Sensors and Wireless Sensor Networks

Roadmap

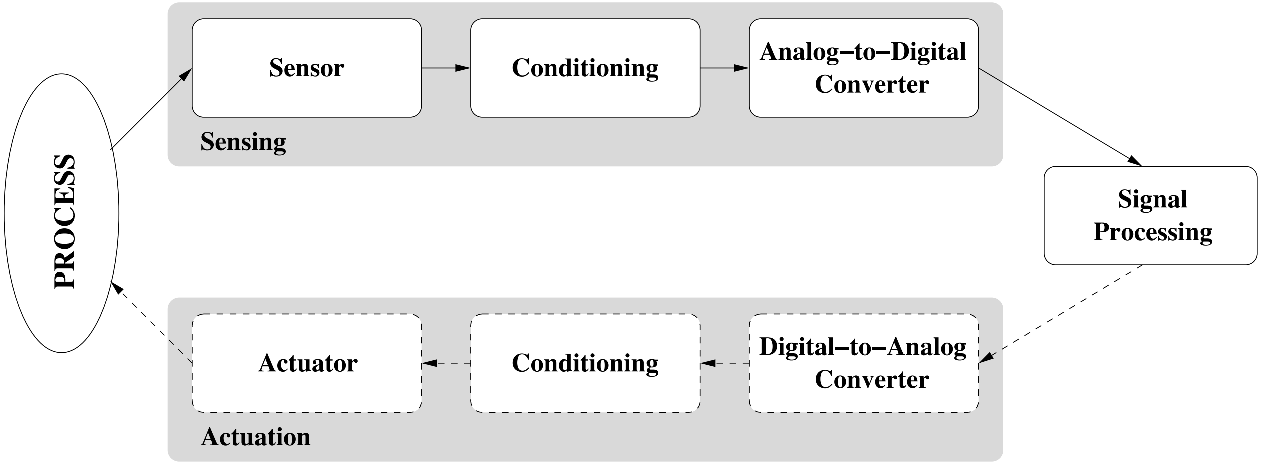
- Motivation for a Network of Wireless Sensor Nodes
  - Definitions and background
  - Challenges and constraints
  - Overview of topics covered

Sensing and Sensors

- Sensing: technique to gather information about physical objects or areas
- Sensor (transducer): object performing a sensing task; converting one form of energy in the physical world into electrical energy

- Examples of sensors from biology: the human body
  - eyes: capture optical information (light)
  - ears: capture acoustic information (sound)
  - nose: captures olfactory information (smell)
  - skin: captures tactile information (shape, texture)

Sensing (Data Acquisition)



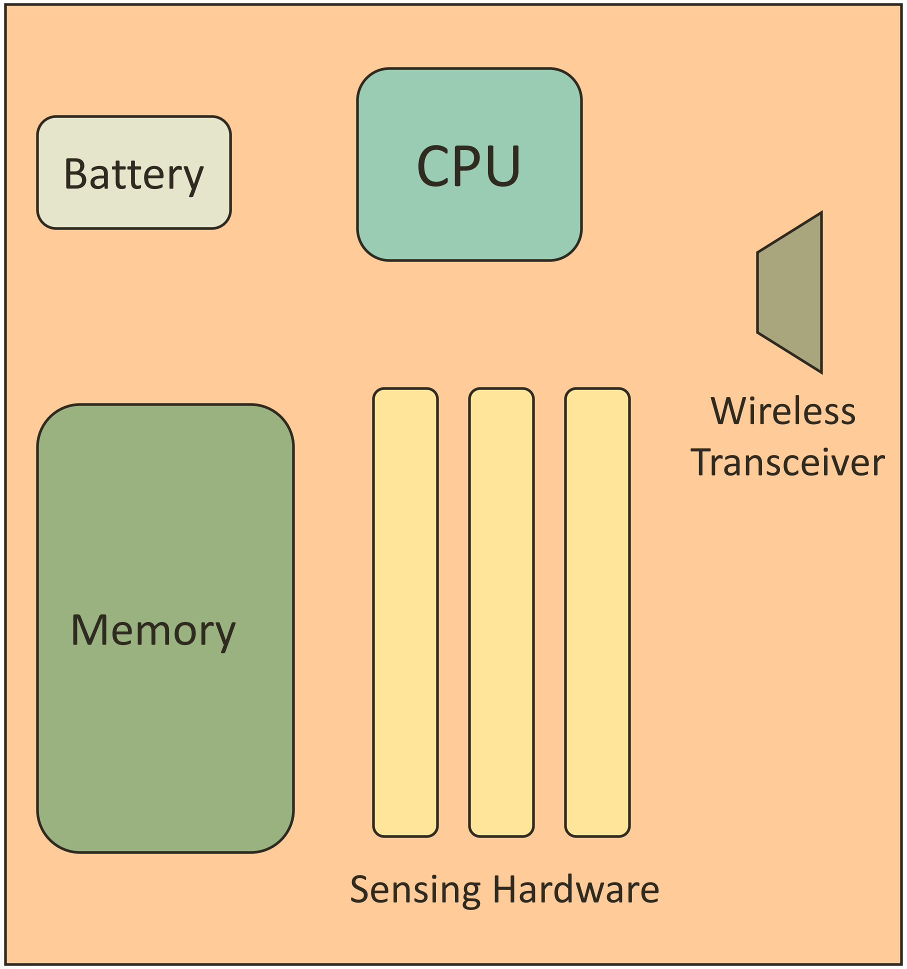
- Sensors capture phenomena in the physical world (process, system, plant)
- Signal conditioning prepare captured signals for further use (amplification, attenuation, filtering of unwanted frequencies, etc.)
- Analog-to-digital conversion (ADC) translates analog signal into digital signal
- Digital signal is processed and output is often given (via digital-analog converter and signal conditioner) to an actuator (device able to control the physical world)

Sensor Classifications

- Physical property to be monitored determines type of required sensor

Type	Examples
Temperature	Thermistors, thermocouples
Pressure	Pressure gauges, barometers, ionization gauges
Optical	Photodiodes, phototransistors, infrared sensors, CCD sensors
Acoustic	Piezoelectric resonators, microphones
Mechanical	Strain gauges, tactile sensors, capacitive diaphragms, piezoresistive cells
Motion, vibration	Accelerometers, mass air flow sensors
Position	GPS, ultrasound-based sensors, infrared-based sensors, inclinometers
Electromagnetic	Hall-effect sensors, magnetometers
Chemical	pH sensors, electrochemical sensors, infrared gas sensors
Humidity	Capacitive and resistive sensors, hygrometers, MEMS-based humidity sensors
Radiation	Ionization detectors, Geiger-Mueller counters

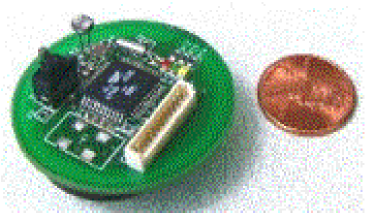
Sensors



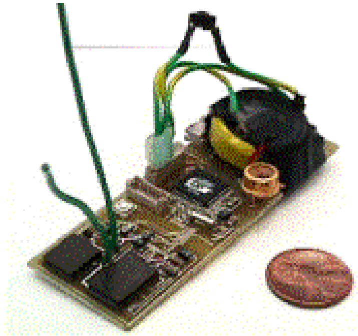
- Enabled by recent advances in MEMS technology
- Integrated Wireless Transceiver
- Limited in
  - Energy
  - Computation
  - Storage
  - Transmission range
  - Bandwidth

Sensors

Modern Sensor Nodes



UC Berkeley: COTS Dust



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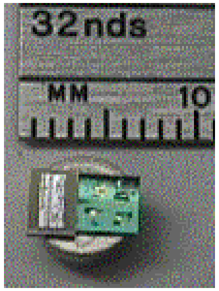
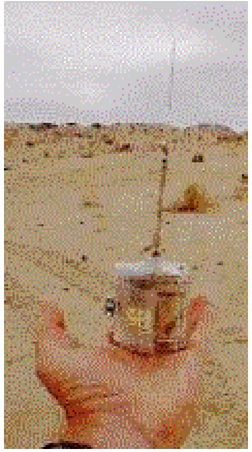
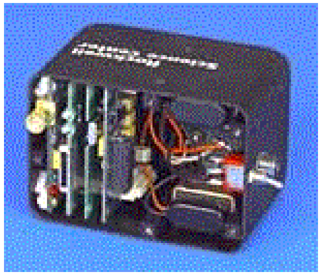


UC Berkeley: Smart Dust



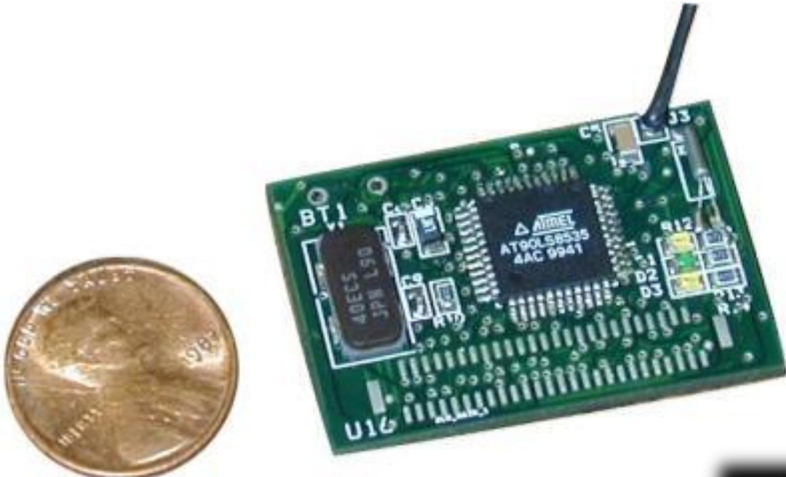
UCLA: WINS



Rockwell: WINS

JPL: Sensor Webs

Sensor Nodes

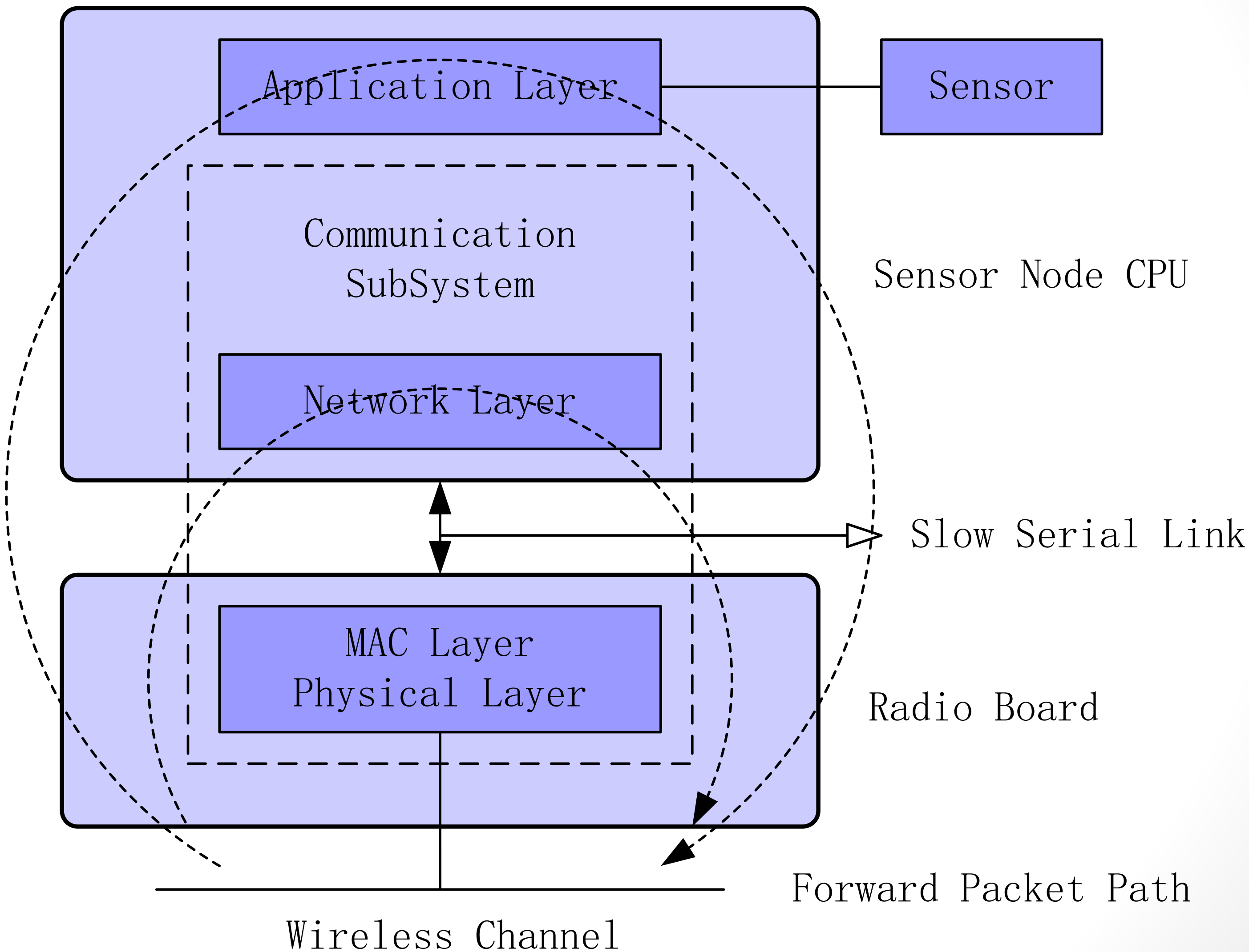


Sensors (contd.)

