redundant/repeated data
- Based on the fact **that processing is less energy consuming than communication**

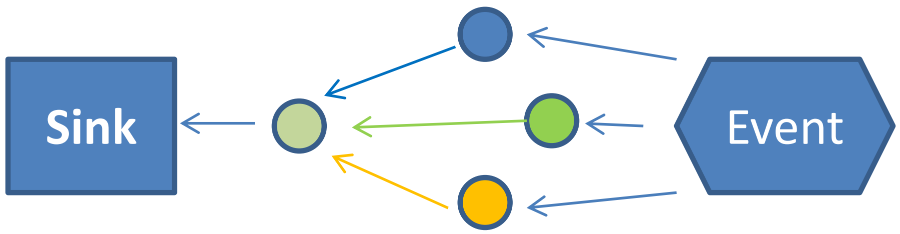


In-network Processing (cont'd)

- Benefits:
    - It prevents the bottleneck problem
    - Solves the overlap problem and implosion (i.e. caused by duplicates)
    - It reduces energy consumption by minimizing the amount of data that is transmitted, and extends the network lifetime

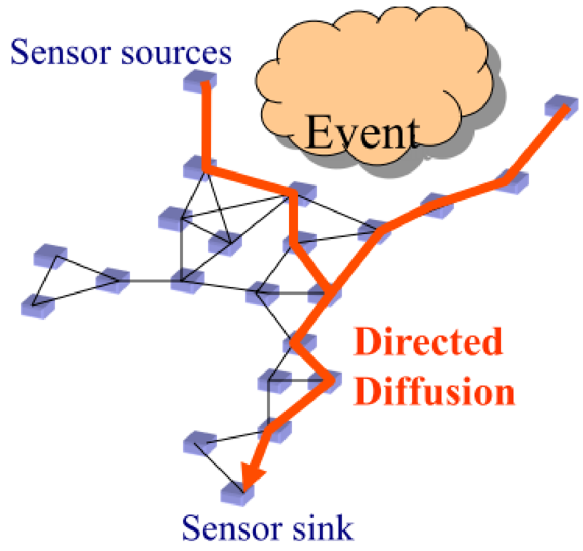


Without in-network processing



With in-network processing

Directed Diffusion



- A data-centric and attribute-value based protocol. It consists of:
  - Interest (what the sender wants)
  - Data (*named* by attribute-value pairs)
  - Gradients
  - Reinforcements
- Diffusion: a sink will broadcast its 'interest'
- Interests are translated into queries using attribute value pairs
  - An example of an interest:

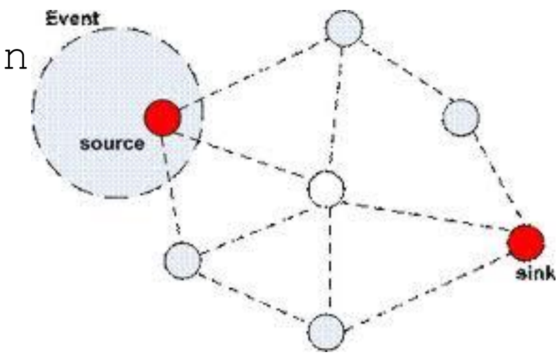
```
Type = wheeled vehicle
Interval = 1s
Rect = [-100, 100, 200, 400] // from sensors within the
rectangle
timestamp=01:20:40              // hh:mm:ss
expiresAt = 01 : 30 : 40
```

Intanagonwiwat, C., Govindan, R., Estrin, D., Heidemann, J., & Silva, F. (2003).

Directed Diffusion (cont'd)

- Any node receiving the interest stores a record (interest cache) and propagates the interest further to subsets of neighbours
- *Gradient Establishment:* nodes establish a gradient (i.e. a reply link) toward the neighbour from which the interest was received
- Gradient includes: a ***data rate*** (calculated based on interval), ***duration*** (calculated based on timestamp and expiry time, and the ***direction*** in which to send the data
  - An example of a gradient:

