POLITECNICO MILANO

Politecnico di Milano

Facoltà di Ingegneria dell'Informazione

9 – Sensor Networks

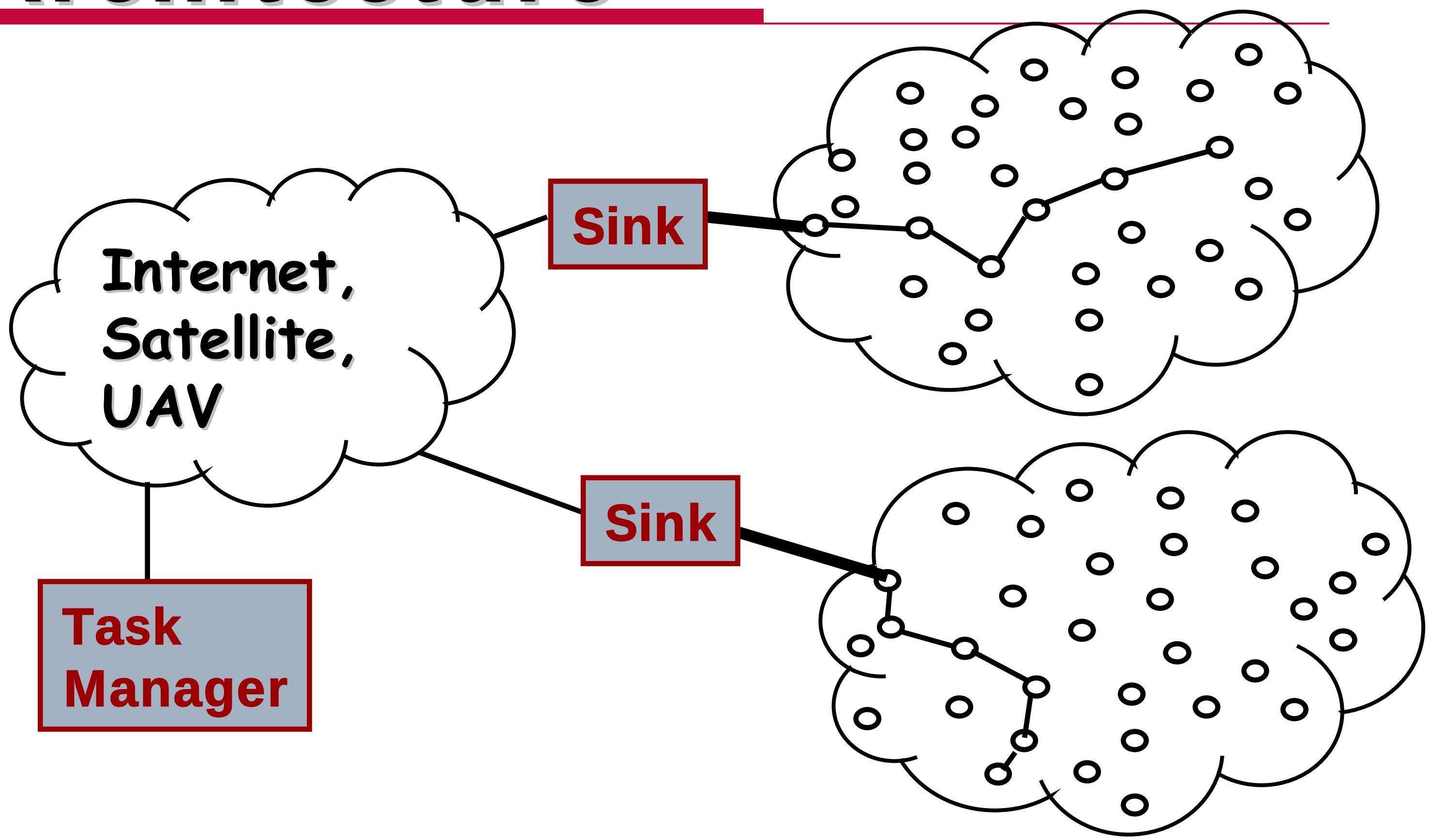
Reti Mobili Distribuite

Prof. Antonio Capone

Acknowlegments

- This class notes are mostly based on the teaching material of:
  - Prof. Ian Akyildiz (Georgia Institute of Technology)
  - Prof. Eylem Ekici (Ohio State University at Columbus)

Sensor Network Architecture



I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci,
"Wireless Sensor Networks: A Survey", Computer Networks (Elsevier) Journal, March 2002.

Characteristics of WSNs

- Very large number of nodes, often in the order of thousands
- Nodes need to be close to each other
- Densities as high as 20 nodes/m3
- Asymmetric flow of information, from sensor nodes to sink
- Communications are triggered by queries or events
- Limited amount of energy (in many applications it is impossible to replace or recharge)
- Mostly static topology
- Low cost*, size, and weight per node
- Prone to failures
- More use of broadcast communications instead of point-to-point
- Nodes do not have a global ID such as an IP address
- The security, both on physical and communication level, is more limited than in classical wireless networks

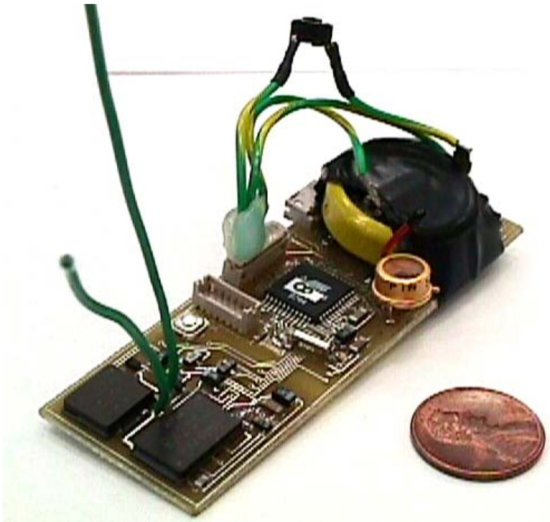
Differences from Ad-hoc Networks

- Number of sensor nodes can be several orders of magnitude higher
- Sensor nodes are densely deployed and are prone to failures
- The topology of a sensor network may change frequently due to node failure and node mobility
- Sensor nodes are limited in power, computational capacities, and memory
- May not have global ID like IP address
- Need tight integration with sensing tasks

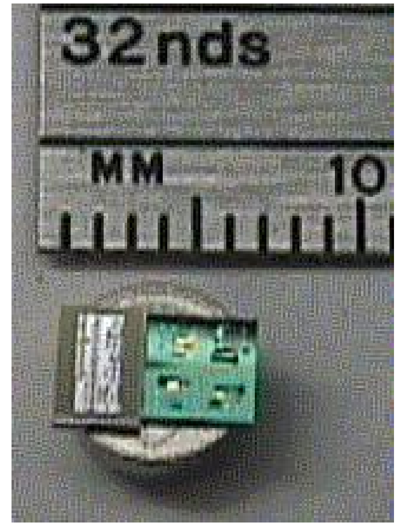
Sensor Network Features

- APPLICATIONS:
  - Military, Environmental, Health, Home, Space Exploration,
  - Chemical Processing, Volcanoes, Mining, Disaster Relief….
- SENSOR TYPES:
  - Seismic, Low Sampling Rate Magnetic, Thermal, Visual, Infrared, Acoustic,
  - Radar…
- SENSOR TASKS:
  - Temperature, Humidity, Vehicular Movement, Lightning Condition,
  - Pressure, Soil Makeup, Noise Levels, Presence or Absence of Certain Types of Objects, Mechanical Stress Levels on Attached Objects, Current Characteristics
  - (Speed, Direction, Size) of an Object ….

Examples for Sensor Nodes



Dust



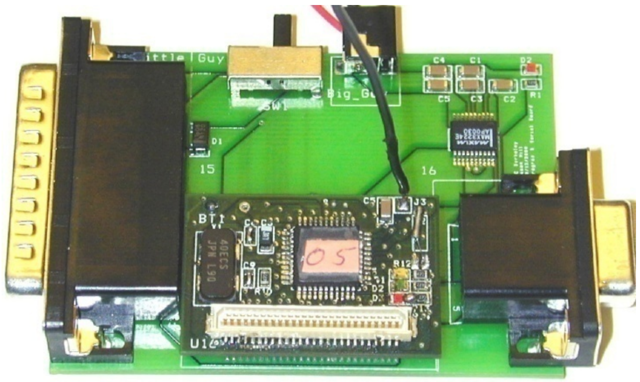
Smart Dust

Rockwell
WINS

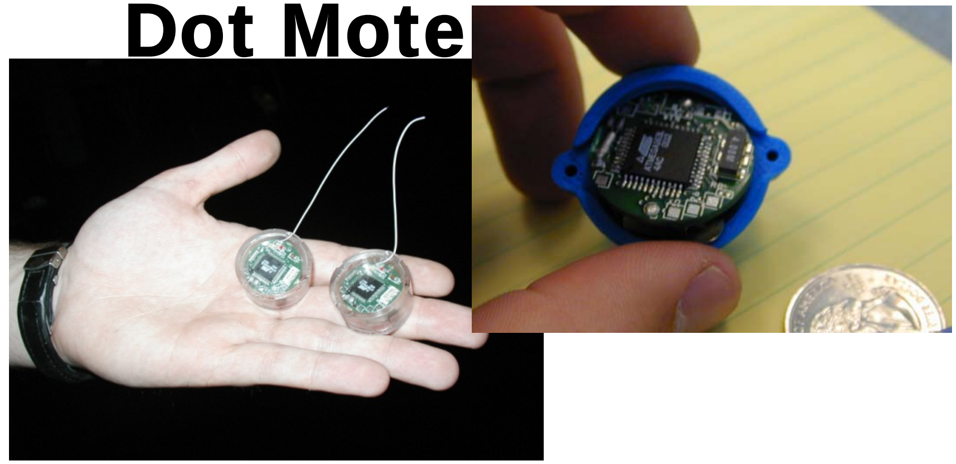
JPL Sensor
Webs

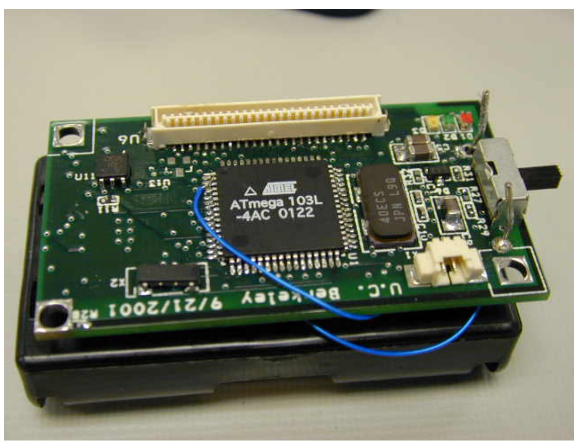
Examples for Sensor Nodes

Rene Mote

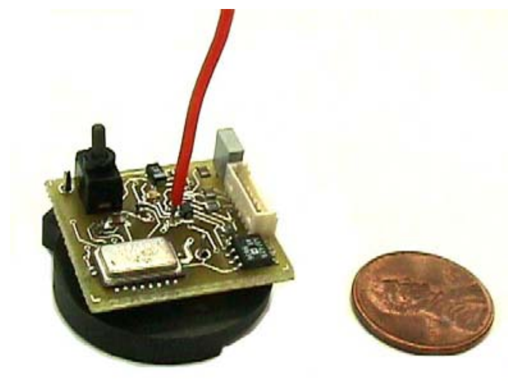


Dot Mote





MICA Mote



weC Mote

Applications

Military Applications

- Command, Control, Communications, Computing, Intelligence, Surveillance, Reconnaissance, Targeting (C4ISRT)
  - Monitoring friendly forces, equipment and ammunition
  - Battlefield surveillance
  - Reconnaissance of opposing forces and terrain
  - Targeting
  - Battle damage assessment
  - Nuclear, Biological and Chemical (NBC) attack detection and reconnaissance

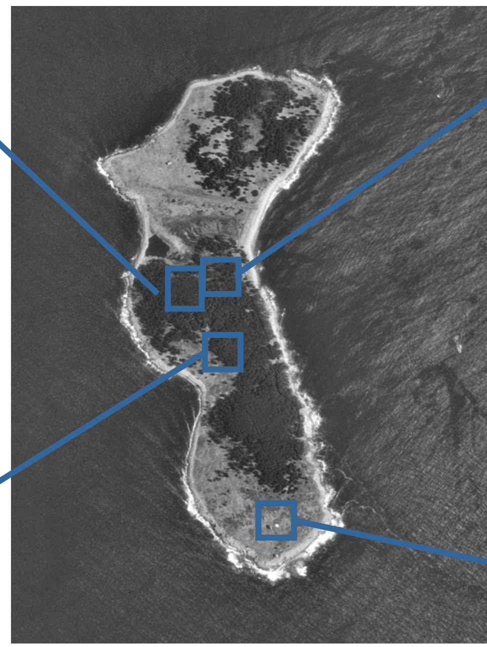
Further Military Applications

- Intrusion detection (mine fields)
- Detection of firing gun (small arms) location
- Chemical (biological) attack detection
- Targeting and target tracking systems
- Enhanced navigation systems
- Battle damage assessment system
- Enhanced logistics systems

Environmental Applications

- Tracking the movements of birds, small animals, and insects
- Monitoring environmental conditions that affect crops and livestock
- Irrigation
- Earth monitoring and planetary exploration
- Chemical/biological detection
- Biological, Earth, and environmental monitoring in marine, soil, and atmospheric contexts
- Meteorological or geophysical research
- Pollution study
- Precision agriculture
- Biocomplexity mapping of the environment
- Flood detection, and Forest fire detection.