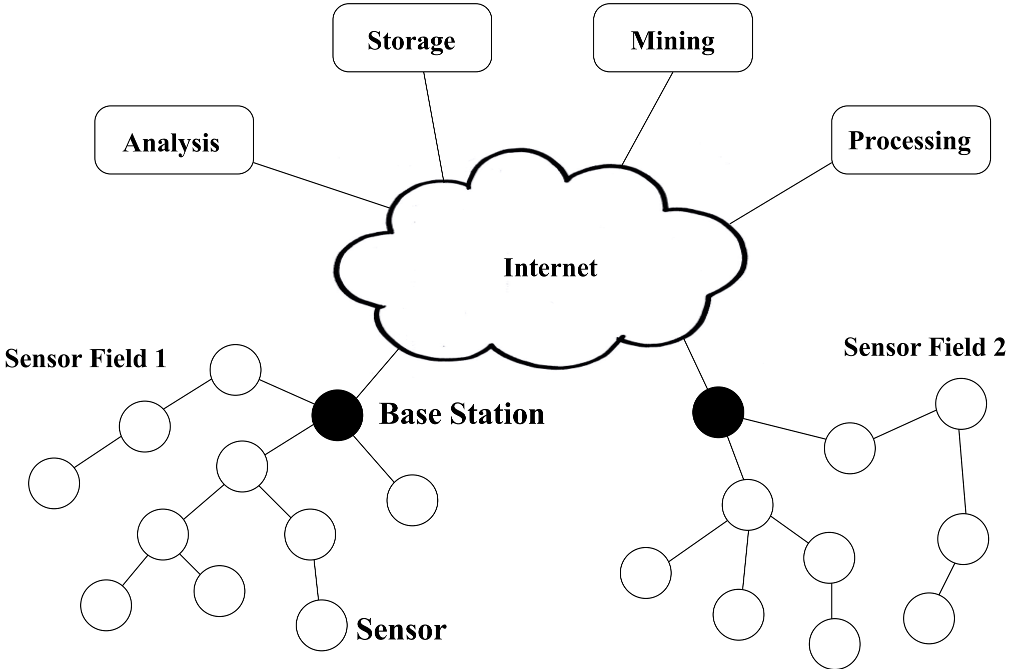
- The overall architecture of a sensor node consists of:
  - The sensor node processing subsystem running on sensor node main CPU
  - The sensor subsystem and
  - The communication subsystem
- The processor and radio board includes:
  - TI MSP430 microcontroller with 10kB RAM
  - 16-bit RISC with 48K Program Flash
  - IEEE 802.15.4 compliant radio at 250 Mbps
  - 1MB external data flash
  - Runs TinyOS 1.1.10 or higher
  - Two AA batteries or USB
  - 1.8 mA (active); 5.1uA (sleep)

Crossbow Mote
TPR2400CA-TelosB

Overall Architecture of a Sensor Node



Wireless Sensor Network (WSN)



- Multiple sensors (often hundreds or thousands) form a network to cooperatively monitor large or complex physical environments
- Acquired information is wirelessly communicated to a base station (BS), which propagates the information to remote devices for storage, analysis, and processing

Networked vs. Individual Sensors

- Extended range of sensing:
  - Cover a wider area of operation
- Redundancy:
  - Multiple nodes close to each other increase fault tolerance
- Improved accuracy:
  - Sensor nodes collaborate and combine their data to increase the accuracy of sensed data
- Extended functionality:
  - Sensor nodes can not only perform sensing functionality, but also provide forwarding service.

History of Wireless Sensor Networks

- DARPA:
  - Distributed Sensor Nets Workshop (1978)
  - Distributed Sensor Networks (DSN) program (early 1980s)
  - Sensor Information Technology (SensIT) program
- UCLA and Rockwell Science Center
  - Wireless Integrated Network Sensors (WINS)
  - Low Power Wireless Integrated Microsensor (LWIM) (1996)
- UC-Berkeley
  - Smart Dust project (1999)
  - Concept of “motes”: extremely small sensor nodes
- Berkeley Wireless Research Center (BWRC)
  - PicoRadio project (2000)
- MIT
  - µAMPS (micro-Adaptive Multidomain Power-aware Sensors) (2005)

History of Wireless Sensor Networks

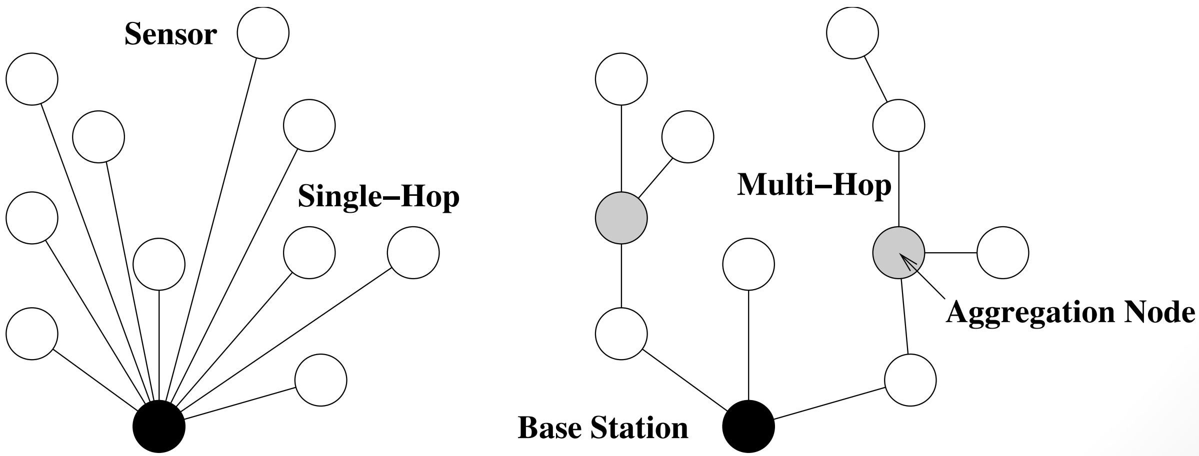
- Recent commercial efforts
  - Crossbow (www.xbow.com)
  - Sensoria (www.sensoria.com)
  - Worldsens (worldsens.citi.insa-lyon.fr)
  - Dust Networks (www.dustnetworks.com)
  - Ember Corporation (www.ember.com)

WSN Communication

- Characteristics of typical WSN:
  - Low data rates (comparable to dial-up modems)
  - Energy-constrained sensors
- IEEE 802.11 family of standards
  - Most widely used WLAN protocols for wireless communications in general
  - Can be found in early sensor networks or sensors networks without stringent energy constraints
- IEEE 802.15.4 is an example for a protocol that has been designed specifically for short-range communications in WSNs
  - Low data rates
  - Low power consumption
  - Widely used in academic and commercial WSN solutions

Single-Hop vs. Multi-Hop

- Star topology
  - Every sensor communicates directly (single-hop) with the base station
  - May require large transmit powers and may be infeasible in large geographic areas
- Mesh topology
  - Sensors serve as relays (forwarders) for other sensor nodes (multi-hop)
  - May reduce power consumption and allows for larger coverage
  - Introduces the problem of routing



Challenges in WSNs: Energy

- Sensors typically powered through batteries
  - replace battery when depleted
  - recharge battery, e.g., using solar power
  - discard sensor node when battery depleted
- For batteries that cannot be recharged, sensor node should be able to operate during its entire mission time or until battery can be replaced

- Energy efficiency is affected by various aspects of sensor node/network design
- Physical layer:
  - switching and leakage energy of CMOS-based processors

$$E_{CPU} = E_{switch} + E_{leakage} = C_{total} * V_{dd}^{2} + V_{dd} * I_{leak} * \Delta t$$

Challenges in WSNs: Energy

- Medium access control layer:
  - contention-based strategies lead to energy-costly collisions
  - problem of idle listening
- Network layer:
  - responsible for finding energy-efficient routes
- Operating system:
  - small memory footprint and efficient task switching
- Security:
  - fast and simple algorithms for encryption, authentication, etc.
- Middleware:
  - in-network processing of sensor data can eliminate redundant data or aggregate sensor readings

Challenges in WSNs: Self-Management

- Ad-hoc deployment
  - many sensor networks are deployed “without design”
    - sensors dropped from airplanes (battlefield assessment)
    - sensors placed wherever currently needed (tracking patients in disaster zone)
    - moving sensors (robot teams exploring unknown terrain)
  - sensor node must have some or all of the following abilities
    - determine its location
    - determine identity of neighboring nodes
    - configure node parameters
    - discover route(s) to base station
    - initiate sensing responsibility

Challenges in WSNs: Self-Management

- Unattended operation
  - Once deployed, WSN must operate without human intervention
  - Device adapts to changes in topology, density, and traffic load
  - Device adapts in response to failures

- Other terminology
  - Self-organization is the ability to adapt configuration parameters based on system and environmental state
  - Self-optimization is the ability to monitor and optimize the use of the limited system resources
  - Self-protection is the ability recognize and protect from intrusions and attacks
  - Self-healing is the ability to discover, identify, and react to network disruptions

Challenges in WSNs: Wireless Networks

- Wireless communication faces a variety of challenges
- Attenuation:
  - limits radio range

$$P_r \; \mu \; \frac{P_t}{d^2}$$

- Multi-hop communication:
  - increased latency
  - increased failure/error probability
  - complicated by use of duty cycles

Challenges in WSNs: Decentralization

- Centralized management (e.g., at the base station) of the network often not feasible to due large scale of network and energy constraints
- Therefore, decentralized (or distributed) solutions often preferred, though they may perform worse than their centralized counterparts

- Example: routing
- Centralized:
  - BS collects information from all sensor nodes
  - BS establishes "optimal" routes (e.g., in terms of energy)
  - BS informs all sensor nodes of routes
  - Can be expensive, especially when the topology changes frequently
- Decentralized:
  - Each sensors makes routing decisions based on limited local information
  - Routes may be nonoptimal, but route establishment/management can be much cheaper

Challenges in WSNs: Design Constraints

- Many hardware and software limitations affect the overall system design
- Examples include:
  - Low processing speeds (to save energy)
  - Low storage capacities (to allow for small form factor and to save energy)
  - Lack of I/O components such as GPS receivers (reduce cost, size, energy)
  - Lack of software features such as multi-threading (reduce software complexity)

Challenges in WSNs: Security

- Sensor networks often monitor critical infrastructure or carry sensitive information, making them desirable targets for attacks

- Attacks may be facilitated by:
  - Remote and unattended operation
  - Wireless communication
  - Lack of advanced security features due to cost, form factor, or energy

- Conventional security techniques often not feasible due to their computational, communication, and storage requirements
- As a consequence, sensor networks require new solutions for intrusion detection, encryption, key establishment and distribution, node authentication, and secrecy