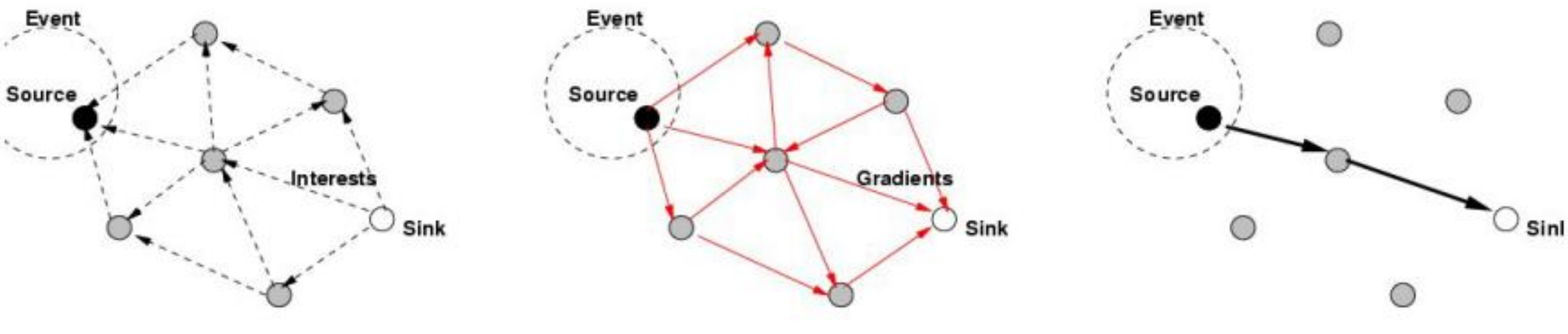
```
Type = wheeled vehicle// type of vehicle seen
Instance : truck // instance of this type
location = [ 125, 220]// node location
Intensity = 0.6 //signal amplitude measure
Confidence = 0.85 // confidence in the match
Timestamp = 01:20:40// event generation time
```



Intanagonwiwat, C., Govindan, R., Estrin, D., Heidemann, J., & Silva, F. (2003).

Directed Diffusion (cont'd)

- ❑ How to distinguish neighbouring nodes?
  - Using a unique identifier such as MAC, Bluetooth or cluster addresses
- ❑ A source node is the one that matches an interest
- ❑ There might be several paths from the source to the sink
- ❑ The sensor network *reinforces* one of the gradient paths
  - E.g. reinforcing the path with lowest delay



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

Intanagonwiwat, C., Govindan, R., Estrin, D., Heidemann, J., & Silva, F. (2003).

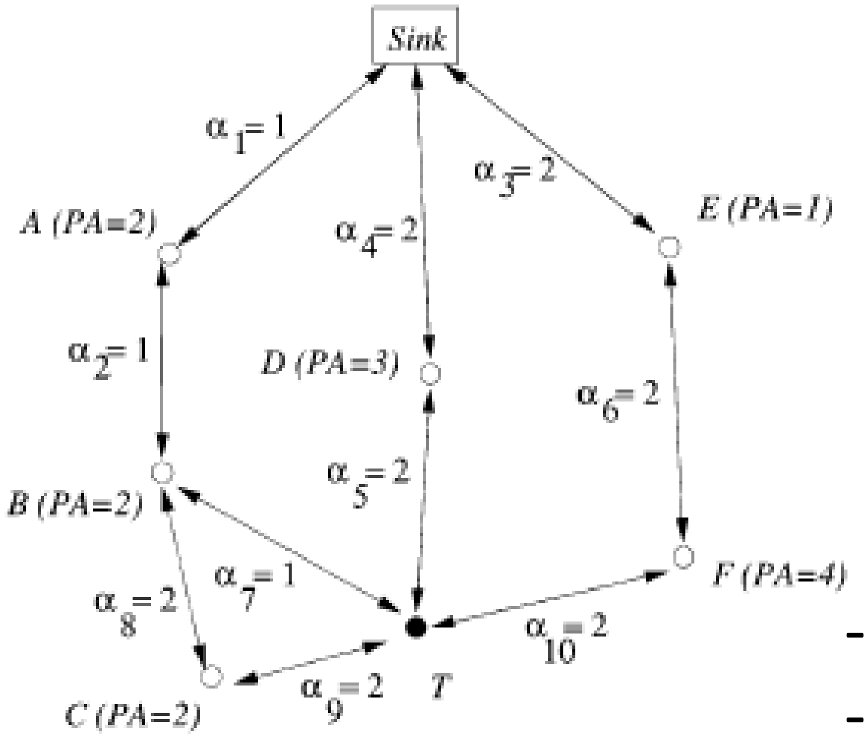
Energy-Efficient Routing

- In a WSN, there are multiple paths to transmit data from the sink to the nodes and vice versa
- Energy-based routing schemes focus on identifying the most efficient path
- The aim is to extend the network lifetime

(García Villalba et al 2009) https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3260592/

Multipath Routing and Energy Efficiency

- To route the query from Sink to T



- PA is the available power
- α is the energy required to transmit a data packet through the related route

- *Route 1*: Sink-A-B-T, total PA = 4, total $\alpha = 3$,
- *Route 2*: Sink-A-B-C-T, total PA = 6, total $\alpha = 6$,
- *Route 3*: Sink-D-T, total PA = 3, total $\alpha = 4$,
- *Route 4*: Sink-E-F-T, total PA = 5, total $\alpha = 6$,