Habitat Monitoring



http://www.greatduckisland.net
Great Duck Island in Maine

Habitat Monitoring

- Approx. 200 nodes including MICA, MICA2, burrow nodes (with IR) and weather station nodes
- Motes detect light, barometric pressure, relative humidity and temperature conditions.
- An infrared heat sensor detects whether the nest is occupied by a seabird, and whether the bird has company.
- Motes within the burrows send readings out to a single gateway sensor above ground, which then wirelessly relays collected information to a laptop computer at a lighthouse (~350 feet).
- The laptop, also powered by photovoltaic cells, connects to the Internet via satellite.
- Computer at base-station logs data and maintains database

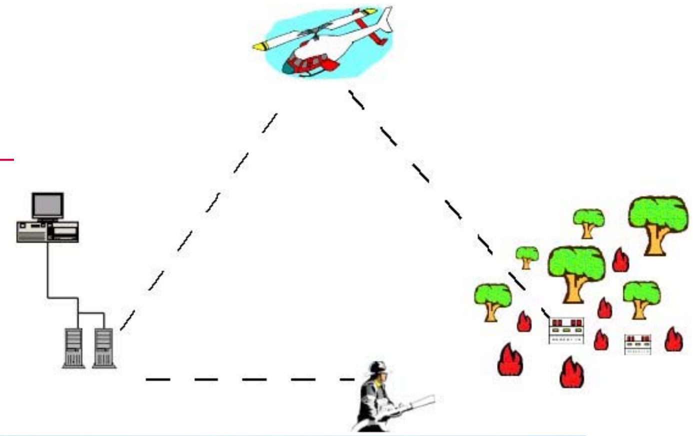
Forest Fire Detection: Firebug

- Design and Construction of a Wildfire Instrumentation System using Networked Sensors
- Network of GPS-enabled, wireless thermal sensors
- FireBug network self-organizes into edge-hub configurations
- Hub motes act are base stations

http://firebug.sourceforge.net/

Firebug

- Firebug - mote/fireboard pair
- Mote - Crossbow MICA board
- Fireboard - Crossbow MTS420CA
  - Temperature and humidity sensor.
  - Barometric pressure sensor.
  - GPS unit.
  - Accelerometer
  - Light Intensity Sensor



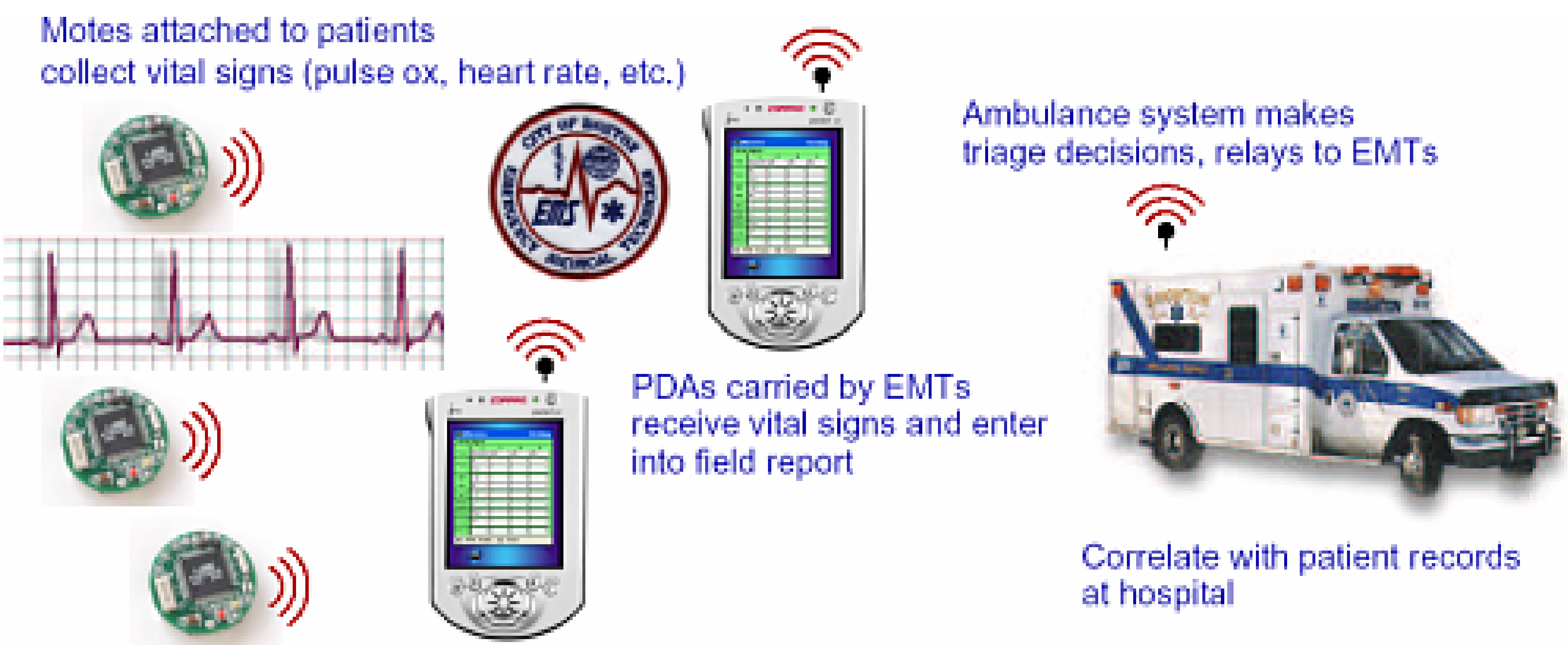
Observation and Forecasting System for the Columbia River

Health Applications

- Providing interfaces for the disabled
- Integrated patient monitoring
- Diagnostics
- Telemonitoring of human physiological data
- Tracking and monitoring doctors and patients inside a hospital
- Drug administration in hospitals

CodeBlue: WSNs for Medical Care

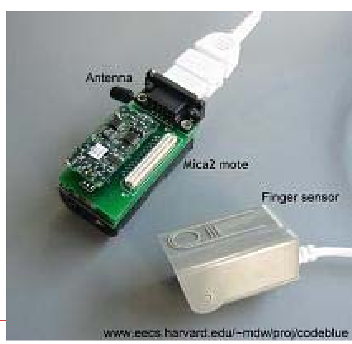
- NSF, NIH, U.S. Army, Sun Microsystems and Microsoft Corporation
- Motivation - Vital sign data poorly integrated with pre-hospital and hospital-based patient care records

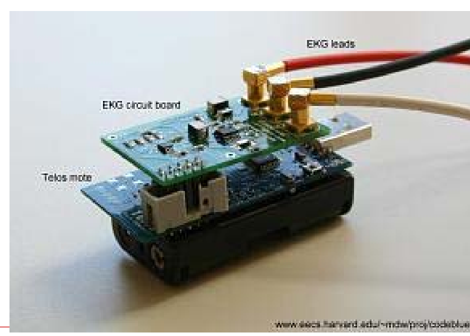


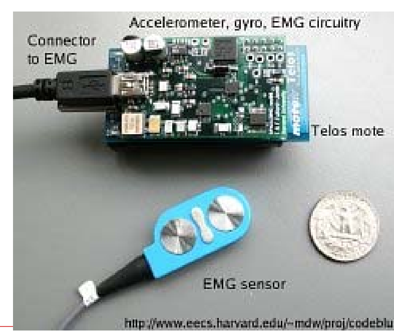
http://www.eecs.harvard.edu/~mdw/proj/codeblue

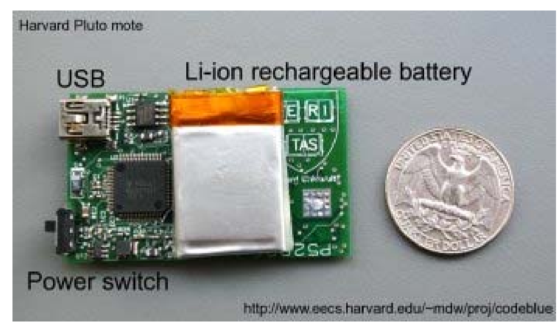
CodeBlue: WSNs for Medical Care

- Hardware
  - Small wearable sensors
  - Wireless pulse oximeter / 2-lead EKG
  - Based on the Mica2, MicaZ, and Telos sensor node platforms
  - Custom sensor board with pulse oximeter or EKG circuitry
  - Pluto mote
    - scaled-down version of the Telos
    - rechargeable Li-ion battery
    - small USB connector
    - 3-axis accelerometer









CodeBlue: WSNs for Medical Care

- CodeBlue - scalable software infrastructure for wireless medical devices
  - Routing, Naming, Discovery, and Security
  - MoteTrack - tracking the location of individ
    patient devices indoors and outdoors

- Heart rate (HR), oxygen saturation (SpO2),
  data monitored
- Relayed over a short-range (100m)
- Receiving devices - PDAs, laptops, ambulance-based terminals
- Data can be displayed in real time and integrated into the developing pre-hospital patient care record
- Can be programmed to process vital sign data (provide alerts)

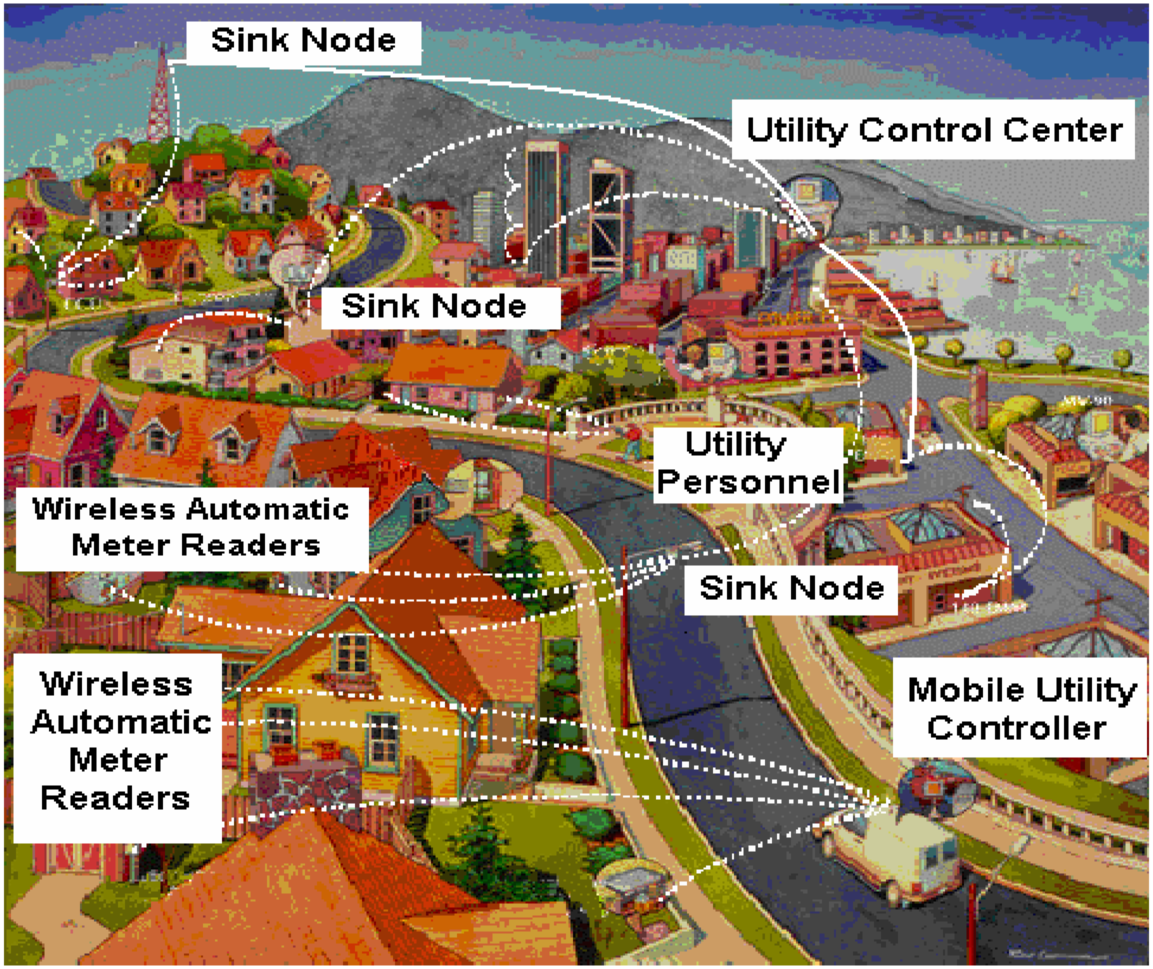
Further Applications

- Monitoring product quality
- Factory Floor Automation
- Constructing smart homes
- Constructing office spaces
- Interactive toys
- Monitor disaster areas
- Smart spaces
- Machine diagnosis
- Interactive museums
- Managing inventory control
- Environmental control in office buildings