Comparison

Traditional Networks	Wireless Sensor Networks
General-purpose design; serving many applications	Single-purpose design; serving one specific application
Typical primary design concerns are network performance and latencies; energy is not a primary concern	Energy is the main constraint in the design of all node and network components
Networks are designed and engineered according to plans	Deployment, network structure, and resource use are often ad-hoc (without planning)
Devices and networks operate in controlled and mild environments	Sensor networks often operate in environments with harsh conditions
Maintenance and repair are common and networks are typically easy to access	Physical access to sensor nodes is often difficult or even impossible
Component failure is addressed through maintenance and repair	Component failure is expected and addressed in the design of the network
Obtaining global network knowledge is typically feasible and centralized management is possible	Most decisions are made localized without the support of a central manager

Roadmap

- Motivation for a Network of Wireless Sensor Nodes
- Applications
  - Structural Health Monitoring
  - Traffic Control
  - Health Care
  - Pipeline Monitoring
  - Precision Agriculture

Structural Health Monitoring

- Motivation
  - Events:
    - On August 2, 2007, a highway bridge unexpectedly collapsed in Minnesota
    - Nine people were killed in the event
    - Potential causes: wear and tear, weather, and the weight of a nearby construction project
    - In fact, the BBC reported (August 14, 2007) that China had identified more than 6,000 bridges that were damaged or considered to be dangerous
  - These accidents motivate wireless sensor networks for monitoring bridges and similar structures

Structural Health Monitoring

- Motivation:
  - Traditional inspections:
    - Visual inspection ➔ everyday
      - Labor-intensive, tedious, inconsistent, and subjective
    - Basic inspections ➔ at least once a year
    - Detailed inspection ➔ at least every five years on selected bridges
    - Special inspections ➔ according to technical needs
      - The rest require sophisticated tools ➔ expensive, bulky, and power consuming

Local and Global Inspections

- ***Local inspection techniques*** focus on detecting highly localized, imperceptible fractures in a structure
  - Requires:
    - a significant amount of time
    - the disruption of the normal operation of the structure
- ***Global inspection techniques*** aim to detect a damage or defect that is large enough to affect the entire structure
  - Researcher have been developing and testing *wireless sensor networks as global inspection techniques*

Wisden

http://enl.usc.edu/projects/wisden/

- First prototype to employ WSN for monitoring structural health
  - Installing a large scale wired data acquisition system may take several weeks and is quite expensive
  - ***First deployment -*** *for conducting seismic experiments*
    - on an imitation of a full-scale 28×28 square foot hospital ceiling
    - the overall weight which the ceiling supports is approximately 12,000 pounds
  - ***Second deployment***
    - 25 nodes (a tree topology) and a 16 bit vibration card
    - a high-sensitive triaxial accelerometer is attached to the vibration card
    - designed for high-quality, low-power vibration sensing
    - the task of the network was to reliably *send time-synchronized vibration data* to a *remote* sink over a *multi-hop route*
      - NACK
      - hop-by-hop scheme

Golden Gate Bridge (University of California)

http://www.cs.berkeley.edu/~binetude/ggb/

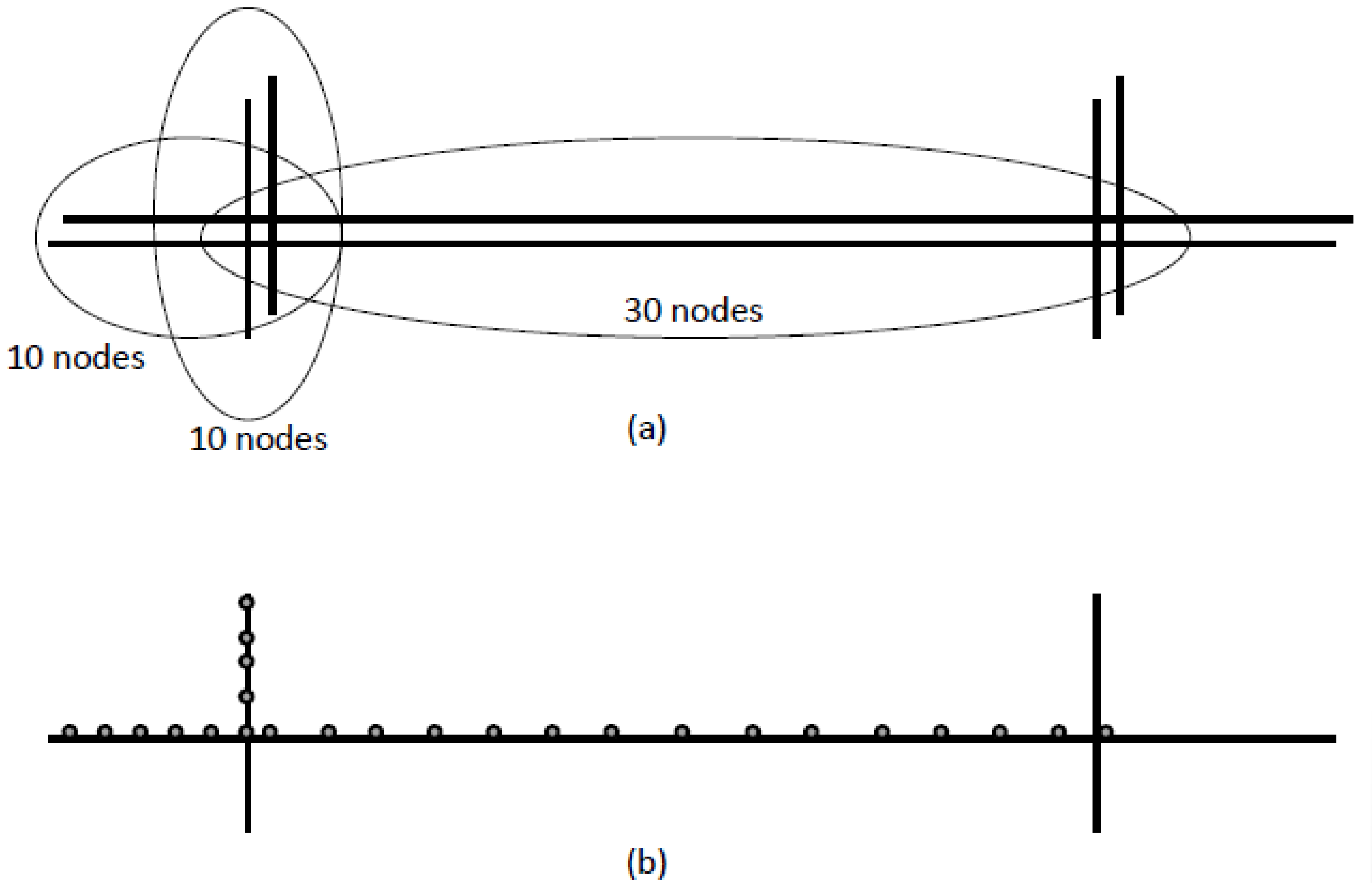


Figure: The deployment scenario on the Golden Gate Bridge

Golden Gate Bridge

- 64 wireless sensor nodes deployed on this bridge
- The network monitors ambient vibrations synchronously
  - 1 KHz rate, ≤10µs jitter, accuracy=30µG, over a 46 hop network
- The *goal* of the deployment:
  - determine the response of the structure to both ambient and extreme conditions
  - compare actual performance to design predictions
  - measure ambient structural accelerations from wind load
  - measure strong shaking from a potential earthquake
  - the installation and the monitoring was conducted without the disruption of the bridge's operation

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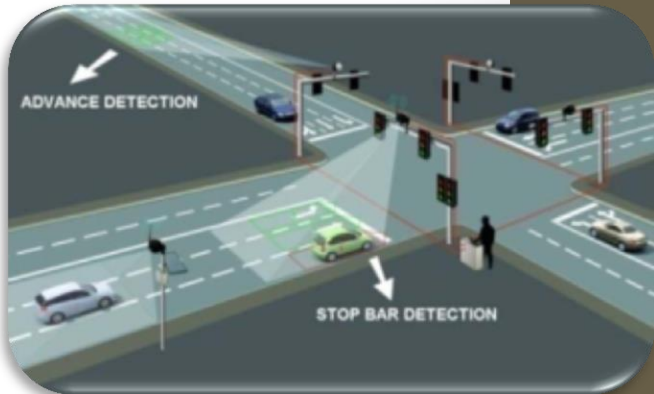
  - Precision Agriculture
  - Underground Mining

Traffic Control

- Motivation:
  - Ground transportation is a vital and a *complex* socio-economic infrastructure
  - It is *linked* with and provides *support* for *a variety of systems*, such as supply-chain, emergency response, and public health
  - The 2009 Urban Mobility Report reveals that in 2007, congestion caused urban Americans to
    - travel *4.2 billion hours more*
    - purchase *an extra 2.8 billion gallons of fuel*
  - Congestion *cost is very high* - $87.2 billion; an increase of more than 50% over the previous decade

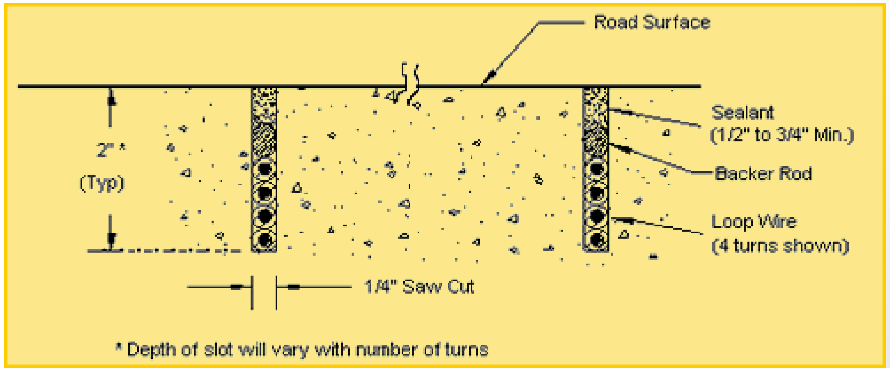


Traffic Control

- Motivation:
  - Building new roads is *not* a feasible solution for many cities
    - lack of free space
    - high cost of demolition of old roads
  - *One approach*: put in place distributed systems that reduce congestions
    - *Gather information* about the density, sizes, and speed of vehicles on roads
    - *Infer congestions*
    - *Suggest alternative routes* and emergency exits

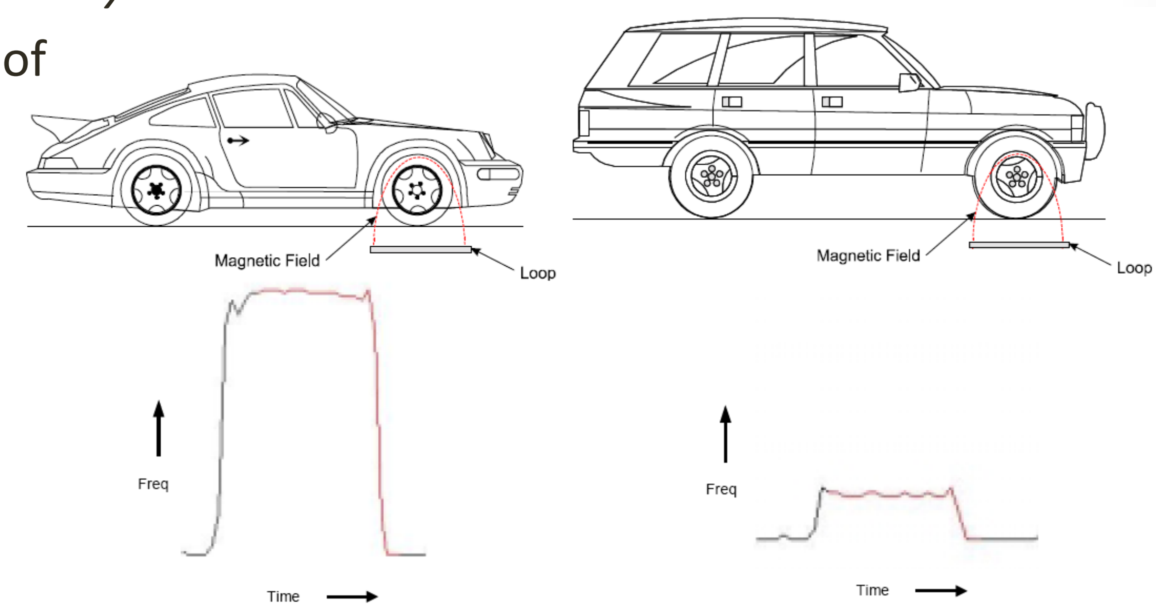
The Sensing Task

- Inductive loops (in-road sensing devices)
  - *Advantages:*
    - Unaffected by weather
    - Provide direct information (few ambiguity)
  - How does it work: using *Faraday's induction law*
    - A coil of wire (several meters in diameter, passes an electric current through the coil)
    - Buried under the road and connected to a roadside control box
    - Magnetic field strength can be induced as a result of a current and the speed and the size of passing vehicles