- Minimum energy route: Route 1
- Minimum hop route: Route 3

Quality of Service (QoS) Routing

- In WSN, applications might have different requirements
- In addition to the routing options discussed, QoS routing can focus on other criteria
- QoS routing aims to balance data quality and energy consumption to achieve route optimisation
- The quality of the networks commonly includes certain QoS metrics:
  - energy, (note overlapping with energy routing protocol)
  - success delivery ratio,
  - delay,
  - bandwidth

Footnote: Since we have multiple QoS criteria to consider, we might develop optimal routing strategies through Pareto optimisation and modern approaches such as Multi-objective Evolutionary Algorithms (MOEAs)

Challenges and Research Directions

- ❑ Energy Management: Duty Cycling, Efficient Routing
- ❑ Limited bandwidth - Reducing amount of data to be transmitted
- ❑ Security and Privacy
- ❑ Time synchronization
- ❑ Localization (sensor positions)
- ❑ “in network” processing
- ❑ QoS Routing
- ❑ Sensor fusion

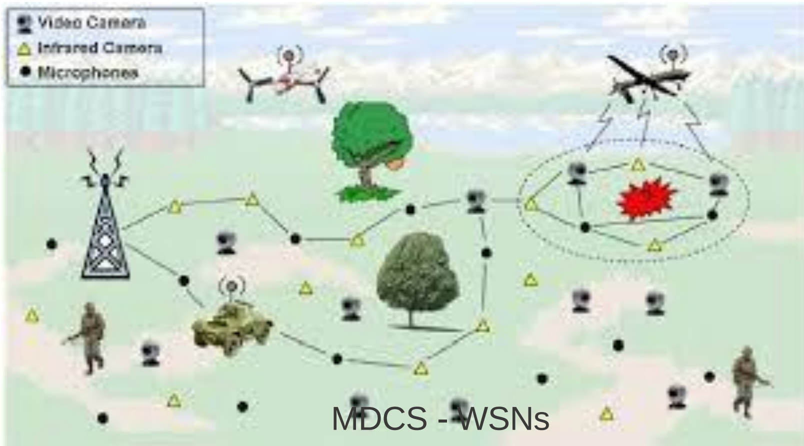
Applications

Environmental monitoring

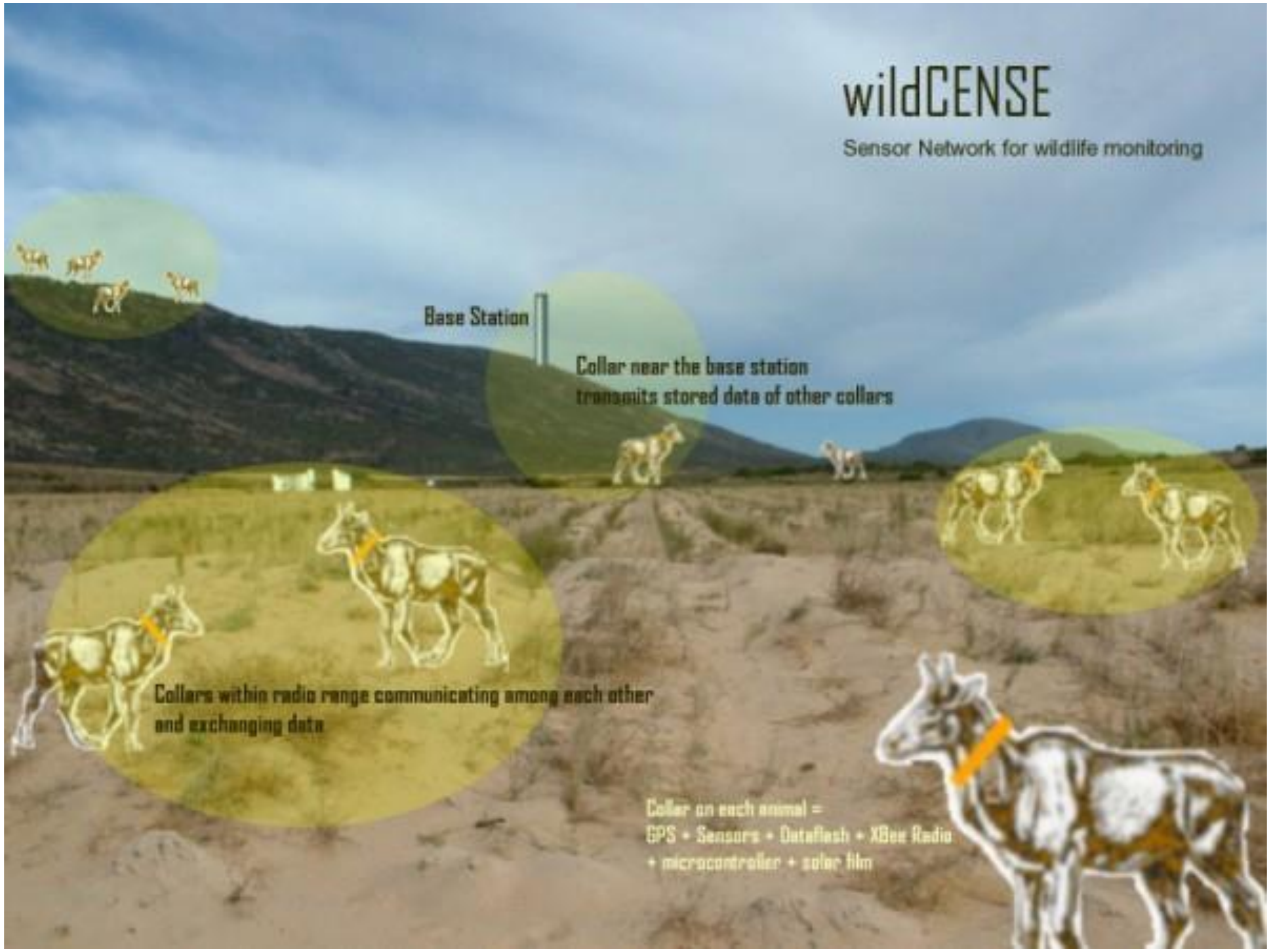
- Habitat monitoring (conditions of wild animals and plants)
- Air/water quality monitoring (e.g. for air pollution control)
- Hazard monitoring (biological/chemical hazards, e.g. in a chemical plat)
- Disaster monitoring (detecting disasters like fire, flood, etc.)