Disaster Relief Operations

- Drop sensor nodes from an aircraft over a WILDFIRE
  - Each node measures temperature
  - Derive a “temperature map”
- Schools detect airborn toxins at low concentrations, trace contaminant transport to source
- Earthquake-rubbled building infiltrated with robots and sensors: locate survivors, evaluate structural damage

Wireless Automatic Meter Reading Systems for Power Utilities

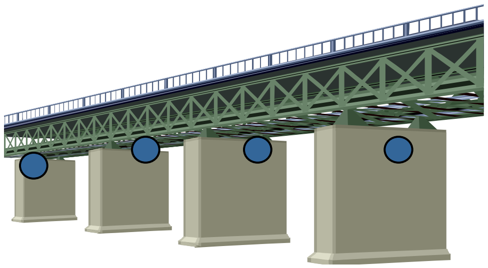


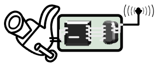
Wireless Automatic Meter Reading (WAMR) Systems

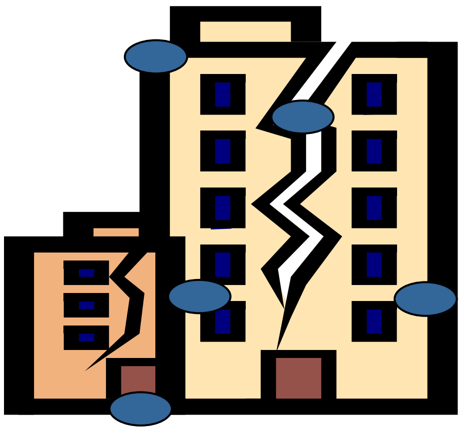
- Automatic meter reading functionalities:
  - Real-time energy consumption statistics
  - Effective billing management
- Telemetry functionalities:
  - Remote control of equipment
- Dynamic configuration functionality:
  - Self-configuration of the network in case of route failures
- Status monitoring functionality:
  - Monitoring the status of the metering devices

Buildings (or Bridges)

- High-rise buildings self-detect structural faults
  - Reduce energy wastage by proper humidity, ventilation, air conditioning (HVAC) control
  - Needs measurements about room occupancy, temperature, air flow, ...
  - Monitor mechanical stress after earthquakes







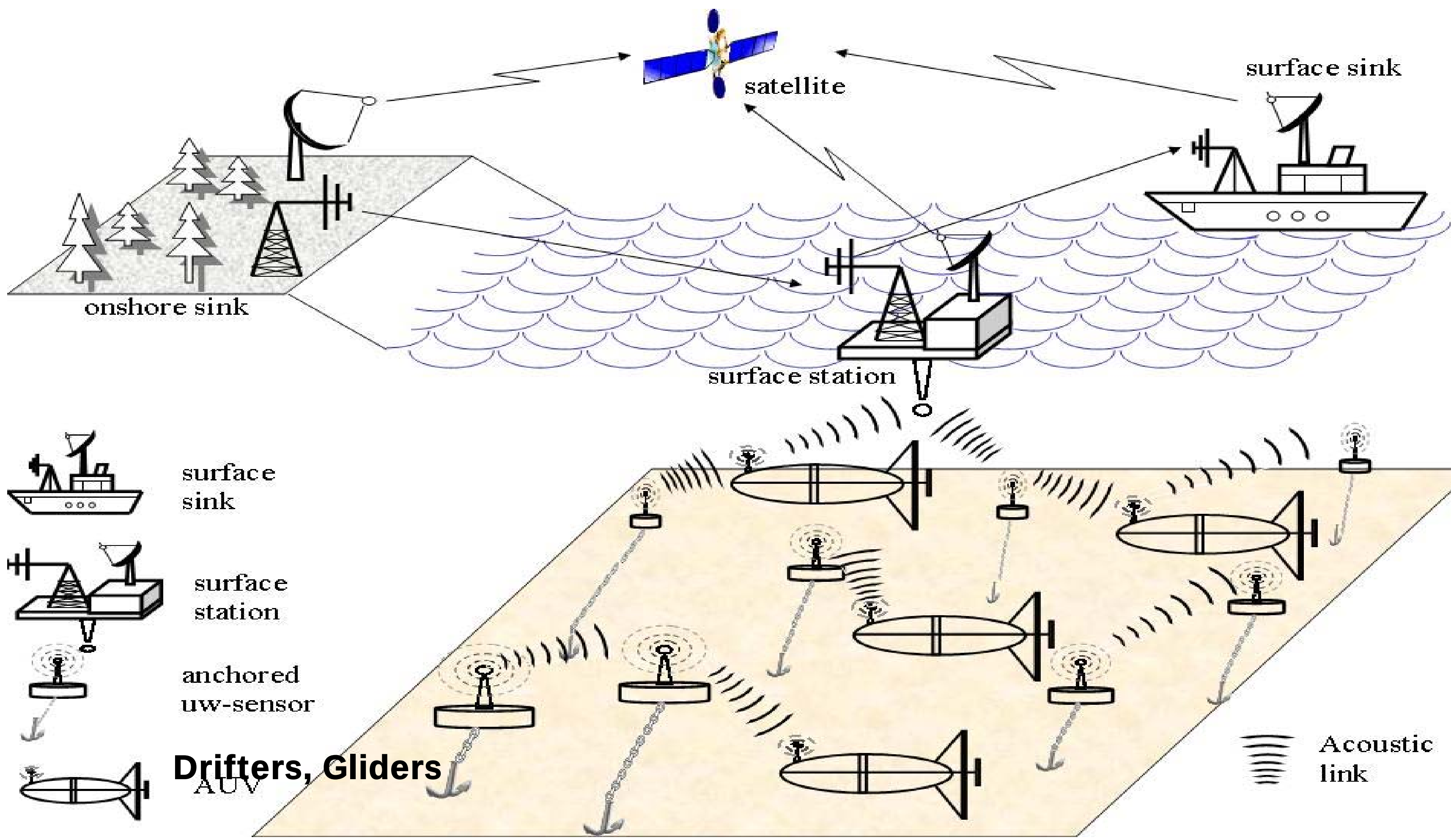
More Applications

- Facility Management
  - Intrusion detection into industrial sites
  - Control of leakages in chemical plants, …
- Machine surveillance and preventive maintenance
  - Embed sensing/control functions into places no cable has gone before
  - E.g., tire pressure monitoring

Underwater Sensor Networks

- Applications:
  - Ocean Sampling Networks
  - Pollution Monitoring and other environmental monitoring (chemical, biological)
  - Buoys alert swimmers to dangerous bacterial levels
  - Disaster Prevention
  - Assisted Navigation
  - Distributed Tactical Surveillance
  - Mine Reconnaissance

Underwater Sensor Networks
3D Dynamic Architecture Using AUVs

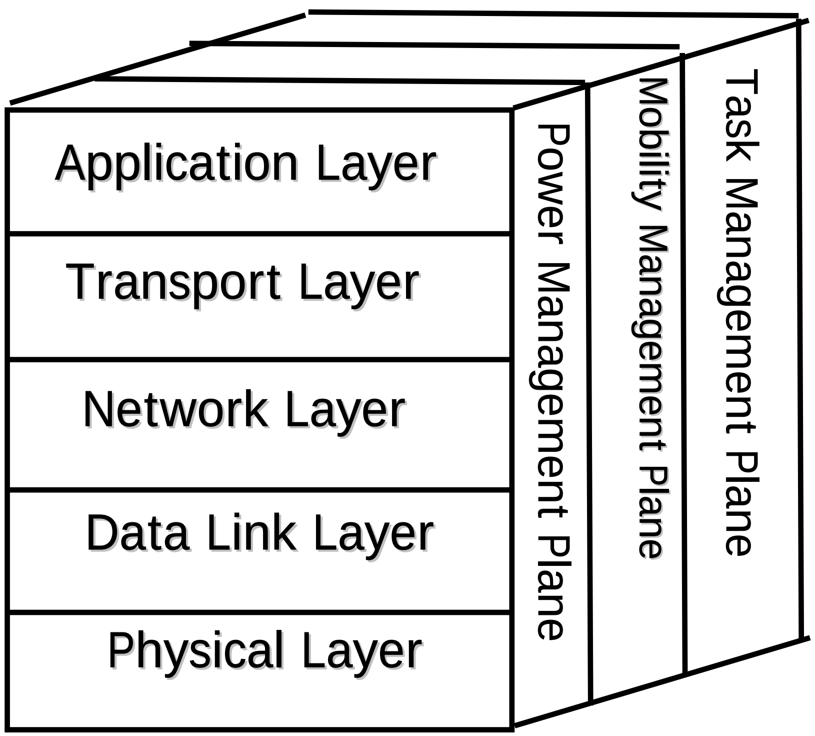


Communication architecture and solutions

Factors Influencing Sensor Network Design

- Fault Tolerance (Reliability)
- Scalability
- Production Costs
- Hardware Constraints
- Sensor Network Topology
- Operating Environment
- Transmission Media
- Power Consumption