Magnetic Sensors

- Magnetic sensors can determine the *direction* and *speed* of a vehicle
  - A moving vehicle can disturb the distribution of the magnetic field
    - by producing its own magnetic field
    - by cutting across it
- The magnitude and direction of the disturbance depends on
  - The *speed*, *size*, *density* and *permeability* of the vehicle



Magnetic Sensors

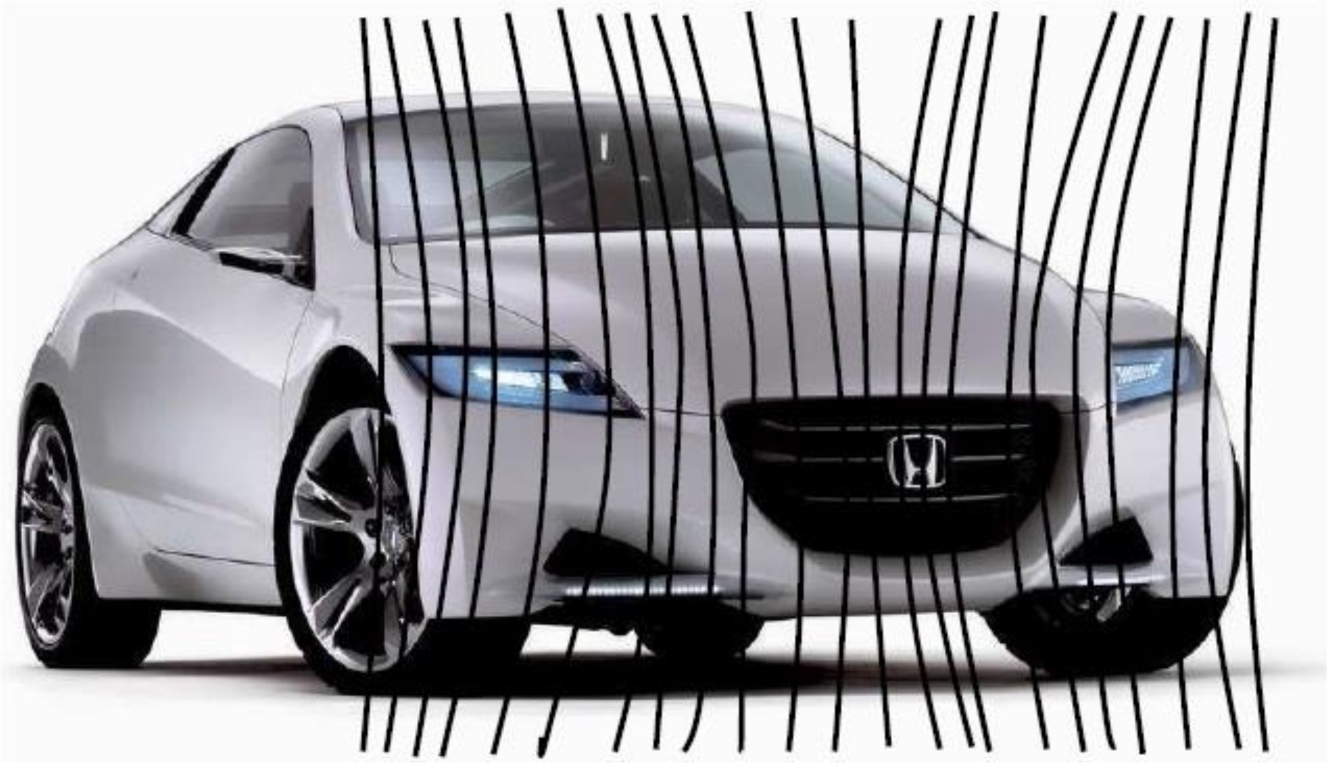


Figure: Detection of a moving vehicle with an ARM magnetic sensor (Caruso and Withanawasam 1999)

Magnetic Sensors

- Almost all road vehicles *contain* a large mass of *steel*
- The magnetic *permeability of steel is* much *higher* than the surrounding air
- *Steel* has the capacity to *concentrate* the *flux lines* of the Earth's magnetic field
- The *concentration* of magnetic flux *varies as* the *vehicle moves*; it can be *detected* from a distance of up to *15m*
- The field variation reveals a *detailed* magnetic signature
- It is possible to distinguish between different types of vehicles

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  - **Health Care**
  - Pipeline Monitoring
  - Precision Agriculture
  - Underground Mining

Health Care

- A wide range of health care applications have been proposed for WSN, including *monitoring patients* with:
  - Parkinson's Disease and epilepsy
  - heart patients
  - patients rehabilitating from stroke or heart attack
  - elderly people
- Health care applications do *not* function as *standalone* systems
- They are *integral parts* of a comprehensive and complex health and rescue system

Health Care

- Motivation:
  - *cost* is very high
    - according to the US Centers for Medicare and Medicaid Services (CMS):
      - the national health spending of the country in 2008 was estimated to be *$2.4 trillion USD*
      - the costs caused by heart disease and stroke are around *$394 billion*
    - this is a concern for *policy makers*, *health care providers*, *hospitals*, *insurance companies,* and *patients*
  - higher spending does *not* imply quality service or prolonged lifetime (Kulkarni and Öztürk 2007)
    - for example, in 2000, the US spent more on health care than any other country in the world – an average of $4,500 USD per person - but ranked 27th in average life expectancy
    - many countries *achieve higher* life expectancy rates *at a lower cost*

Health Care

- Motivation:
  - preventive health care - to reduce health spending and mortality rate
    - but some patients find certain practices *inconvenient, complicated,* and *interfering* with their daily life (Morris 2007)
    - many *miss* checkup visits or therapy sessions because of *a clash of schedules with* established living and working *habits*, *fear* of overexertion, or transportation *cost*

Health Care

- To deal with these problems, researchers proposed comprehensible solutions that involve the following tasks:
  - building *pervasive systems* that *provide* patients with *rich information* about diseases and their prevention mechanisms
  - seamless integration of health infrastructures with *emergency and rescue operations* as well as *transportation systems*
  - developing reliable and unobtrusive health *monitoring systems* that can be worn by patients to *reduce the task* and *presence of medical personnel*
  - *alarming* nurses and doctors *when* medical intervention is *necessary*
  - *reducing inconvenient* and *costly check-up visits* by *creating reliable links* between autonomous health monitoring systems and health institutions

Commercially Available Sensors

- Pulse oxygen saturation sensors
- Blood pressure sensors
- Electrocardiogram (ECG)
- Electromyogram (EMG) for measuring muscle activities
- Temperature sensors (core body temperature and skin temperature)
- Respiration sensors
- Blood flow sensors
- Blood oxygen level sensor

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Pipeline Monitoring

- *Objective:* monitoring gas, water and oil pipelines
- Motivation:
  - management of pipelines presents *a formidable challenge*
    - long length, high value, high risk
    - difficult access conditions
    - requires continuous and unobtrusive monitoring
  - *leakages* can occur due to excessive deformations
    - earthquakes
    - landslides or collisions with an external force
    - corrosion, wear, material flaws
    - intentional damage to the structure

Pipeline Monitoring

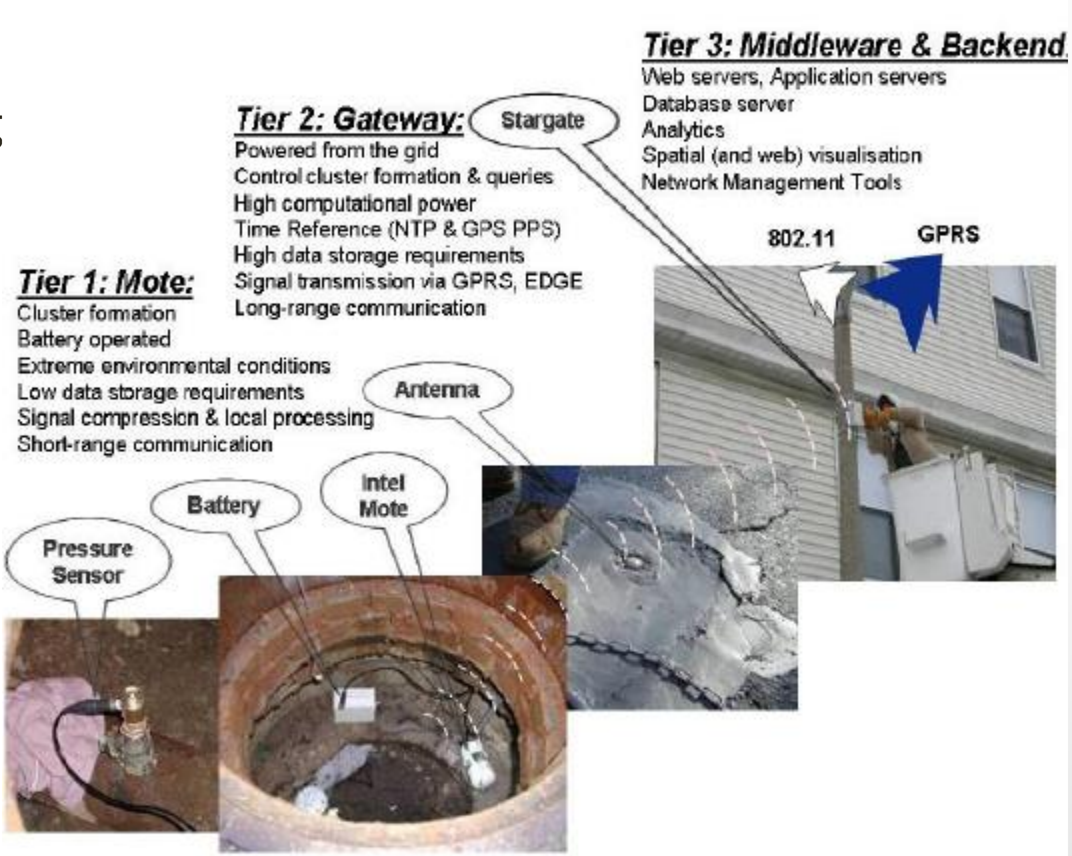
- To detect leakages, it is vital to *understand the characteristics* of the substance *the pipelines transport*
  - fluid pipelines generate a hot-spot at the location of the leak
  - gas pipelines generate a cold-spot due to the gas pressure relaxation
  - fluid travels at a higher propagation velocity in metal pipelines than in a Polyvinyl Chloride (PVC)
  - a large number of commercially available sensors to detect and localize thermal anomalies
    - fiber optics sensors
    - temperature sensors and
    - acoustic sensors

PipeNet

- Motivation:
  - sewerage systems convey *domestic sewage*, *rainwater runoff,* and *industrial wastewater* to sewerage treatment plants
  - *historically*, these systems are designed to *discharge* their content to *nearby streams and rivers*
  - subsequently, *combined sewer* overflows are among *the major* sources of water quality *impairment*
  - nearly 770 large cities in the US, mainly older communities, have combined sewer systems (Stoianov et al. 2007)

PipeNet

- The PipeNet prototype has been developed to monitor water pipelines in urban areas
- The task is to monitor:
  - *hydraulic* and *water quality* by measuring pressure and pH
  - the *water level* in combined sewer systems
    - sewer collectors and combined sewer outflows