Military applications

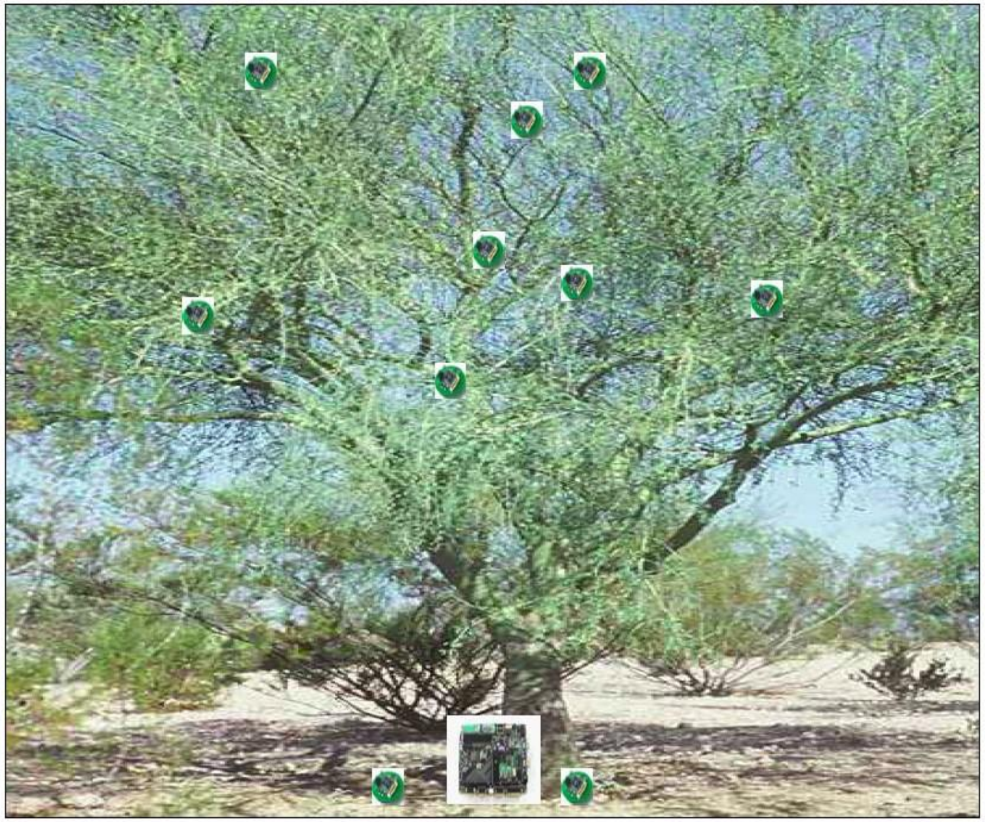
- For tracking vehicles and forces, protecting objects, remote sensing, intelligent guiding using robotic vehicles, etc.