Sensor Networks Communication Architecture



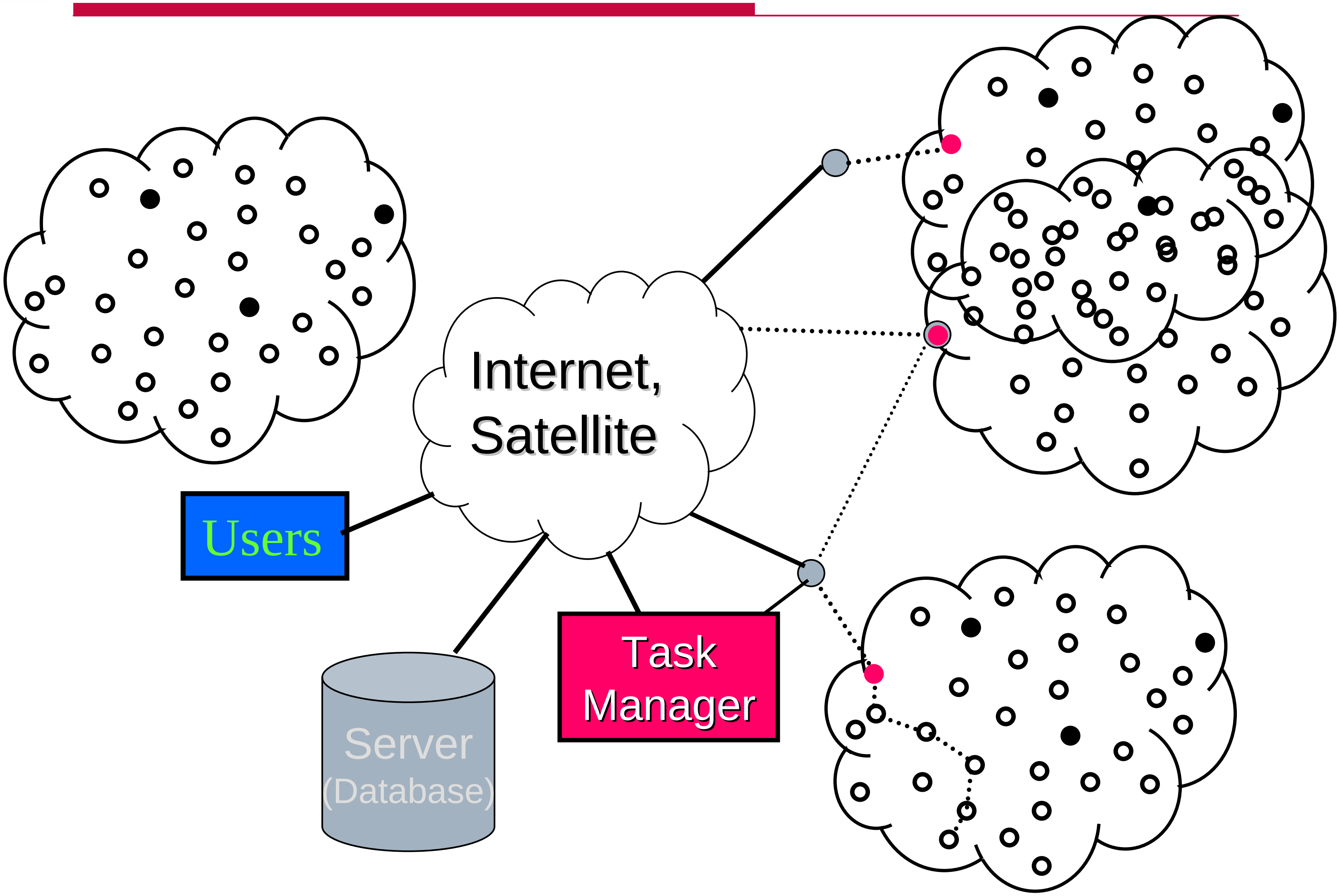
Used by sink and all sensor nodes
Combines power and routing awareness
Integrates data with networking protocols
Communicates power efficiently through wireless medium and
Promotes cooperative efforts.

Why Can't Ad-hoc Network Protocols Be Used Here?

- Number of sensor nodes can be several orders of magnitude higher
- Sensor nodes are densely deployed and are prone to failures
- The topology of a sensor network may change frequently due to node mobility and node failure
- Sensor nodes are limited in power, computational capacities, and memory
- May not have global ID like IP address
- Need tight integration with sensing tasks

Application Layer

Sensor Network Topology



SMP: Sensor Management Protocol

- System Administrators interact with sensors via SMP
- Tasks:
  - Turning sensors on and off
  - Moving the sensor nodes
  - Querying the sensor network configuration and the status of nodes and re-configuring the sensor network
  - Authentication, key distribution and security
  - Time-synchronization of sensor nodes
  - Exchanging data related to location finding algorithms
  - Introducing rules related to data aggregation, attribute-based naming, and clustering to sensor nodes

Query Processing

- Users can request data from the network
  → Efficient Query Processing
- User Query Types:
  - Historical Queries:
    - Used for analysis of historical data stored in a storage area
      “What was the temp. 2 hours back in the NW quadrant?”
  - One Time Queries:
    - Gives a snapshot of the network”
      What is the current temperature in the NW quadrant?”
  - Persistent Queries:
    - Used to monitor the network over a time interval with respect to some parameters
      “Report the temperature for the next 2 hours”

Sensor Query and Tasking Language (SQTL)

- SQTL is a procedural scripting language
- It provides interfaces to access sensor hardware:
  - getTemperature, turnOn
- for location awareness:
  - isNeighbor, getPosition
- and for communication:
  - tell execute.

C-C Shen, et.al., “Sensor Information Networking Architecture and Applications”, IEEE Personal Communications Magazine, August 2001

SQTL

- By using the upon command, a programmer can create an “event handling block” for 3 types of events:
  - Events generated when a message is received by a sensor node (RECEIVE)
  - Events triggered periodically (EVERY),
  - Events caused by the expiration of a timer (EXPIRE)

Simple Querying Example

Select [task, time, location, [distinct | all], amplitude,
[[avg | min |max | count | sum] (amplitude)]]
from [any , every , aggregate *m*]
where [power available [<|>] *PA* |
location [in | not in] *RECT* |
t_{min} < time < t_{max} |
task = *t* |
amplitude [<|==|>] *a*]
group by task
based on [time limit = l_t | packet limit = l_p |
resolution = *r* | region = *xy*]

Task Assignment and Data Advertisement Protocol

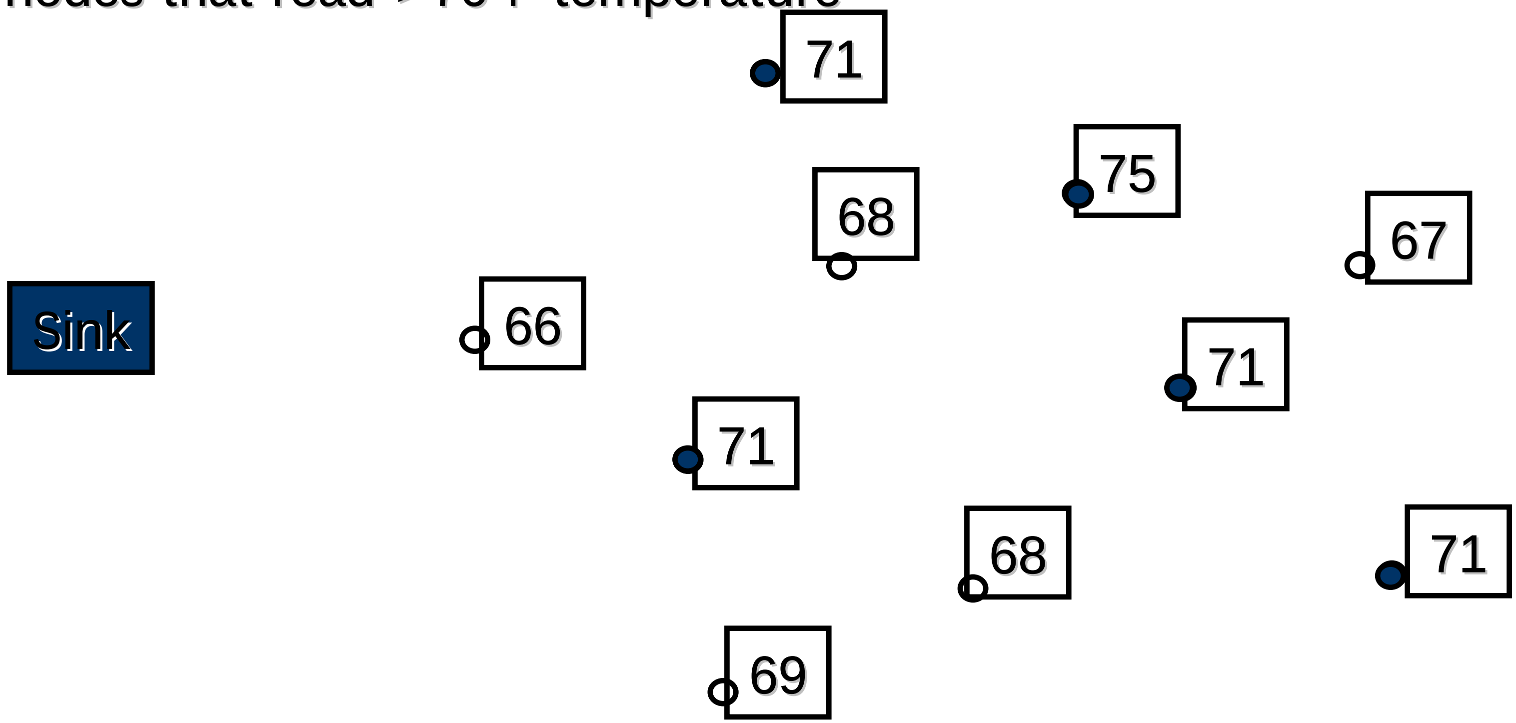
- Interest Dissemination
  - Users send their interest to a sensor node, a subset of the nodes or the entire network
  - This interest may be about a certain attribute of the sensor field or a triggering event
- Advertisement Of Available Data
  - Sensor nodes advertise the available data to the users and the users query the data which they are interested in

Sensor Query and Data Dissemination Protocol

- Provides user applications with interfaces to issue queries, respond to queries and collect incoming replies.
  - Attribute Based Query
    - “The locations of the nodes that sense temperature higher than 70F”
  - Location Based Query
    - “Temperatures read by the nodes in region A”