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Precision Agriculture

- Motivation:
  - traditionally, a large farm is taken as homogeneous field in terms of *resource distribution* and its response to *climate change*, *weeds,* and *pests*
  - accordingly, farmers administer
    - *fertilizers*, *pesticides*, *herbicides,* and *water resources*
  - in reality, wide spatial diversity in *soil types*, *nutrient content,* and other important factors
  - therefore, treating it as a uniform field can cause
    - *inefficient use of resources*
    - *loss of productivity*
- Precision agriculture is a method of farm management that enables farmers to produce *more efficiently* through *a frugal use of resources*

Precision Agriculture

- Precision agriculture *technologies*:
  - yield monitors
  - yield mapping
  - variable rate fertilizer
  - weed mapping
  - variable spraying
  - topography and boundaries
  - salinity mapping
  - guidance systems

- *Requirements* of precision agriculture technologies:
  - collect a large amount of data
  - over several days

Wine Vineyard (2004)

- Motivation:
  - in a vineyard, *temperature* is the predominant parameter that *affects* the quality as well as the quantity of the *harvest*
  - grapes see no real growth until the temperature goes above 10° C
  - different grapes have *different requirements* for heat units
  - subsequently, the deployment aims to
    - measure the temperature over a 10° C baseline that a site accumulates over the growing season

Wine Vineyard (2004)

- Beckwith et al. deploy a WSN to *monitor* and characterize variation in *temperature* of a wine vineyard
  - heat summation and periods of freezing temperatures
- *65 nodes* in a grid like pattern 10 to 20 meters apart, covering about two acres
- *Easy to develop* the network (1 person day)
  - due to the self-configuration nature of the network
  - inherent structured layout of vineyard fields
- Two essential constraints of the network topology
  - placement of nodes in an area of viticulture interest
  - the support for multi-hop communication

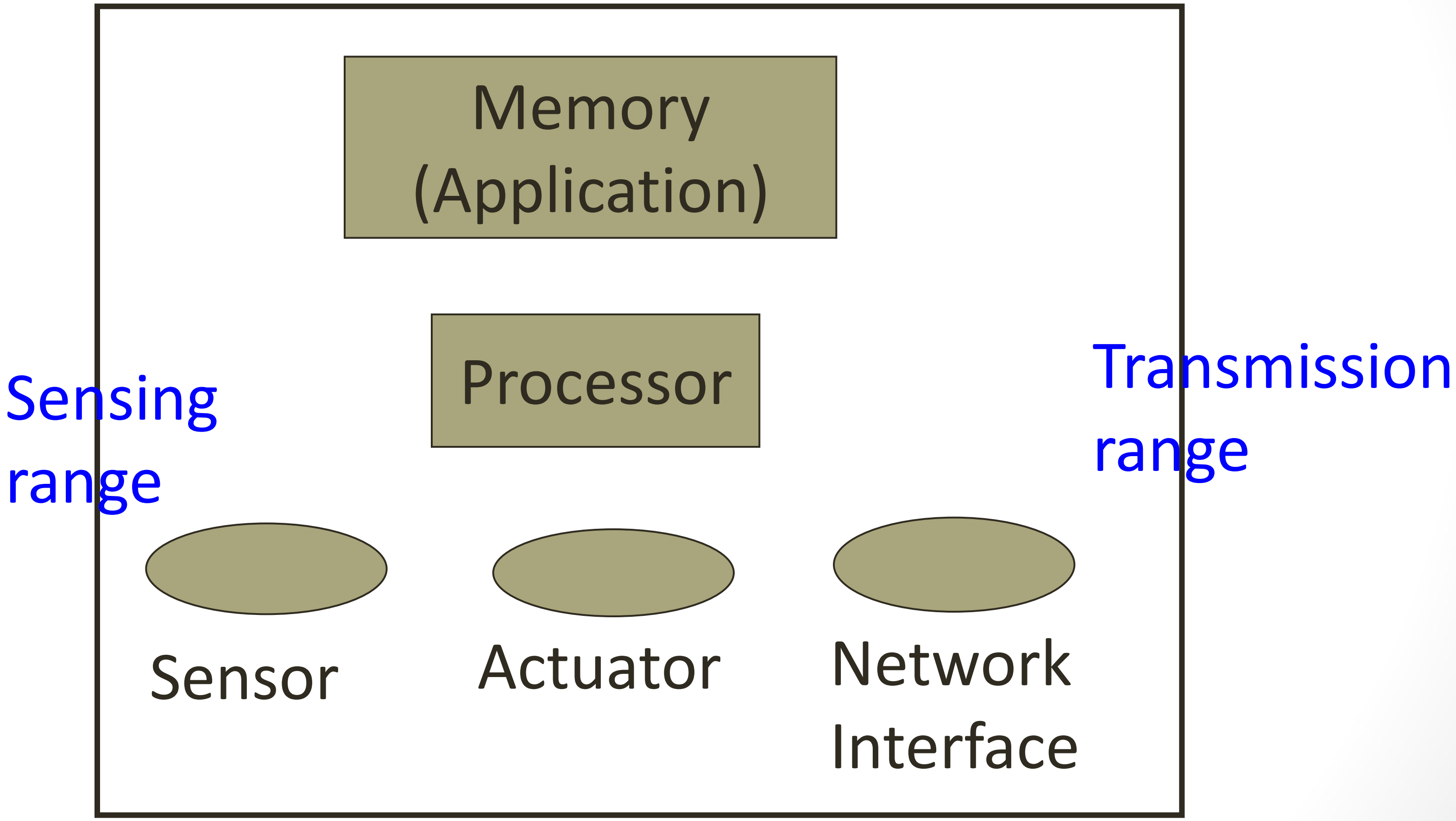
Wine Vineyard (2004)

- The data were used to investigate several aspects:
  - the existence of *co-variance between the temperature* data collected by the network
  - *growing degree day differences*
  - *potential frost damage*
- The *mean data* enabled to observe the relative differences between heat units accumulation during that period
  - according to the authors’ report, the extent of variation in this vineyard – there was a measured difference of over 35% of heat summation units (HSUs) in as little as 100 meters

Roadmap

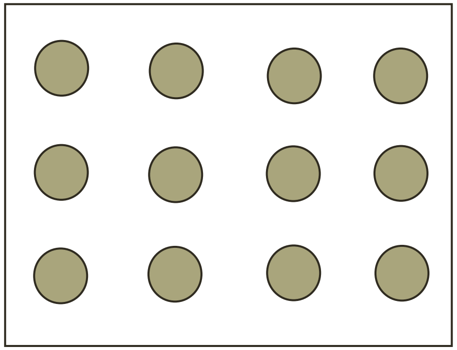
- Motivation for a Network of Wireless Sensor Nodes
- Applications
- Coverage and Connectivity Issues in Sensor Networks
  - Coverage
  - Connectivity

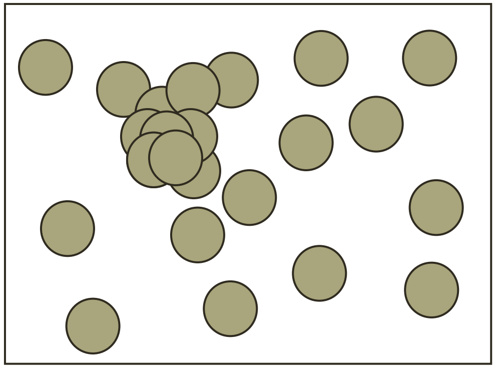
A Sensor Node



Sensor Deployment

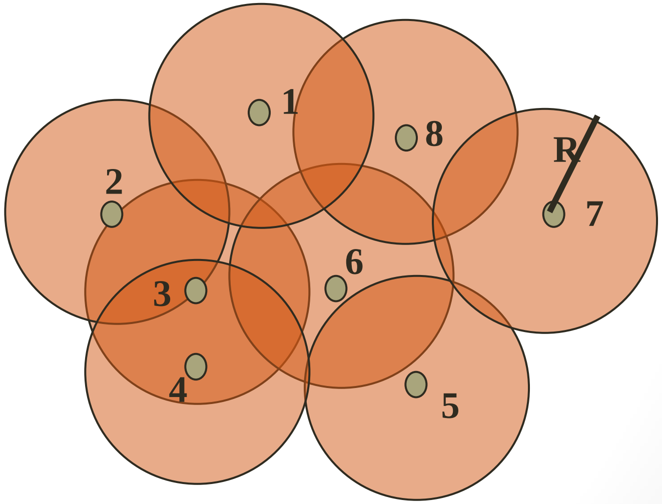
- How to deploy sensors over a field?
  - Deterministic, planned deployment
  - Random deployment
- Desired properties of deployments?
  - Depends on applications
  - Connectivity
  - Coverage





Coverage, Connectivity

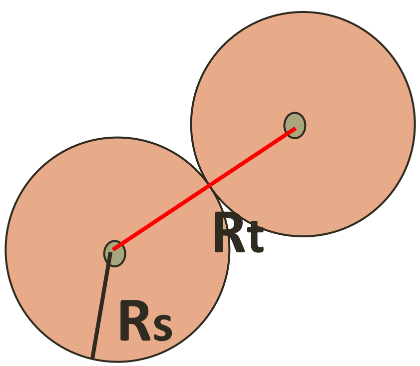
- Every point is covered by 1 or K sensors
  - 1-covered, K-covered
- The sensor network is connected
  - K-connected
- Others



Coverage & Connectivity: not independent, not identical

- If region is continuous & $Rt \geq 2Rs$

  Region is covered ⇨ sensors are connected

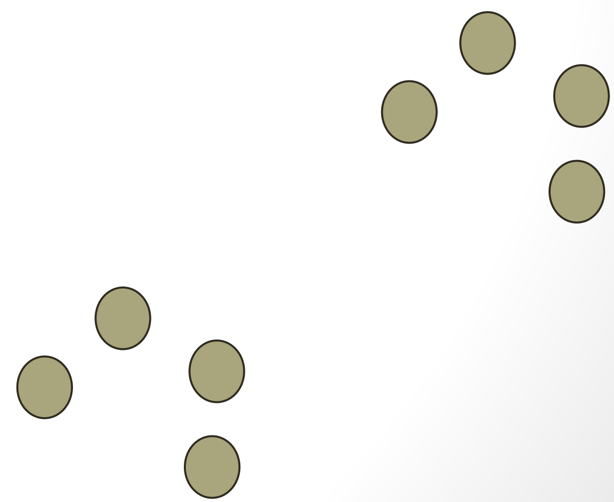


Connectivity Issues

Power Control for Connectivity

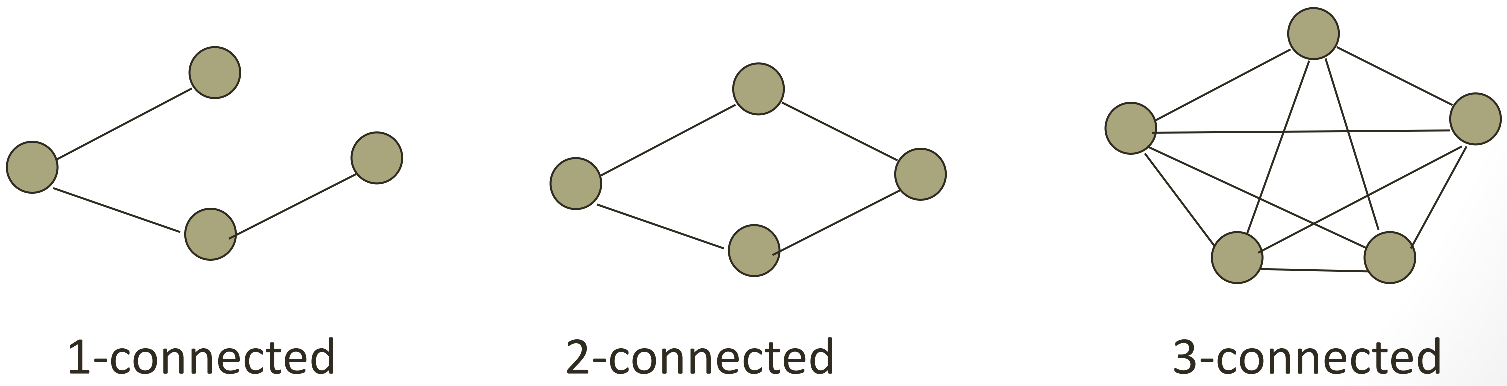
- Adjust transmission range (power)
  - Resulting network is connected
  - Power consumption is minimum