Wildlife monitoring



Ecosystem monitoring



Primary node

Secondary nodes

•Dense network of physical, chemical sensors in soil and canopy

•Measure and characterize previously unobservable ecosystem processes

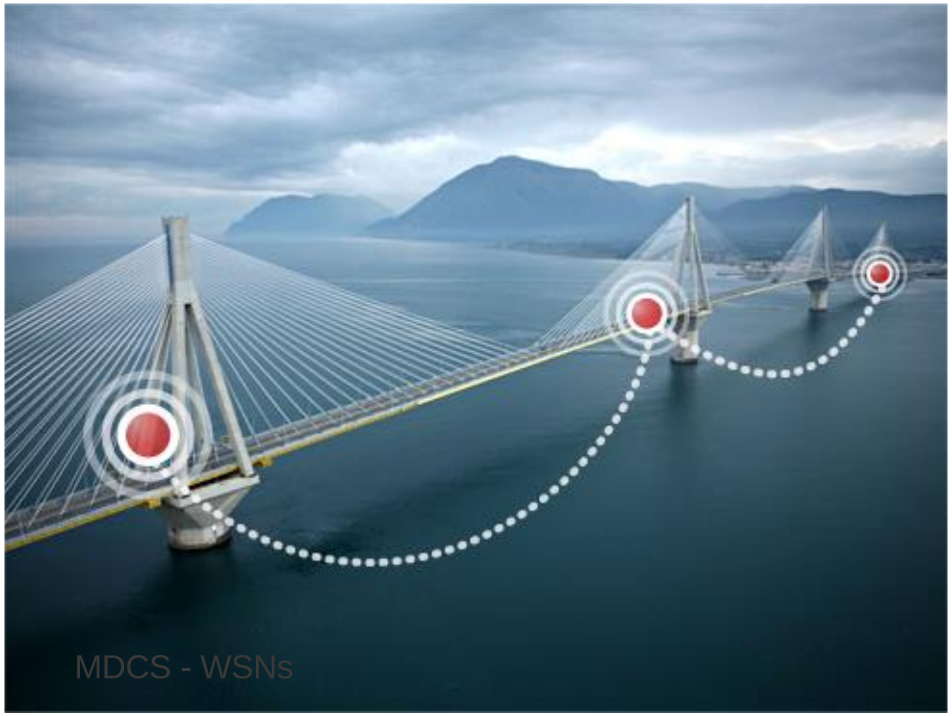
Wireless Sensor Networks to monitor food sustainability