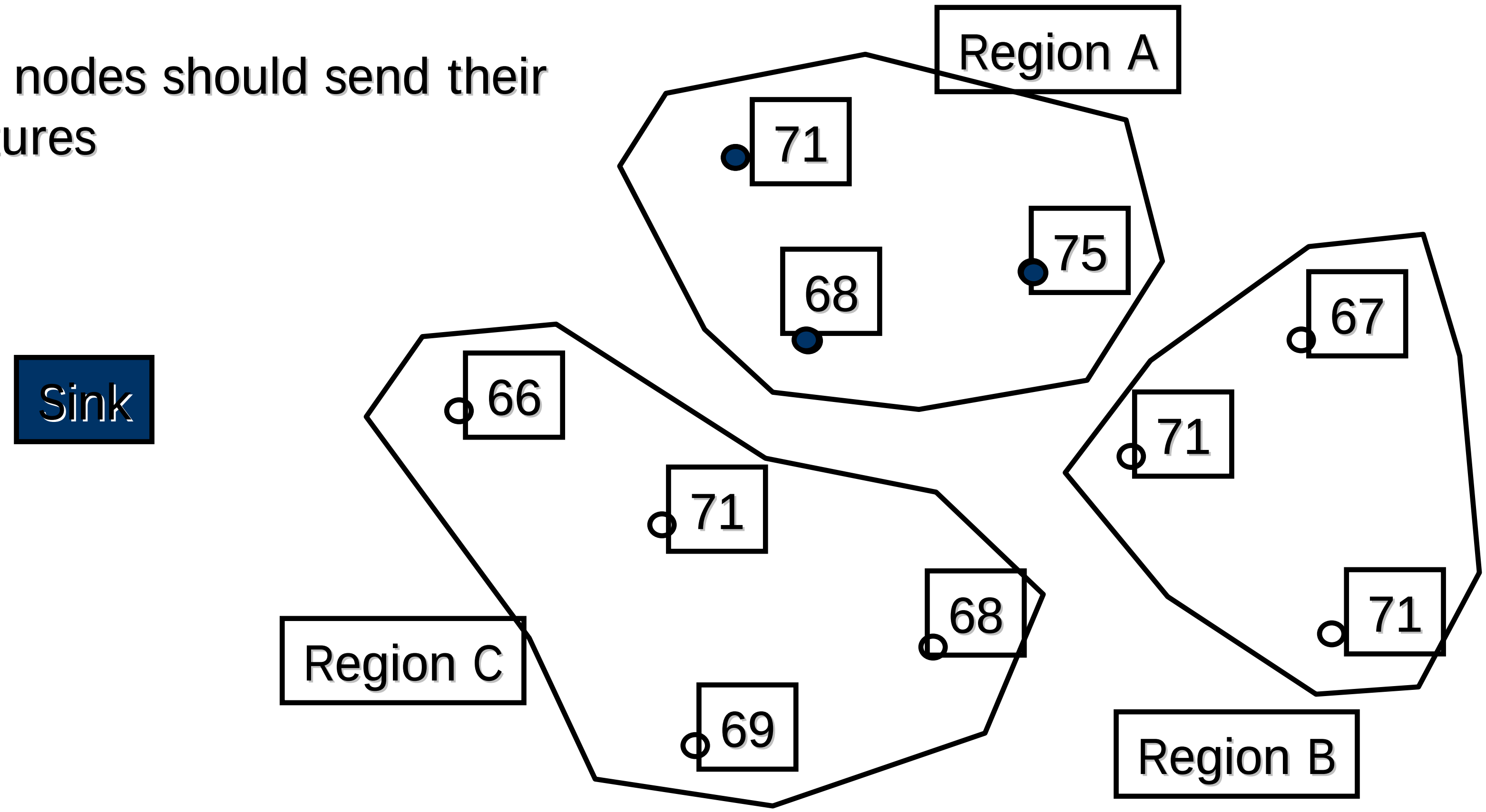
Attribute Based Query

Query:
Sensor nodes that read $>70^{\circ}$F temperature



Location Based Query

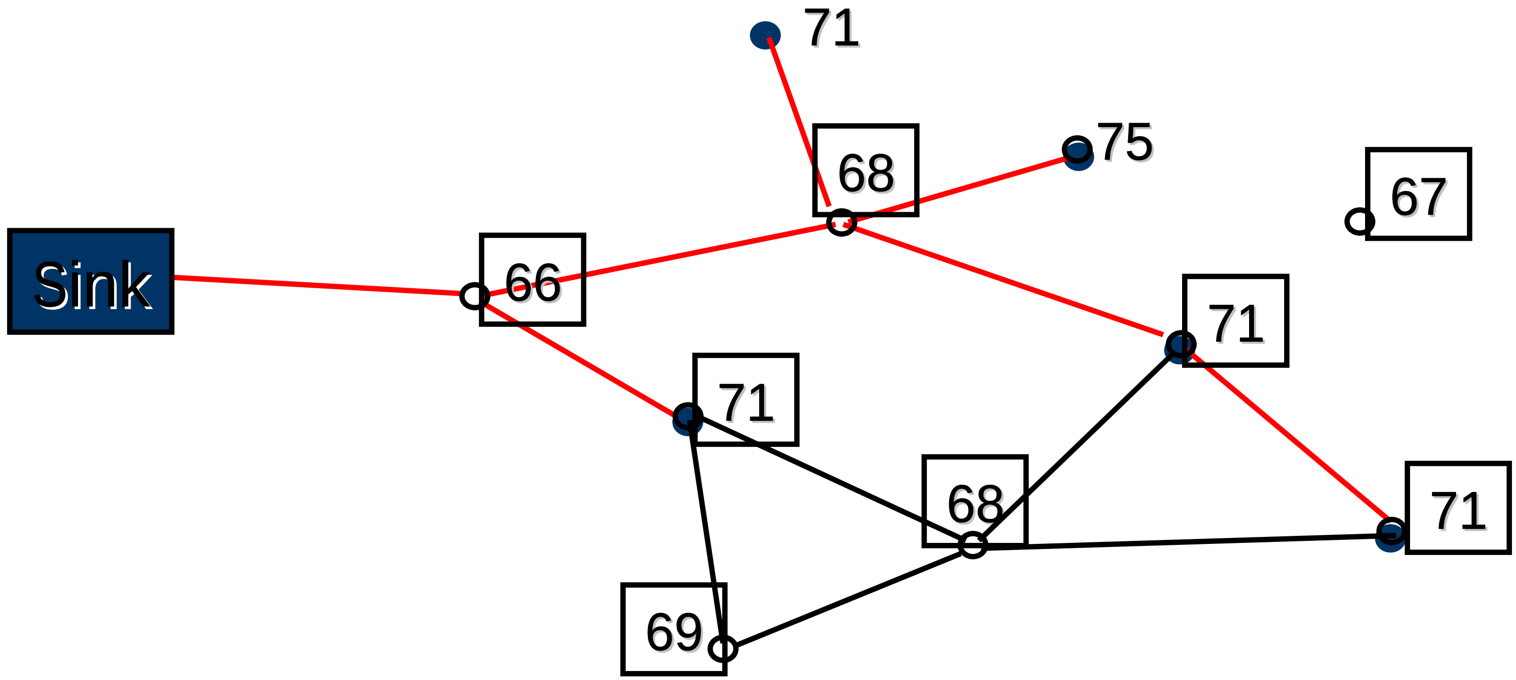
Query:
Region A nodes should send their temperatures



Important for broadcasting, multicasting, geocasting and anycasting

Data Aggregation (Data Fusion)

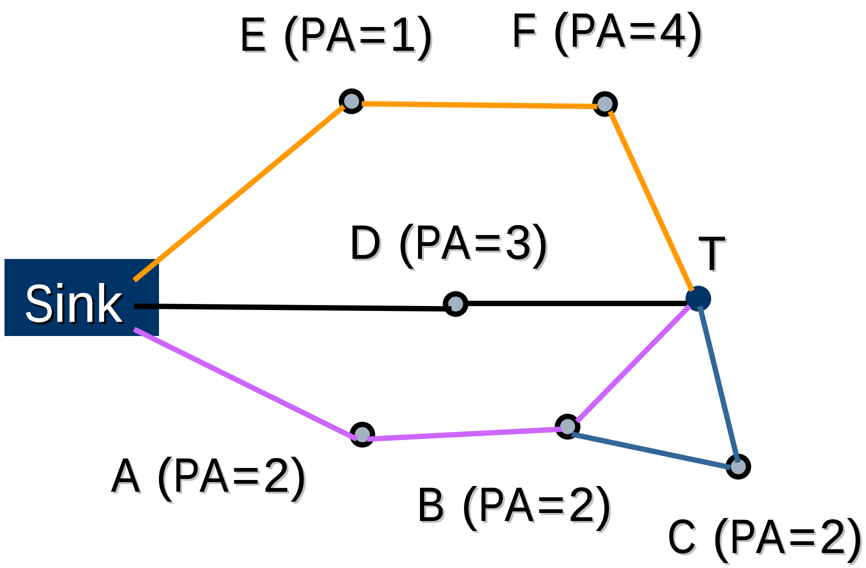
The sink asks the sensor nodes to report certain conditions. Data coming from multiple sensor nodes are aggregated.



Query:
Sensor nodes that read >70^{o}F temperature

Network layer

Energy Efficient Routing



Route 1: Sink-A-B-T (PA=4)
Route 2: Sink-A-B-C-T (PA=6)
Route 3: Sink-D-T (PA=3)
Route 4: Sink-E-F-T (PA=5)

- Maximum power available (PA) route
- Minimum hop route
- Minimum energy route
- Maximum minimum PA node route (Route along which the minimum PA is larger than the minimum PAs of the other routes is preferred, e.g., Route 3 is the most efficient; Route 1 is the second).

Routing in WSNs

- Why not use conventional routing algorithms?
  - Global (Unique) addresses, local addresses
  - Unique node addresses cannot be used in many sensor networks
    - sheer number of nodes, energy constraints, data centric approach
  - Node addressing is needed for
    - node management, querying, data aggregation and fusion, service discovery, routing
  - Very limited in power, computational capacities, and memory
  - Very prone to failures
  - Frequent topology change
  - May not have global ID like IP address
  - Densely deployed
  - Need tight integration with sensing tasks

Taxonomy of Routing Protocols

- Data Centric Protocols
  - Flooding, Gossiping, SPIN, SAR (Sequential Assignment Routing) , Directed Diffusion, Rumor Routing, Constrained Anisotropic Diffused Routing, COUGAR, ACQUIRE
- Hierarchical Protocols
  - LEACH, TEEN (Threshold Sensitive Energy Efficient Sensor Network Protocol), APTEEN, PEGASIS
- Location Based Protocols
  - MECN, SMECN (Small Minimum Energy Com Netw), GAF (Geographic Adaptive Fidelity), GEAR, Distributed Topology/Geographic Routing Algorithm

K. Akkaya and M. Younis, "A Survey on Routing Protocols for Wireless Sensor Networks," AdHoc Networks (Elsevier) Journal, 2004

Data-Centric Routing

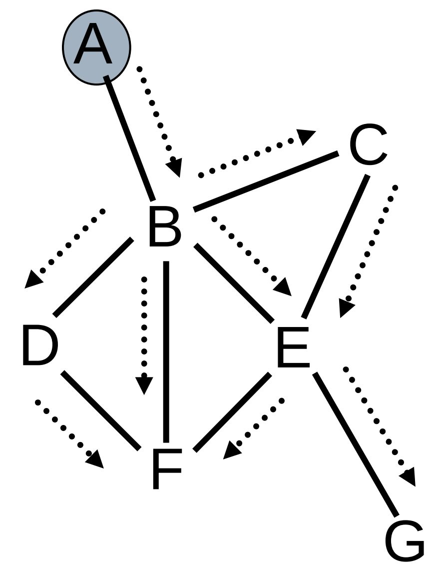
- Since sensor nodes are deployed randomly in large number, it is hard to assign specific IDs to each of the sensor nodes.
- Without a unique identifier, gathering data may become a challenge.
- To overcome this challenge, some routing protocols gather/route data based on the description of the data, i.e., data-centric

Data-Centric Routing

- The data-centric routing requires attribute based naming where the users are more interested in querying an attribute of the phenomenon, rather than querying an individual node.
- Example:
  - "the areas where the temperature is over 70F“ is a more common query than "the temperature read by a certain node”

Data Dissemination Approaches

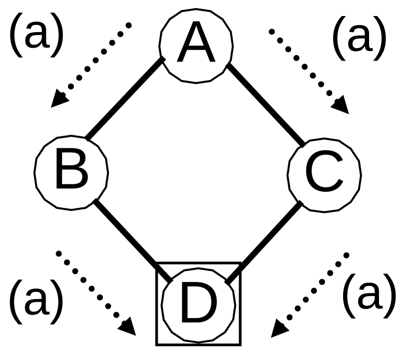
- Flooding
  - Send data to all neighbors
- Gossiping
  - Send data to one randomly selected neighbor
- Both are simple, but...
  - Implosions
  - Overlaps
  - Resource blindness
  - Energy inefficiency

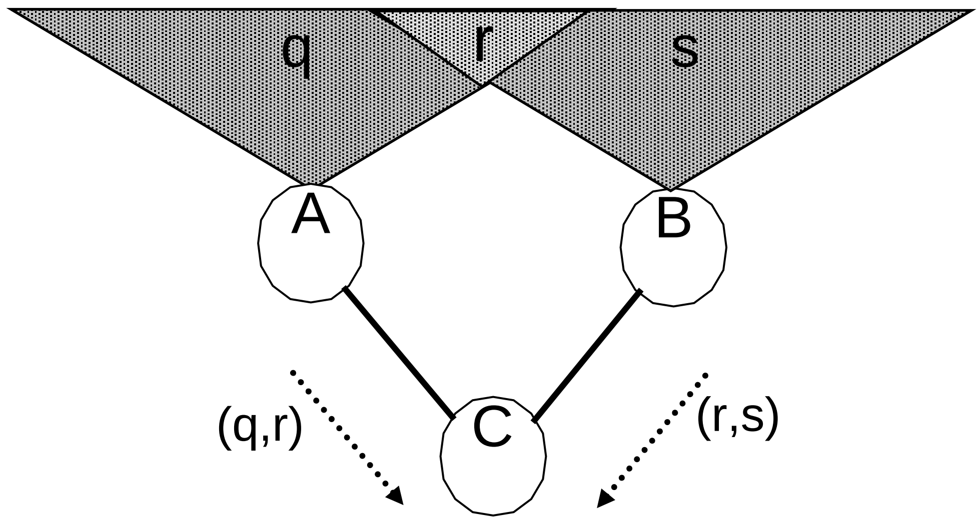


Problems

Implosion

Data Overlap





Resource Blindness

No knowledge about the available power of resources

Gossiping

- Uses randomization to save energy
- Selects a single node at random and sends the data to it
- Avoids implosions
- Distributes information slowly
- Energy dissipates slowly

SPIN: Sensor Protocol for Information via Negotiation

- Two basic ideas:
  - Sensors communicate with each other about the data that they already have and the data they still need to obtain
    - to conserve energy and operate efficiently
    - exchanging data about sensor data may be cheap
  - Sensors must monitor and adapt to changes in their own energy resources

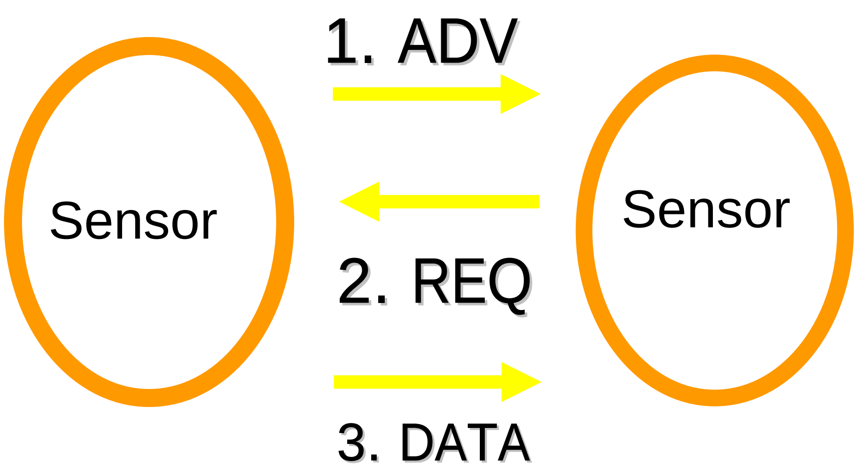
W.R. Heinzelman, J. Kulik, and H. Balakrishnan, “Adaptive Protocols for Information Dissemination in Wireless Sensor Networks”, ACM MobiCom’99