- Transmission range
  - Homogeneous
  - Node-based



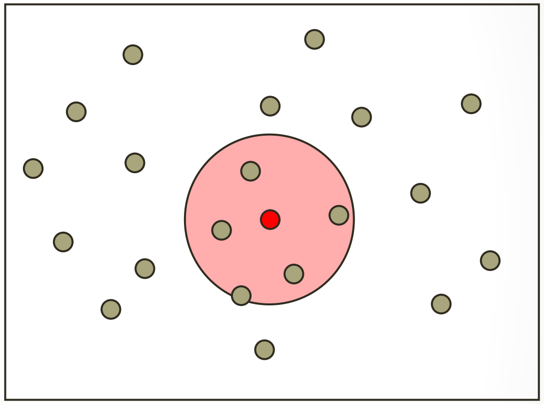
Power Control for K-Connectivity

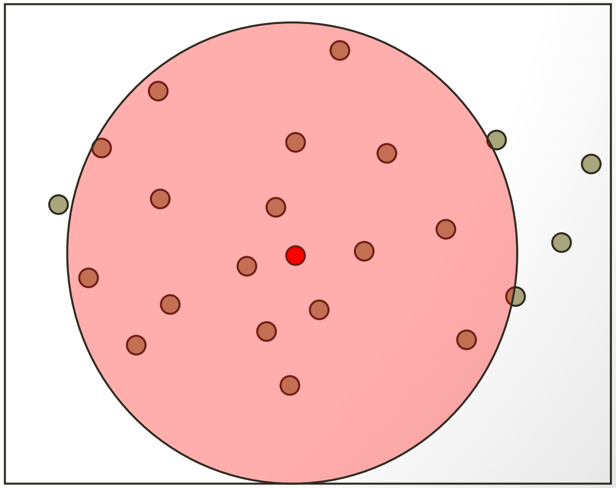
- For fault tolerance, k-connectivity is desirable
- K-connected graph:
  - K paths between every two nodes
  - with k-1 nodes removed, graph is still connected



Two Types of Approaches

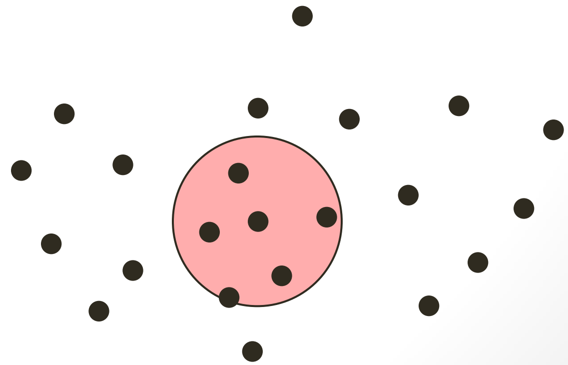
- Probabilistic
  - How many neighbors are needed?
- Algorithmic
  - Gmax connected
  - Construct a connected subgraph with desired properties





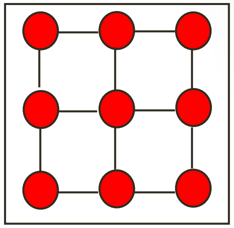
Probabilistic Approach

How many neighbors are necessary and/or sufficient to ensure connectivity?



How Many Neighbors are Needed?

- Regular deployment of nodes – easy

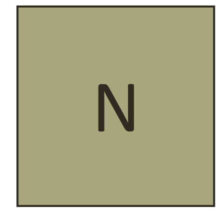


- Random deployment (Poisson distribution)
- N: number of nodes in a unit square
- Each node connects to its k nearest neighbors
- For what values of k, is network almost sure connected?

  P(network connected) → 1, as N → ∞

An Alternative View

- A square of area N
- Poisson distribution of a fixed density λ
- Each node connects to its k nearest neighbors
- For what values of k, is the network almost sure connected?



$$P(\text{ network connected }) \to 1, \text{ as } N \to \infty$$

A Related Old Problem

- Packet radio networks (1970s/80s)
- Larger transmission radius
  - Good: more progress toward destination
  - Bad: more interference
- Optimum transmission radius?

Magic Number

- Kleinrock and Silvester (1978)
  - Model:
    - slotted Aloha
    - homogeneous radius R
    - Poisson distribution
    - maximize one hop progress toward destination
  - Set R so that every station has 6 neighbors on average
  - 6 is the magic number

More Magic Numbers

- Tobagi and Kleinrock (1984)
  - Eight is the magic number

- Other magic numbers for various protocols and models:
  - 5, 6, 7, 8

Are Magic Numbers Magic?

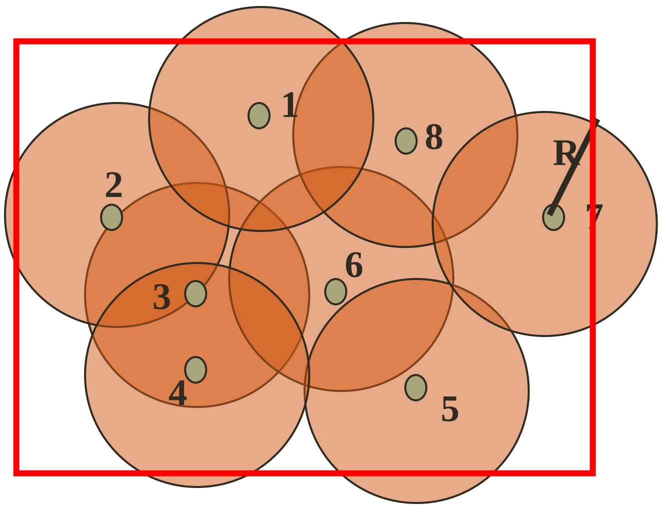
- Xue & Kumar (2002)
- For the network to be almost sure connected, $\Theta(\log n)$ neighbors are necessary and sufficient
- Heterogeneous radius

8, 7, 6, 5
(Magic numbers)

Coverage Issues

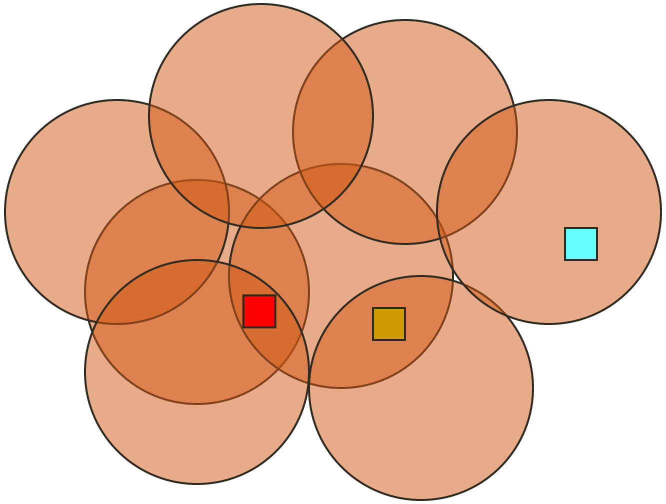
Simple Coverage Problem

- Given an area and a sensor deployment
- Question: Is the entire area covered?



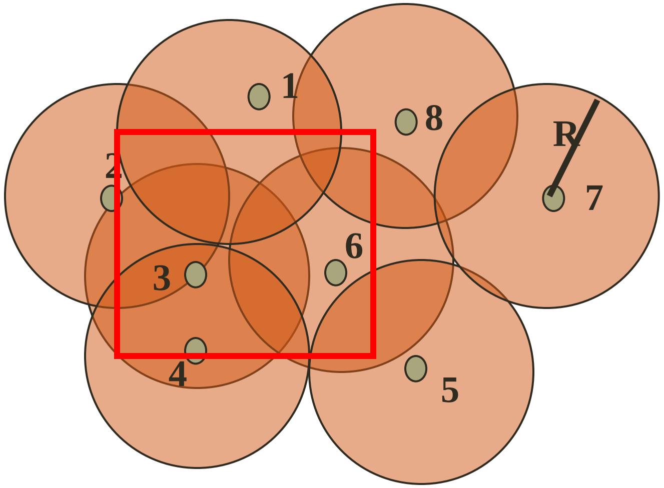
K-Covered

- 1-covered
- 2-covered
- 3-covered



K-Coverage Problem

- Given: region, sensor deployment, integer k
- Question: Is the entire region k-covered?

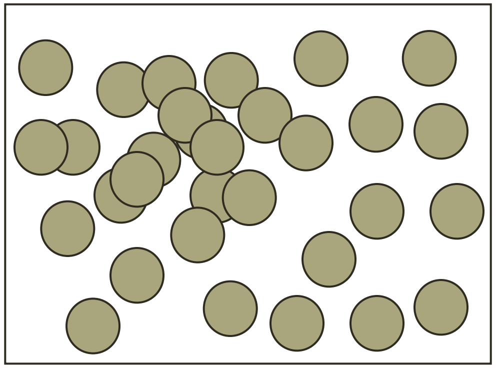


Reference

- C. Huang and Y. Tseng, “The coverage problem in a wireless sensor network,”
  - In *WSNA*, 2003.
  - Also MONET 2005.

Density (or Topology) Control

- Given: an area and a sensor deployment
- Problem: turn on/off sensors to maximize the sensor network's life time

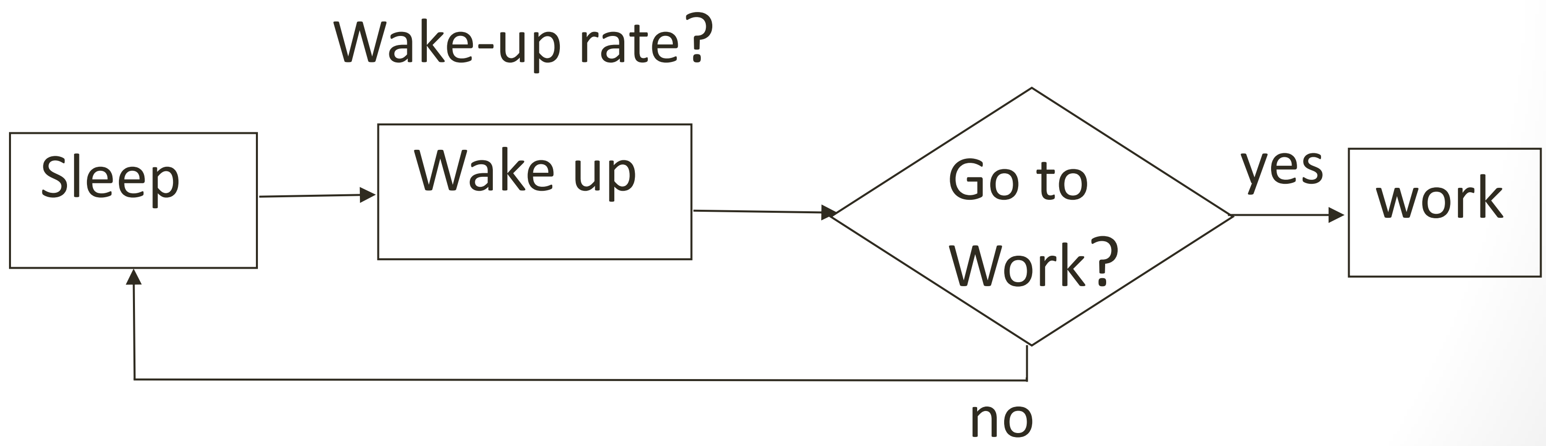


PEAS and OGDC

- PEAS: A robust energy conserving protocol for long-lived sensor networks
  - Fan Ye, et al (UCLA), ICNP 2002
- “Maintaining Sensing Coverage and Connectivity in Large Sensor Networks”
  - H. Zhang and J. Hou (UIUC), MobiCom 2003

PEAS: Basic Ideas

- How often to wake up?
- How to determine whether to work or not?



How Often to Wake Up?