- Frost monitoring in vineyards

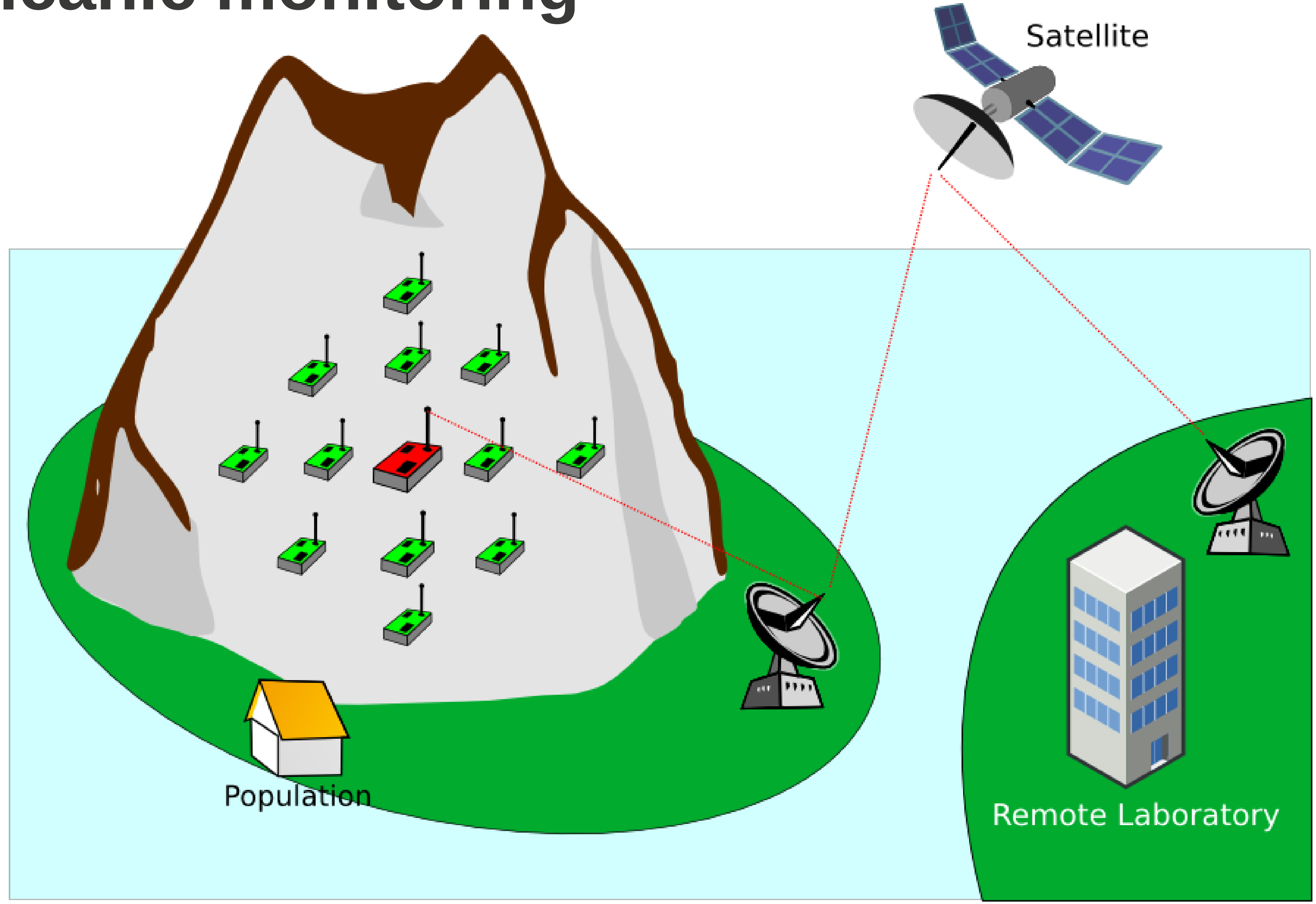
Smart Roads and Infrastructures

An Example:

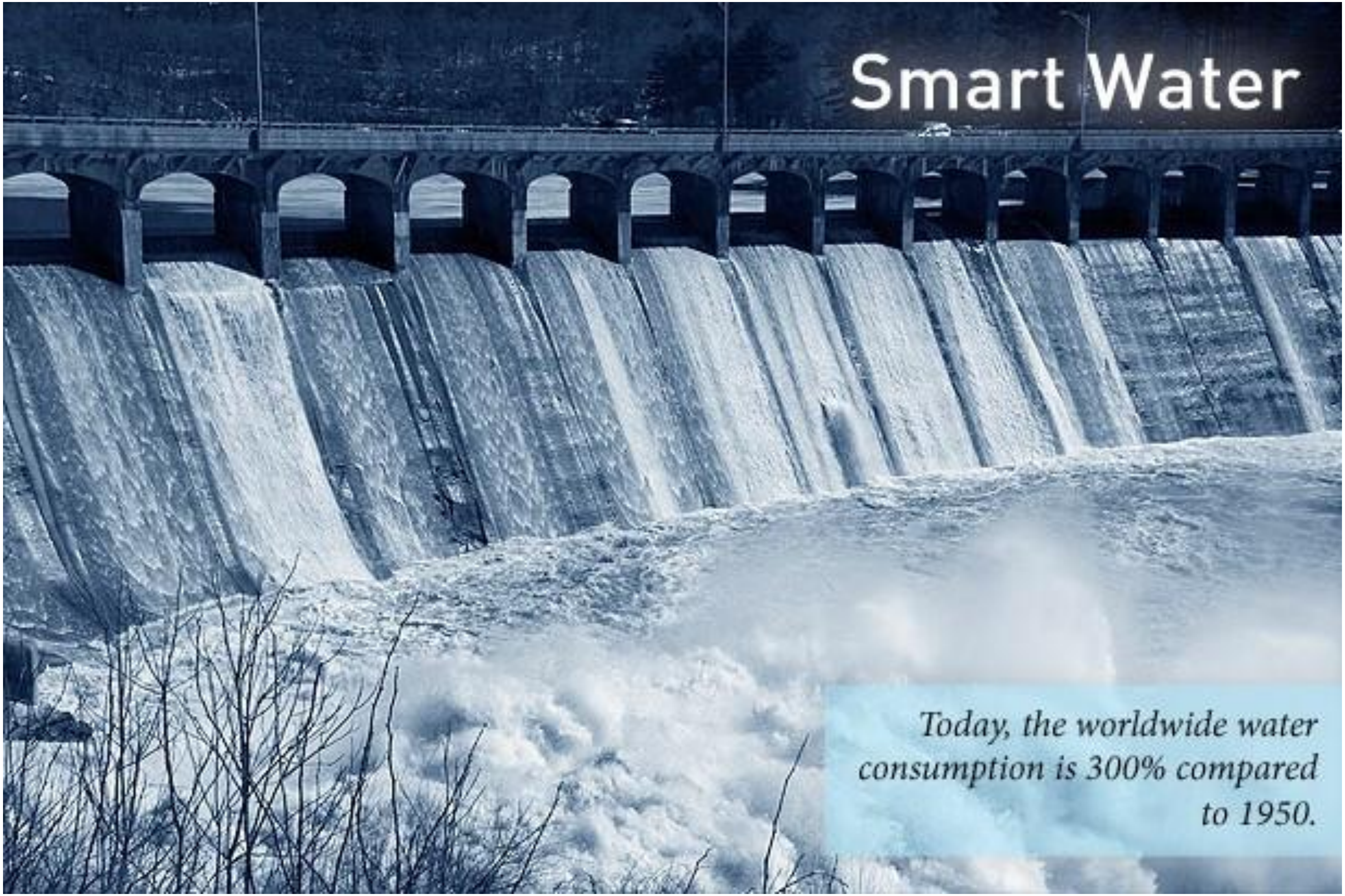
- A six-lane, 2.9 km bridge in Greece with 100 sensors
- Soon after opening in 2004, the sensors detected abnormal vibrations in the cables
- The sensors included accelerometers, strain gauges, weigh-in-motion devices and temperature and wind speed sensors.”