SPIN

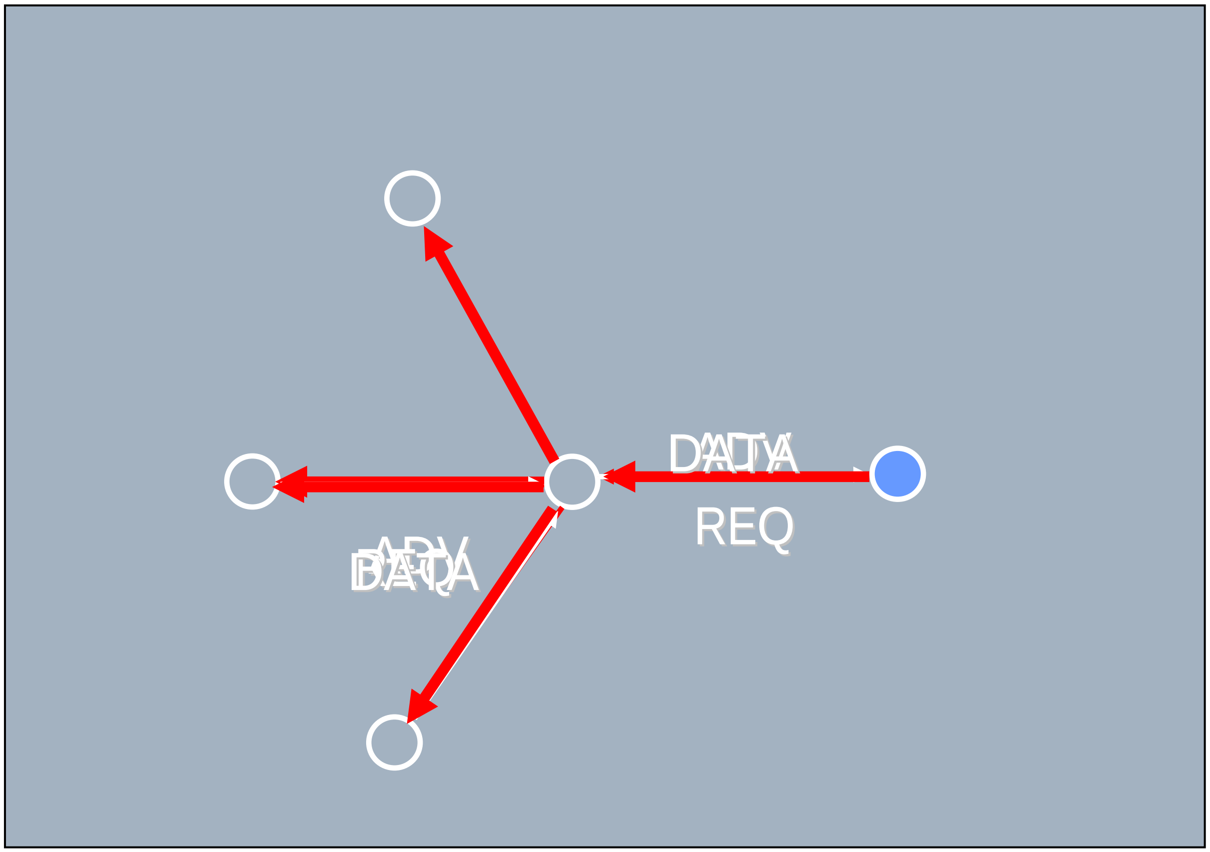
- Uses three types of messages: ADV, REQ, and DATA
- When a sensor node has something new, it broadcasts an advertisement (ADV) packet that contains the new data, i.e., the meta data
- Interested nodes send a request (REQ) packet.
- Data are sent to the nodes that request by DATA packets.
- This will be repeated until all nodes will get a copy.

SPIN

Good for disseminating information to all sensor nodes.
SPIN is based on data-centric routing where the sensors broadcast an advertisement for the available data and wait for a request from interested sinks



SPIN



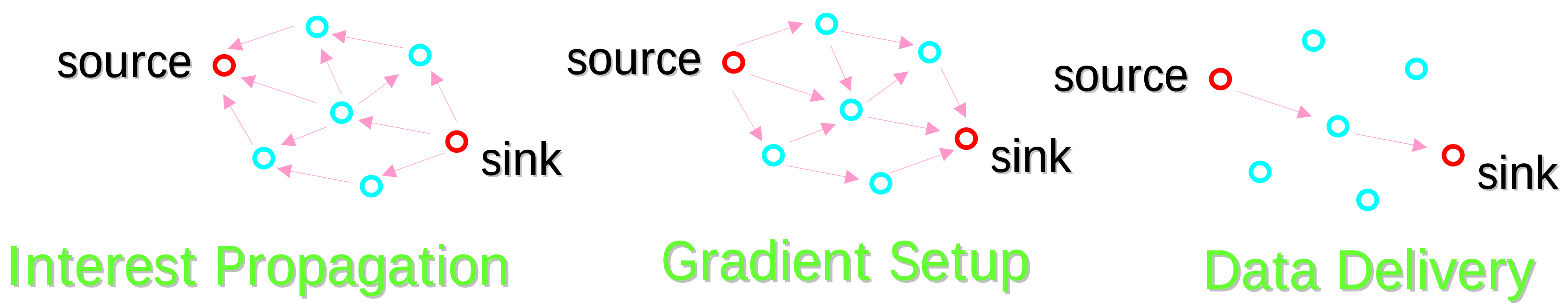
SPIN Protocol

- SPIN
  - 3-stage handshake protocol
  - Advantages
    - Simple, Implosion avoidance
  - Disadvantages
    - Cannot isolate the nodes that do not want to receive the information.
    - Consume unnecessary power

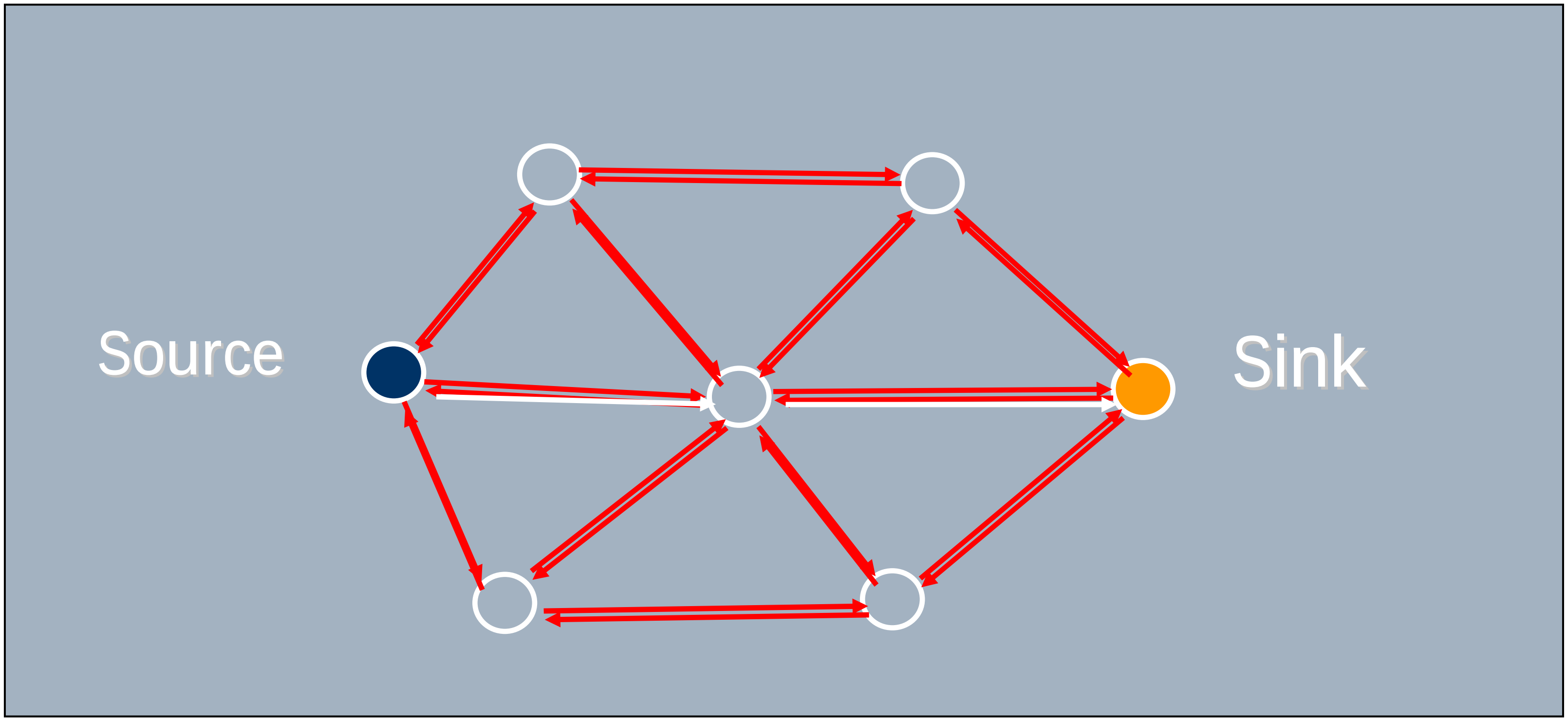
Directed Diffusion Routing Algorithm

Features

Sink sends interest, i.e., task descriptor, to all sensor nodes.
Interest is named by assigning attribute-value pairs.



Directed Diffusion Routing Algorithm



Gradient Setup

Data Delivery

C. Intanagonwiwat, et.al., "Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks", IEEE/ACM Transactions on Networking, 2003.

Directed Diffusion Routing Algorithm

- This is a DATA CENTRIC ROUTING scheme
- MAIN IDEA
  - DIFFUSE data through sensor nodes using a NAMING SCHEME
- REASON
  - Get rid off unnecessary operations of routing schemes to SAVE ENERGY.

What is DATA CENTRIC?

- Data-Centric
  - Sensor node does not need an identity!!!
    - What is the temp at node #27 ?
  - Data is named by attributes
    - Where are the nodes whose temperature recently
    - exceeded 30 degrees ?
    - How many pedestrians do you observe in region X?
    - Tell me in what direction that vehicle in region Y is
    - moving?
- Application-Specific
  - Nodes can perform application specific data aggregation, caching and forwarding

Directed Diffusion

- NAMING SCHEME: Data generated by sensor nodes is NAMED by ATTRIBUTE-VALUE pairs
- In order to create a query, an interest is defined using a list of attribute-value pairs such as name of objects, interval, duration, geographical area, etc.
- An arbitrary sensor node (usually the SINK) uses attribute-value pairs (interests) for the data and queries the sensors in an on-demand basis

Example for Attribute-Value Pairs

Example: (Animal Tracking Task)

Type = four legged animal (detect animal location)
Interval = 20 ms (send back events every 20 ms)
Duration = 10 seconds (.. for the next 10 seconds)
Rec = [-100,100,200,00] (from sensors within the rectangle)

The task description specifies an interest for data matching for attributes
→ called INTEREST.

Example for Attribute-Value Pairs

The data sent in response to interests are also named similarly.

Example:
Sensor detecting the animal generates the following data:

Type – four legged animal (type of animal seen)
Instance= elephant (instance of this type)
Locaton = (125,220) (node location)
Intensity = 0.6 (signal amplitude measure)
Confidence = 085 (confidence in the match)
Timestamp= 01:20:40 (event generation time)

Directed Diffusion Overview

- The sink broadcasts this interest to sensor nodes to query information from a particular area in the field.
- As the interest propagates, data may be locally transformed (e.g., aggregated) at each node, or be cached
- Other nodes express interests based on these attributes
- Network nodes propagate interests
  - Interests establish gradients that direct diffusion of data
  - Path of interest propagation sets up a reverse data path for data that matches the interest
- The interests in the caches are then used to compare the received data with the values in the interests.