- Desired: the total wake-up rate around a node equals some given value

Inter Wake-up Time

$f(t) = \lambda \exp(-\lambda t)$

- exponential distribution
- λ = average # of wake-ups per unit time

Wake-Up Rates

A

$$f(t) = \lambda \exp(-\lambda t)$$

B

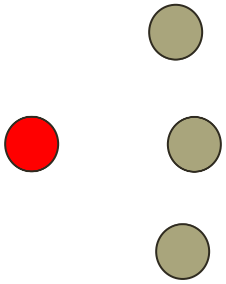
$$f(t) = \lambda' \exp(-\lambda' t)$$

A + B: $$f(t) = (\lambda + \lambda') \exp(-(\lambda + \lambda')\, t)$$

Adjust Wake-Up Rates

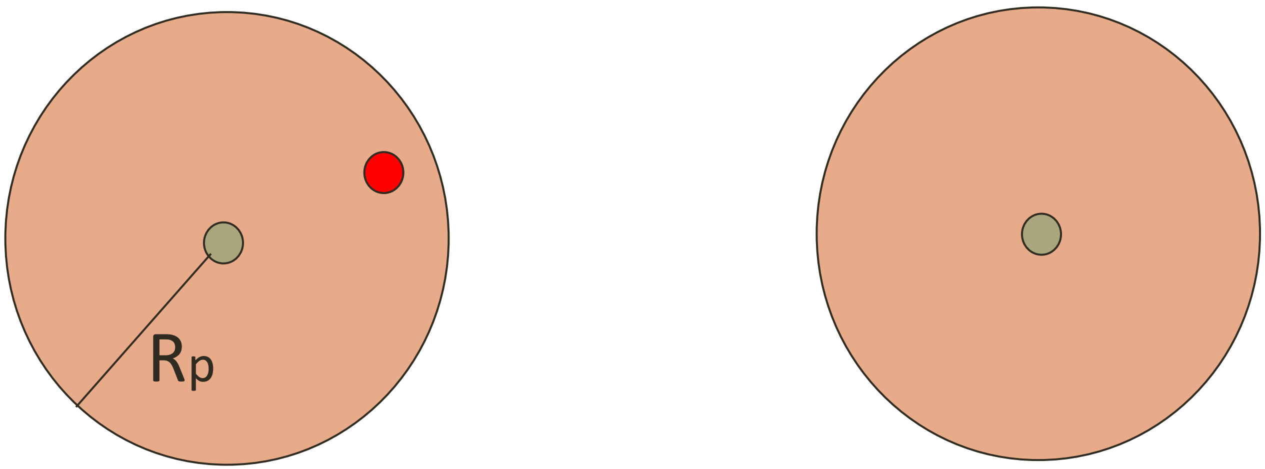
- Working node knows
  - Desired total wake-up rate λ_d
  - Measured total wake-up rate λ_m
- When a node wakes up, adjusts its λ by

$$\lambda := \lambda\,(\lambda_d / \lambda_m)$$



Go to Work or Return to Sleep?

- Depends on whether there is a working node nearby



Go back to sleep

go to work

Is the Resulting Network Covered or Connected?

- If Rt $\geq (1 + \sqrt{5})$ Rp and … then

  P(connected) $\rightarrow$ 1

- Simulation results show good coverage

Roadmap

- Motivation for a Network of Wireless Sensor Nodes
- Applications
- Coverage and Connectivity Issues in Sensor Networks
- Routing Protocols for Wireless Sensor Networks

Usage and Constraints

- Gather data locally (Temperature, Humidity, Motion Detection, etc.)
- Send them to a command center (sink)
- Limitations
  - Energy Constrains
  - Bandwidth
  - All layers must be energy aware
  - Need for energy efficient and reliable network routing
  - Maximize the lifetime of the network

Differences of Routing in WSN and Traditional Networks

- No global addressing
  - Classical IP-based protocols cannot be applied to sensor networks
- Redundant data traffic
  - Multiple sensors may generate same data within the vicinity of a phenomenon
  - Such redundancy needs to be exploited by the routing protocols to improve energy and bandwidth utilization
- Multiple-source single-destination network
  - Almost all applications of sensor networks require the flow of sensed data from multiple regions (sources) to a particular sink
- Careful resource management
  - Sensor nodes are tightly constrained in terms of:
    - Transmission power
    - On-board energy
    - Processing capacity
    - Storage

Classification of Routing Protocols

- Data Centric:
  - Data-centric protocols are query-based
- Hierarchical:
  - Aim at clustering the nodes so that cluster heads can do some aggregation and reduction of data in order to save energy
- Location-based:
  - Utilize the position information to relay the data to the desired regions rather than the whole network.
- Network Flow & QoS Aware:
  - Are based on general network-flow modeling and protocols that strive for meeting some QoS requirements along with the routing function

Hierarchical Routing Protocols

- Scalability is one of the major design attributes of sensor networks
- A single-tier network can cause the gateway to overload with the increase in sensors density
  - Such overload might cause latency in communication and inadequate tracking of events
- The single-gateway architecture is not scalable for a larger set of sensors covering a wider area of interest

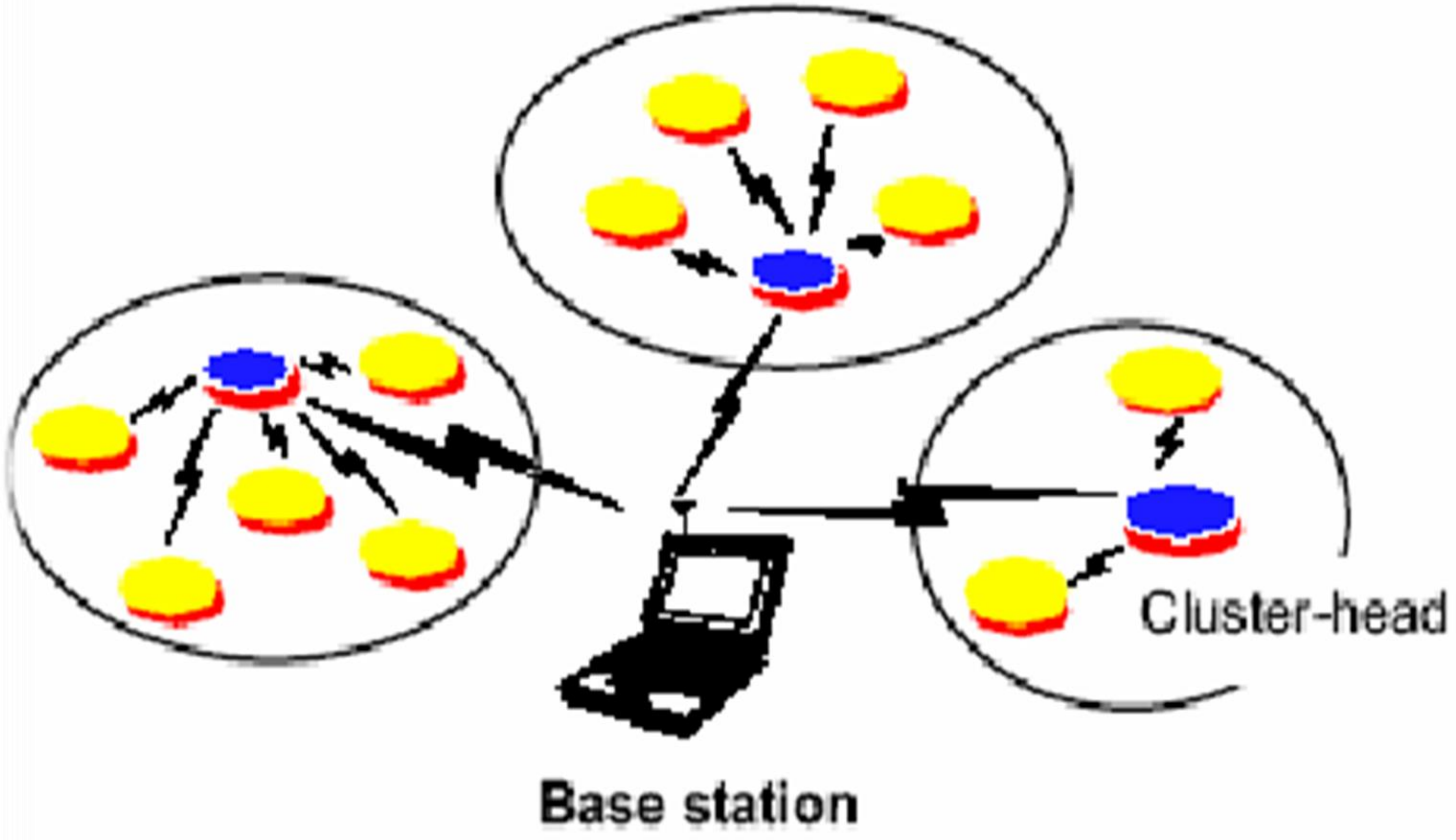
Hierarchical Protocols

- Maintain energy consumption of sensor nodes
  - By multi-hop communication within a particular cluster
  - By data aggregation and fusion → decrease the number of the total transmitted packets
- LEACH: Low-Energy Adaptive Clustering Hierarchy
- PEGASIS: Power-Efficient GAthering in Sensor Information Systems
  - Hierarchical PEGASIS
- TEEN: Threshold sensitive Energy Efficient sensor Network protocol
  - Adaptive Threshold TEEN (APTEEN)
- Energy-aware routing for cluster-based sensor networks
- Self-organizing protocol

LEACH : Low-Energy Adaptive Clustering Hierarchy

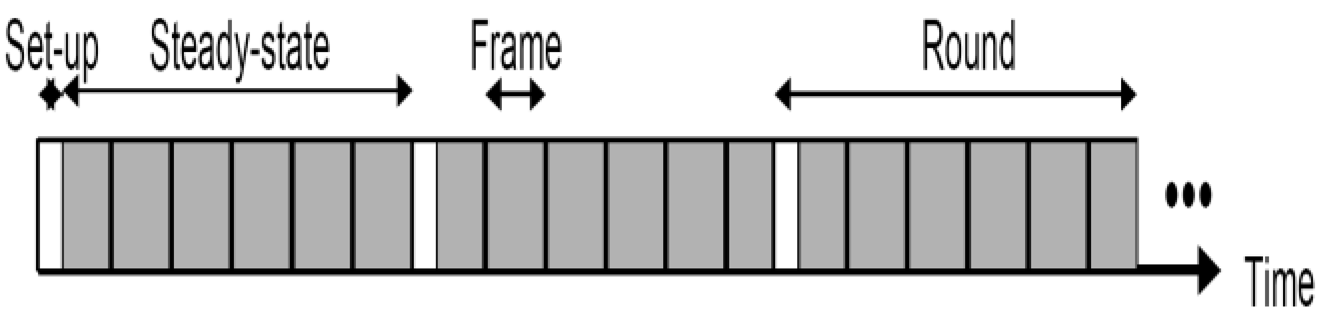
- One of the first hierarchical routing protocols
- Forms clusters of the sensor nodes based on received signal strength
- Self-organizing, adaptive clustering protocol
- *Dynamic* cluster formation
- Local cluster heads route the information of the cluster to the sink
- Data processing & aggregation done by cluster head
- Cluster heads change randomly over time balance energy dissipation

LEACH – Architecture



LEACH's Two Phases

- The LEACH network has two phases: the set-up phase and the steady-state
  - The set-up phase
    - Where cluster-heads are chosen
    - Cluster formation
  - The steady-state
    - The cluster-head is maintained
    - When data is transmitted between nodes