Volcanic monitoring

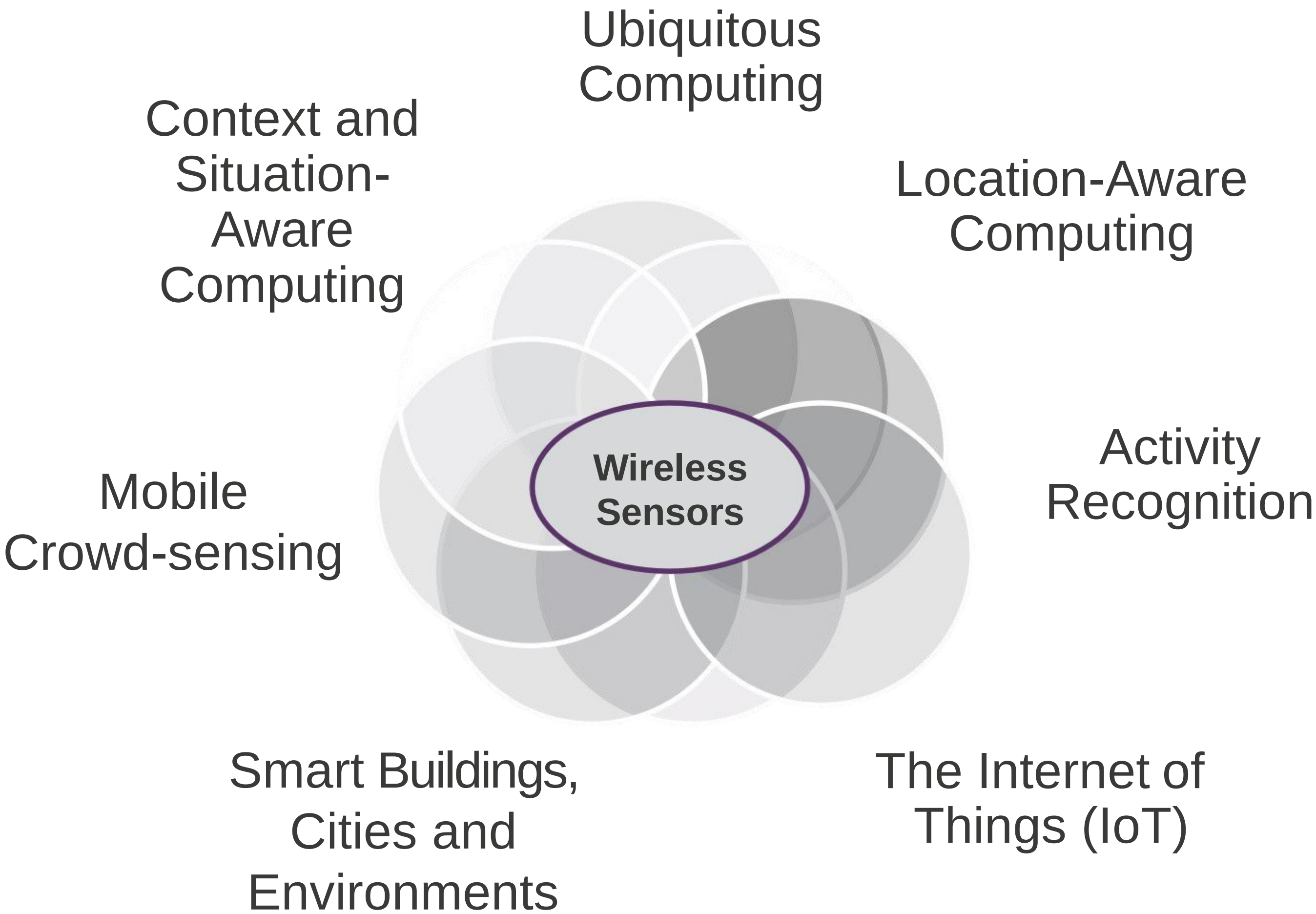


Forest fire detection, air pollution, snow level monitoring, landslide and avalanche prevention, earthquake early detection