Rules for Interests and Gradients

- What are the local rules for propagating interests?
  - E.g., just flood interest
  - More sophisticated techniques possible:
  - directional interest propagation, based on cached aggregate information
    - "I recently heard about suspicious activity from neighbor A, so let me try sending this interest for recent intrusions to that neighbor"
- What are the local rules for establishing gradients?
  - E.g., highest gradient towards neighbor who first sends interest
  - Others possible e.g., towards neighbor with highest remaining energy

Data Transmission Choices

- Different local data forwarding rules can result in different kinds of transmission
  - single path delivery
  - multi-path delivery, with traffic on each link proportional to its gradient
    - data probabilistically striped along different paths
    - redundant delivery across different paths
    - layered transmission along different paths
  - delivery from single source to multiple sinks
  - delivery from multiple sources to multiple sinks

Directed Diffusion vs SPIN

- On-Demand Data Query is different
  - In DD → Sink queries sensors if a specific data is available by flooding some tasks
  - In SPIN → Sensors advertise the availability of data allowing sinks to query that data.

Directed Diffusion Advantages

- DD is data centric → no need for a node addressing mechanism
- Each node can do aggregation, caching and sensing
- DD is energy efficient since it is on demand and no need to maintain global network topology.

Directed Diffusion Disadvantages

- Not generally applicable since it is based on a query driven data delivery model.
- For applications needing continuous data delivery (e.g., environmental monitoring) → DD is not a good choice.
- Naming schemes are application dependent and each time must be defined a-priori.
- Matching process for data and queries cause some overhead at sensors.

Hierarchical Protocols

- Sensor nodes are deployed with a limited amount of energy
- Hierarchical-architecture protocols are proposed to address the scalability and energy consumption challenges of sensor networks
- Sensor nodes form clusters where the cluster-heads aggregate and fuse data to conserve energy
- The cluster-heads may form another layer of clusters among themselves before reaching the sink.
- Examples
  - Low-Energy Adaptive Clustering Hierarchy (LEACH) (Heinzelman'00)
  - Power-efficient GAthering in Sensor Information Systems (PEGASIS) (Lindsey01, Lindsey02),
  - Threshold sensitive Energy Efficient sensor Network protocol (TEEN) (Manjeshwar01)
  - AdaPtive Threshold sensitive Energy Efficient sensor Network Protocol (APTEEN) (Manjeshwar02)

Low Energy Adaptive Clustering Hierarchy (LEACH)

- LEACH is a clustering based protocol which minimizes energy dissipation in sensor networks
- Idea:
  - Randomly select sensor nodes as cluster heads, so the high energy dissipation in communicating with the base station is spread to all sensor nodes in the network
  - Forming clusters is based on the received signal strength
  - Cluster heads can then be used kind of routers (relays) to the sink.

W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, “Energy-Efficient Communication Protocol for Wireless Microsensor Networks,'' IEEE Proc. of the Hawaii Int. Conf. on System Sciences, January 2000.

LEACH

Two Phases: Set-up Phase and Steady-Phase

Set-up Phase:

* Sensors may elect themselves to be a local cluster head at any time with a certain probability. (Reason: to balance the energy dissipation)

* A sensor node chooses a random number between 0 and 1.

* If this random number is less than the threshold T(n), the sensor node becomes a cluster-head.

$$T(n) = P / \{1 - P[r \bmod (1/P)]\} \quad \text{if } n \text{ is element of } G$$

where *P* is the desired percentage to become a cluster head (e.g., 0.05)

r is the current round

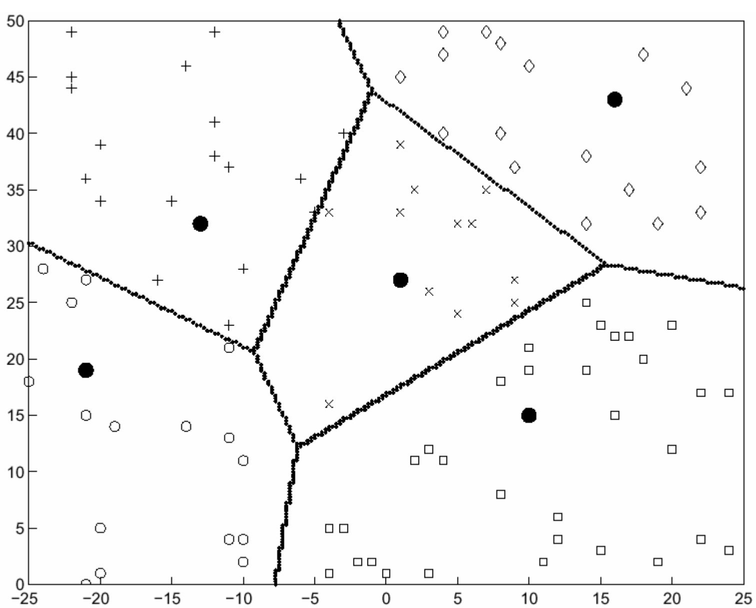
G is the set of nodes that have not been a cluster head in the last 1/P rounds.

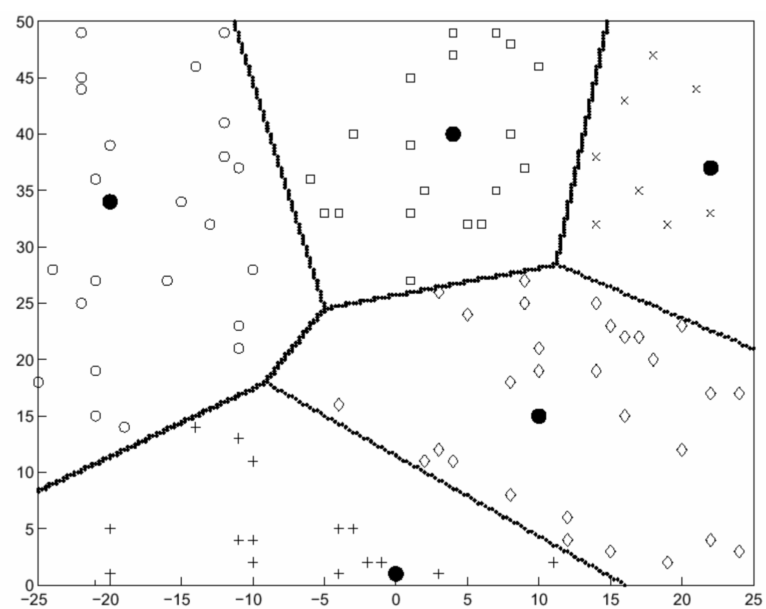
LEACH

* After the cluster heads are selected, the cluster heads advertise to all sensor nodes in the network that they are the new cluster heads.

* Each node accesses the network through the cluster head that requires minimum energy to reach.

Dynamic Clusters





LEACH

- Once the nodes receive the advertisement, they determine the cluster that they want to belong based on the signal strength of the advertisement from the cluster heads to the sensor nodes.
- The nodes inform the appropriate cluster heads that they will be a member of the cluster
- Afterwards the cluster heads assign the time on which the sensor nodes can send data to them

LEACH

STEADY STATE PHASE:

Sensors begin to sense and transmit data to the cluster heads which aggregate data from the nodes in their clusters.

After a certain period of time spent on the steady state, the network goes into start-up phase again and enters another round of selecting cluster heads.

LEACH

- Optimum Number of Clusters --- ????????
- - too few: nodes far from cluster heads
  - too many: many nodes send data to SINK.
  -

LEACH

- Achieves over a factor of 7 reduction in energy dissipation compared to direct communication.
- The nodes die randomly and dynamic clustering increases lifetime of the system.
- It is completely distributed and requires no global knowledge of the network.
- It uses single hop routing where each node can transmit directly to the cluster head and the sink.
- It is not applicable to networks deployed in large regions.
- Furthermore, the idea of dynamic clustering brings extra overhead, e.g., head changes, advertisements etc. which may diminish the gain in energy consumption.

Location-Based Protocols

- If the locations of the sensor nodes are known, the routing protocols can use this information to reduce the latency and

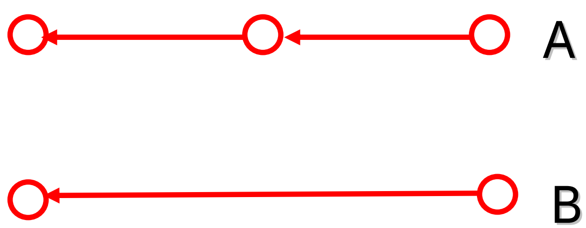
  energy consumption of the sensor network.
- Although GPS is not envisioned for all types of sensor networks, it can still be used if stationary nodes with large amount of energy are allowed

Example: Minimum Energy Communication Network

Minimum Energy Communication Network (MECN), L. Li and J.Y. Halpern, "Minimum-Energy Mobile Wireless Networks Revisited" IEEE ICC 2001

Uses graph theory:

* Each node knows its exact location
* Network is represented by a graph G', and it is assumed that the resulting graph is connected
* A sub-graph G of G' is computed.
* G connects all nodes with minimum energy cost.



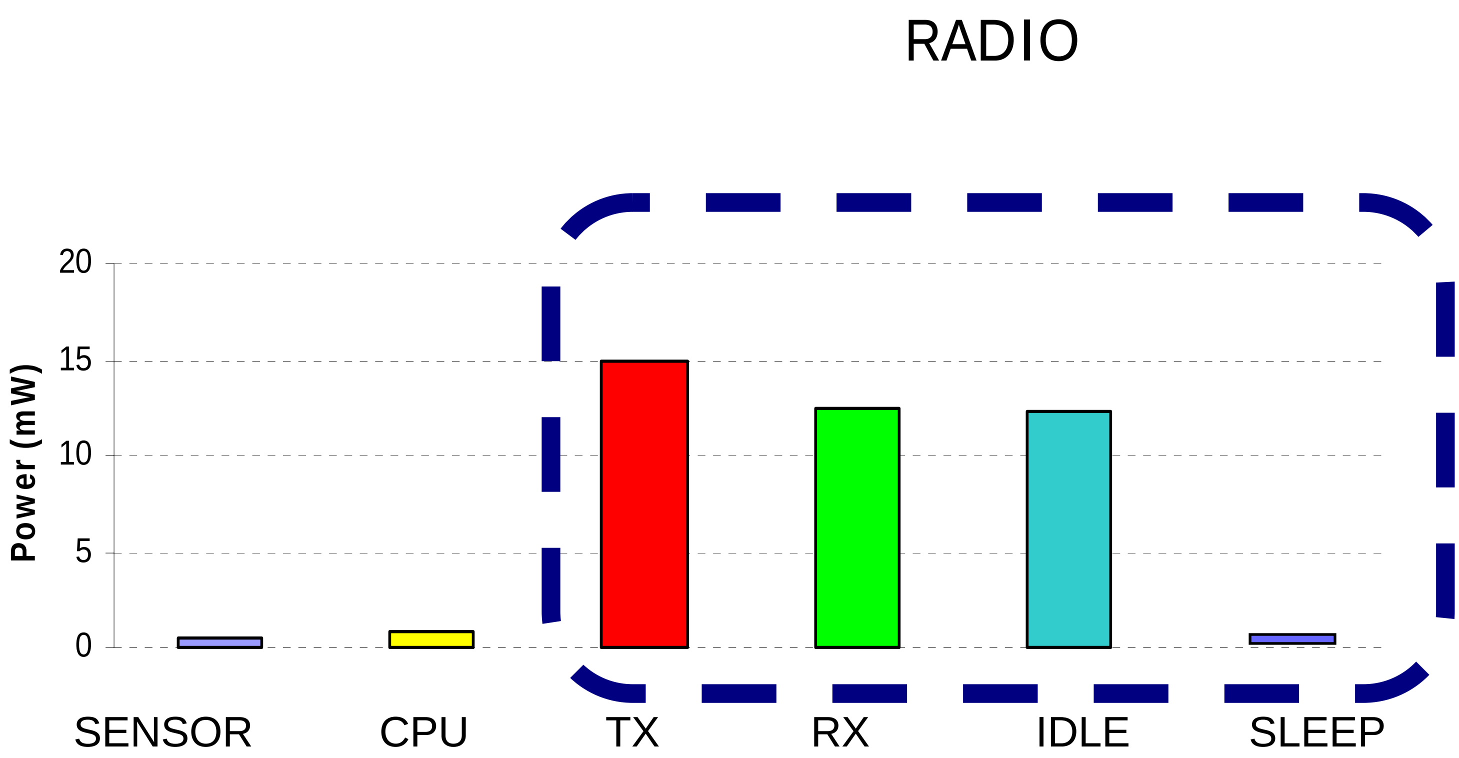
Connection A requires less energy than connection B because the power required to transmit between a pair of nodes increases as the n^{th} power of the distance between them ($n>=2$).

MAC

Objectives of MAC Protocols

- Collision Avoidance
- Energy Efficiency
- Scalability
- Latency
- Fairness
- Throughput
- Bandwidth Utilization

Power Consumption



Major Sources of Energy Waste

* Idle Listening
  - Long idle time when no sensing event happens
  - Collisions
  - Control Overhead
  - Overhearing
* Transmitter
* Receiver

Common to all wireless networks

OBJECTIVE: Reduce energy consumption !!

Challenges in Medium Access Control in WSNs

- 1. WSN Architecture
  - High density of nodes
  - Increased collision probability
  - Signaling overhead should be minimized to prevent further collisions
  - Sophisticated and simple collision avoidance protocols required

Challenges in Medium Access Control in WSNs

- 2. Limited Energy Resources
  - Connectivity and the performance of the network is affected as nodes die
  - Transmitting and receiving consumes almost same energy
  - Frequent power up/down eats up energy
  - Need very low power MAC protocols
  - Minimize signaling overhead
  - Avoid idle listening
  - Prevent frequent radio state changes (active←→sleep)

Challenges in Medium Access Control in WSNs

- 3. Limited Processing and Memory Capabilities
  - Complex algorithms cannot be implemented
  - Conventional layered architecture may not be appropriate
  - Centralized or local management is limited
  - Simple scheduling algorithms required
  - Cross-layer optimization required
  - Self-configurable, distributed protocols required

Challenges in Medium Access Control in WSNs

- 4. Limited Packet Size
  - Unique node ID is not practical
  - Limited header space
  - Local IDs should be used for inter-node communication
  - MAC protocol overhead should be minimized

- 5. Cheap Encoder/Decoders
  - Cheap node requirement prevents sophisticated encoders/decoders to be implemented
  - Simple FEC codes required for error control
  - Channel state dependent MAC can be used to decrease error rate

Challenges in Medium Access Control in WSNs

- 6. Inaccurate Clock Crystals
  - Cheap node requirement prevents expensive crystals to be implemented
  - Synchronization problems
  - TDMA-based schemes are not practical
- 7. Event-based Networking
  - Observed data depends on physical phenomenon
  - Spatial and temporal correlation in the physical phenomenon should be exploited

BOTTOMLINE: Existing MAC protocols cannot be used for sensor networks!!!!

Overview of MAC Protocols

- 1. Contention-Based MAC Protocols
- 2. Reservation-Based MAC Protocols
- 3. HYBRID MAC PROTOCOLS
- 4. CROSS LAYER PROTOCOLS

Contention-Based MAC Protocols

- Every node tries to access the channel based on carrier sense mechanism
- Contention-based protocols provide robustness and scalability to the network
- The collision probability increases with increasing node density
- They can support variable, but highly correlated and dominantly periodic traffic.

SMAC

- Aims to decrease energy consumption by sleep schedules
- Virtual clustering of sensor nodes
- Overhear avoidance and message passing
- Trades off latency for reduced energy consumption
- Neighbor discovery and channel assignment combined
- Random wake up of sensors from sleep schedules

W. Ye, et. al., “Medium Access Control with Coordinated Adaptive Sleeping for Wireless Sensor Networks,“ IEEE/ACM Trans. on Networking, June 2004.

S-MAC

- Trade Off
  - Energy Efficiency versus Node-Level Fairness & Latency
- Basic Scheme: Periodic Listen and Sleep
- Choosing Schedule
  - The node randomly chooses a time to go to sleep.
  - The node receives and follows its neighbor’s schedule by setting its schedule to be the same.
  - If the node receives a different schedule after it selects its own schedule, it adopts both schedules
- Maintaining Schedule
  - To update schedule by sending a SYNC packet periodically

S-MAC

- Collision Avoidance
  - Virtual carrier sense
    - Checking the keeping silent time recorded in the NAV (network allocation vector)
  - Physical carrier sense
    - Listening to the channel for possible transmission
  - RTS/CTS exchange
- Overhearing Avoidance
  - Let interfering nodes go to sleep after they hear an RTS or CTS packet

S-MAC

- Message passing
  - Only one RTS packet and one CTS packet are used
    - To avoid large control overhead and long delay
  - ACK would be sent after each data fragment
    - To avoid fragment loss or error
    - To prevent hidden terminal problem
  - After the neighbor node hears the RTS and CTS, it will go to sleep for the time that is needed to transmit all the fragments (using the duration field)

S-MAC

- Energy Saving vs. Increasing Latency (Multi-hop Network)
  - Carrier sense delay
    - Determined by the contention window size
  - Backoff delay
    - Because the node detects another transmission or the collision occurs
  - Transmission delay
    - Determined by channel bandwidth, packet length and the coding scheme adopted
  - Propagation delay
    - Determined by the distance between the sending and receiving nodes
  - Processing delay
    - Depends on the computing power of the node and the efficiency of in-network data processing algorithms
  - Queueing delay
    - Depends on the traffic load
  - Sleep delay
    - Caused by the nodes periodic sleeping

S-MAC

- SMAC has very good energy conserving compared with IEEE802.11
- Shortcomings
  - Nodes belonging to different subnets might not be able to connect
  - A mainly static network is assumed
- Trades off latency for reduced energy consumption
- Redundant data is still sent with increased latency
- Increased collision rate due to sleep schedules

T-MAC

- One of the disadvantages of S-MAC is that it can not provide adaptivity to bursty traffic since the sleep schedules are fixed length
- T-MAC introduces an adaptive duty cycle.
- The nodes listen to the channel only when there is traffic which reduces the amount of energy wasted on idle listening
- Variable sleep schedules are introduced for different traffic
- Both S-MAC and T-MAC provide significant energy savings compared to IEEE 802.11, however, at the cost of increased latency and throughput degradation

T. van Dam, K. Langendoen, ``An Adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks,'' Proc. ACM SenSys, November 2003

Remarks On Contention Based Protocols

- Generally, contention-based protocols provide scalability and lower delay, when compared to reservation-based protocols
- On the other hand, the energy consumption is significantly higher than the TDMA-based approaches due to collisions and collision avoidance schemes
- Moreover, contention-based protocols are more adaptive to the changes in the traffic volume and hence applicable to applications with bursty traffic such as event-based applications
- Furthermore, the synchronization and clustering requirements of reservation-based protocols make contention-based more favorable in scenarios where such requirements can not be fulfilled.

Reservation Based MAC Protocols

- These are collision-free MAC protocols!
- The advantage of collision-free communication since each node transmits data to a central agent during its reserved slot
- Hence, the duty cycle of the nodes is decreased resulting in further energy efficiency
- Generally, these protocols follow common principles where the network is divided into clusters and each node communicates according to a specific super-frame structure

Reservation Based MAC Protocols

- The super-frame structure consists of two main parts
  - 1. Reservation Period is used by the nodes to reserve their slots for communication through a central agent, i.e., cluster-head
  - 2. Data Period consists of multiple slots, that is used by each sensor for transmitting information
- Among the proposed TDMA schemes, the contention schemes for reservation protocols, the slot allocation principles, the frame size and clustering approaches differ in each protocol

TRAMA: Energy Efficient Collision-Free MAC

- The protocol is based on a time-slotted structure and uses a distributed election scheme based on traffic requirements of each node to determine the time slot that a node should use
- Each node gets information about its every two-hop neighbor and the traffic information of each node during a random access period, i.e., the reservation period
- Based on this information, each node calculates its priority and decides on which time slot to use
- Nodes sleep during their allocated slots if they do not have any packets to send or receive

V. Rajendran, K. Obraczka, and J. J. Garcia-Luna-Aceves,
``Energy-Efficient, Collision-Free Medium Access Control for Wireless Sensor Networks,''
Proc. ACM SenSys 2003, LA, CA, Nov. 2003

Bit-Map-Assisted (BMA) MAC Protocol

- An intra-cluster communication bit-map-assisted (BMA) MAC protocol with an energy efficient TDMA (E-TDMA) scheme
- The protocol consists of cluster set-up phase and steady state phase
- In the cluster set-up phase, cluster head is selected based on the available energy in each node
- Accordingly, an E-TDMA MAC scheme is used in each of the clusters formed by the cluster-heads
- In each super frame, the reservation period is slotted for contention and the data period is divided into two periods, i.e., data transmission period and idle period
- The duration of the data period is fixed and the data transmission period is changed based on the traffic demands of the nodes

J. Li, G. Y. Lazarou, ``A bit-map-assisted energy-efficient MAC Scheme for wireless sensor networks,'' Proc. ACM IPSN, April 2004

Remarks On Reservation Based Protocols

- Overall, Contention Based Protocols, i.e., TDMA-based protocols provide collision-free communication and achieve improved energy efficiency
- However, such TDMA-based protocols require an infrastructure consisting of cluster heads which coordinate the time slots assigned to each node
- Although many clustering algorithms have been proposed with these protocols, the optimality and the energy efficiency of these algorithms still need to be investigated
- In addition, TDMA-based protocols cause high latency due to the frame structure

Remarks On Reservation Based Protocols

- Hence TDMA-based MAC protocols may not be suitable for WSN applications where delay is important in estimating event features and the traffic has bursty nature
- Moreover, since a time slotted communication is performed in the clusters, inter-cluster interference has to be minimized such that nodes with overlapping schedules in different clusters do not collide which each other
- Finally, time synchronization is an important part of the TDMA-based protocols and synchronization algorithms are required

Hybrid Medium Access Control Schemes

- While a pure TDMA-based access scheme dedicates the entire channel to a single sensor node, a pure Frequency-Division Multiple Access (FDMA) or Code-Division Multiple Access (CDMA) scheme allocates minimum signal bandwidth per node
- Such contrast brings the tradeoff between the access capacity and the energy consumption
- Hybrid schemes in reservation-based protocols aim to leverage the tradeoff introduced in channel allocation by combining TDMA approaches with FDMA or CDMA schemes

Hybrid TDMA/FDMA

- An analytical formula is derived to find the optimum number of channels for each node, which gives the minimum system power consumption.
- This determines the hybrid TDMA-FDMA scheme to be used
- Although the MAC protocol also assumes that clusters are formed in the network, it is a good example of cross-layer optimization where the MAC protocol is designed according to the physical layer properties.

E.Shih, et al., Physical Layer Driven Protocol and Algorithm Design for Energy-Efficient Wireless Sensor Networks, Proc. of ACM Mobicom'01, July 2001

Remarks On Hybrid Protocols

- ADVANTAGES:
  - The hybrid reservation protocols provide performance enhancements in terms of collision avoidance and energy efficiency due to improved channel organization
- DISADVANTAGES:
  - They require sophisticated physical and MAC layer protocols that support CDMA or FDMA communication or unique radio components
  - Hence, these protocols may not be applicable for high density WSN where sensor node cost is an important factor

Cross Layer Solutions

- Incorporating physical layer and network layer information into the MAC layer design improves the performance in WSN
- Route-aware protocols provide lower delay bounds while physical layer coordination improve the energy efficiency of the overall system
- Moreover, since sensor nodes are characterized by their limited energy capabilities and memory capacities, cross-layer solutions provide efficient solutions in terms of both performance and cost
- However, care must be taken while designing cross-layer solutions since the interdependence of each parameter should be analyzed in detail

Cross-Layer Solutions

- Multi-hop introduces a network delay in S-MAC.
- Latency increases linearly with the hop count.
- Although the slope of the linearity is reduced to half by the adaptive listening algorithm, the protocol still introduces significant latency compared to pure contention-based protocols.
- Also the frame structure in TDMA-based protocols plus multi-hopping imposes significant network delay.
- Multi-hop route of the packets should be considered in MAC
- Consequently, route-aware protocols have been proposed

W. C. Park et.al., ``Trade-off Energy and Delay between MAC Protocols for Wireless Sensor Networks,“ in Proc. Int. Conf. on Advanced Communication Technology, Feb’04

DMAC: Data Gathering MAC

- A route-aware contention-based MAC protocol for data gathering
- Data is collected through a unidirectional tree
- DMAC introduces a sleep schedule such that the nodes on a multihop path wake up sequentially as the packet traverses
- Moreover, since small sized packets are used, RTS/CTS mechanism is not used.
- DMAC incorporates local synchronization protocols in order to perform local scheduling and uses data prediction in case a node requires a higher duty cycle for data transmission
- Based on these techniques, multi-hop effects on the delay performance is minimized specifically for data gathering applications where a unidirectional tree is used

“An Adaptive Energy-Efficient and Low-Latency MAC for Data Gathering in Wireless Sensor Networks”, G. Lu, B. Krishnamachari, C.S. Raghavendra, Proc. IEEE Int. Parallel and Distributed Processing Symposium, April 2004