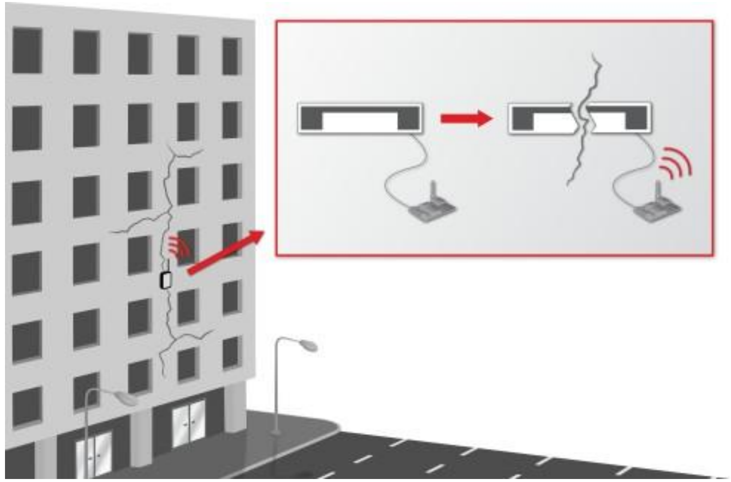


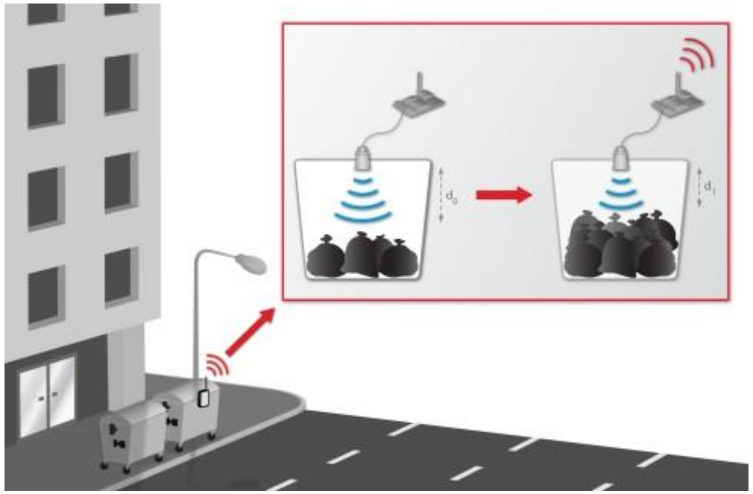
Monitoring water quality, Water Leakages, river floods

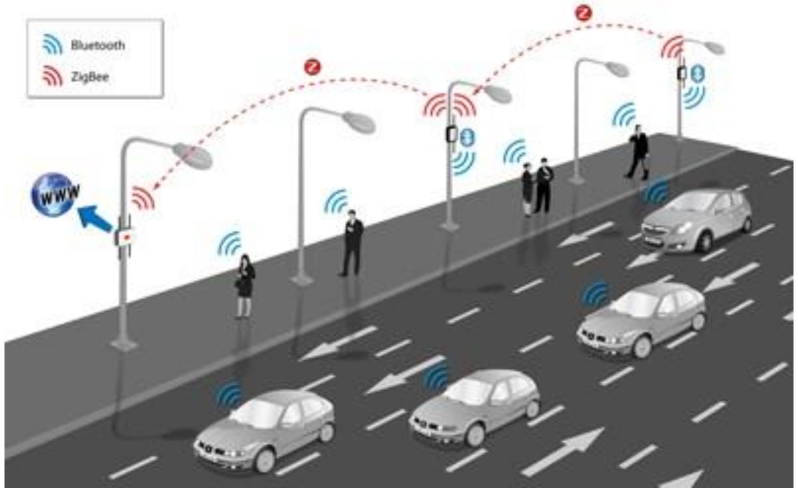
WSNs are the Core



Future … Smart Cities







Smart Cities

- ❑ Barcelona
  - Barcelona City Council has designed and promoted a platform that enables information generated by sensors distributed around cities to be gathered, used and disseminated
- ❑ Sentilo
  - Sentilo developed with open-source software components so that any city can use it directly to interconnect the sensors and actuators that it deploys.

Smart Cities

Questions:

- What mobile applications do you think can benefit the smart city's university students?
- Data privacy is a key issue in the smart cities. Identify different types of sensitive and personal data that can be collected in a smart city.
- Building smart cities will bring changes to the job market. What types of new jobs, do you think, will be created as a result, and which existing jobs will no longer be required?

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