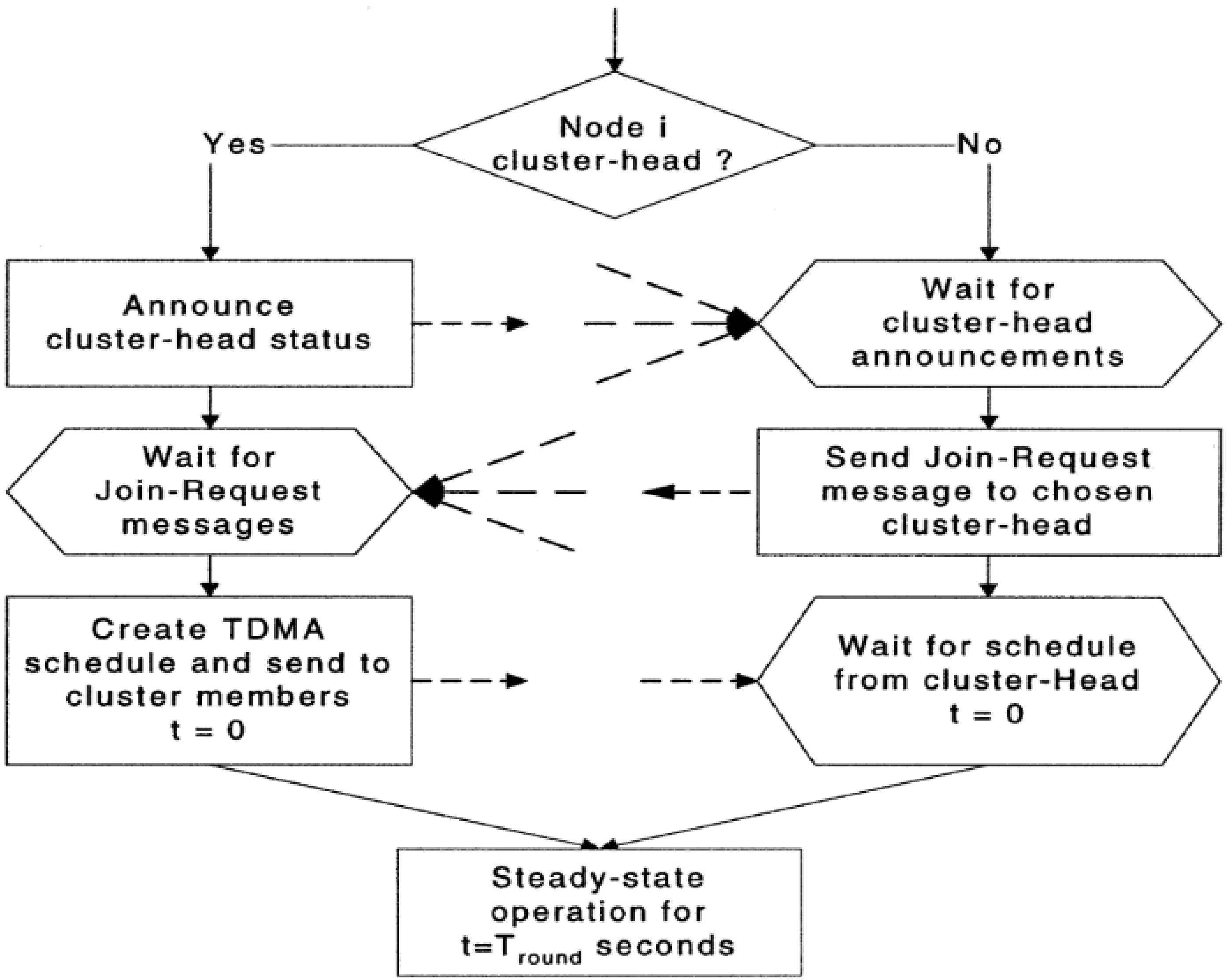


Timeline showing LEACH operation

Setup Phase

- At the beginning of each round, each node advertises it probability, (depending upon its current energy level) to be the **Cluster Head**, to all other nodes
  - Nodes (k for each *round*) with higher probabilities are chosen as the Cluster Heads
- Cluster Heads broadcasts an *advertisement message* (ADV) using CSMA MAC protocol
- Based on the *received signal strength,* each non-Cluster Head node determines its Cluster Head for this round *(random selection with obstacle)*
- Each non-Cluster Head transmits a join-request message (Join-REQ) back to its chosen Cluster Head using a CSMA MAC protocol
- Cluster Head node sets up a TDMA schedule for data transmission coordination within the cluster

Flow Graph for Setup Phase



Cluster Head Selection Algorithm

- $P_i(t)$ is the probability with which node *i* elects itself to be Cluster Head at the beginning of the round *r+1* (which starts at time *t*) such that expected number of cluster-head nodes for this round is *k*

$$E[\#CH] = \sum_{i=1}^{N} P_i(t) * 1 = k. \qquad (1)$$

k = number of clusters during each round

N = number of nodes in the network

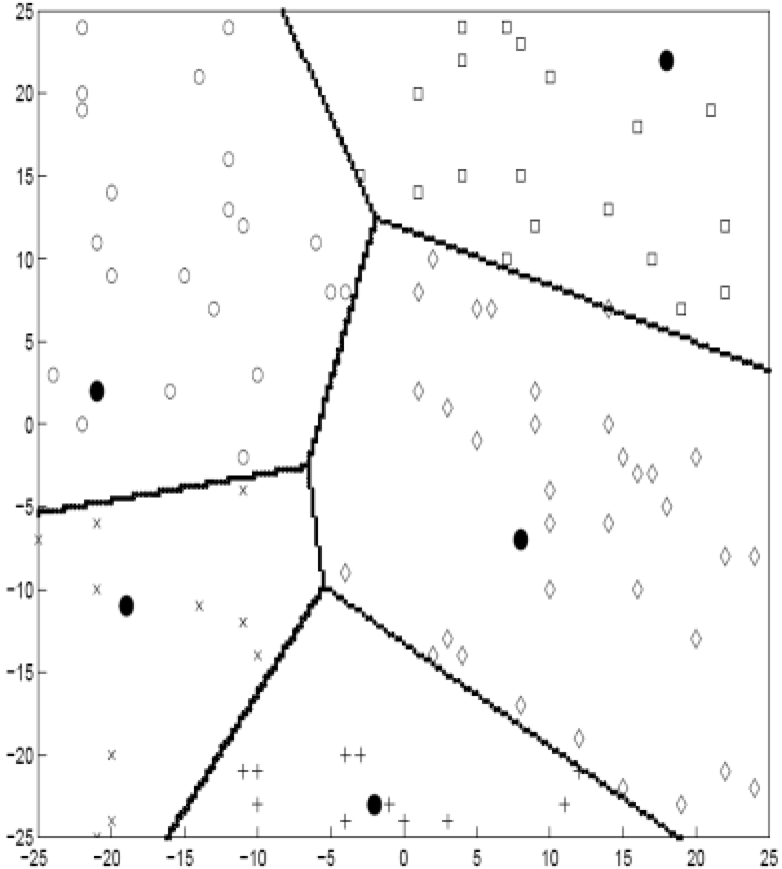
Cluster Head Selection Algorithm

- Each node will be Cluster Head once in *N/k* rounds
- Probability for each node *i* to be a cluster-head at time *t*

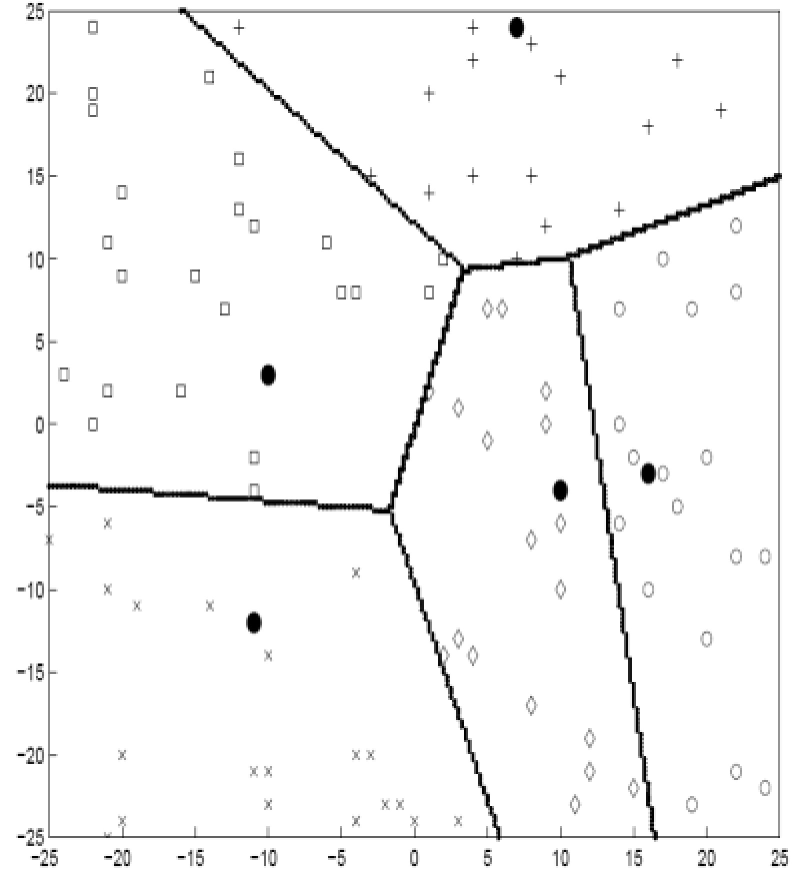
$$P_i(t) = \begin{cases} \frac{k}{N-k*(r \bmod \frac{N}{k})} & : \quad C_i(t) = 1 \\ 0 & : \quad C_i(t) = 0 \end{cases} \qquad (2)$$

$C_i(t)$ = it determines whether node *i* has been a Cluster Head in most recent *(r mod(N/k))* rounds

Dynamic Cluster Formation

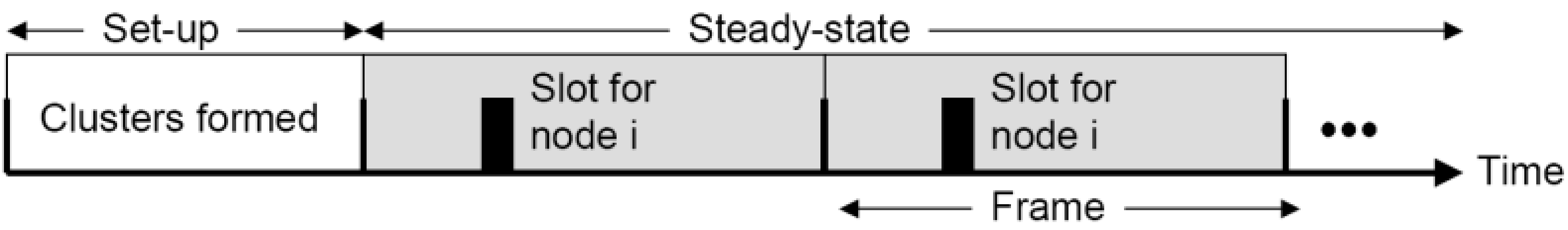


Clusters at time t



Clusters at time t+d

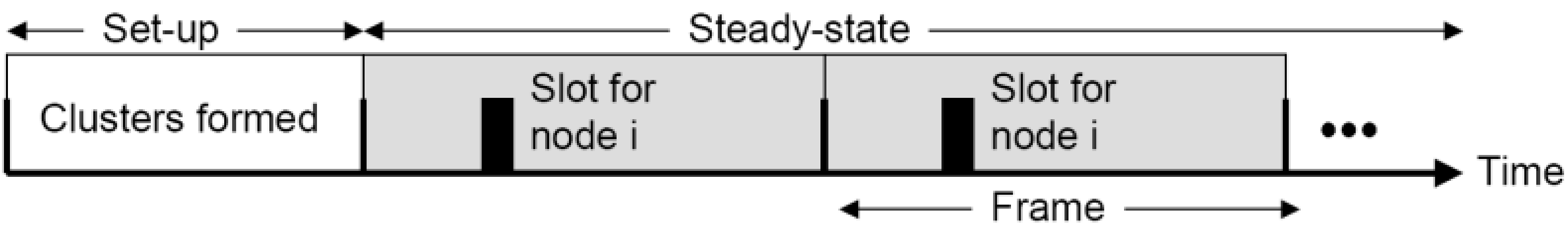
Steady-State Phase



Timeline showing LEACH operation

- TDMA schedule is used to send data from node to head cluster
- Head Cluster aggregates the data received from node cluster’s
- Communication is via direct-sequence spread spectrum (DSSS) and each cluster uses a unique spreading code to reduce inter-cluster interference
- Data is sent from the cluster head nodes to the BS using a fixed spreading code and CSMA

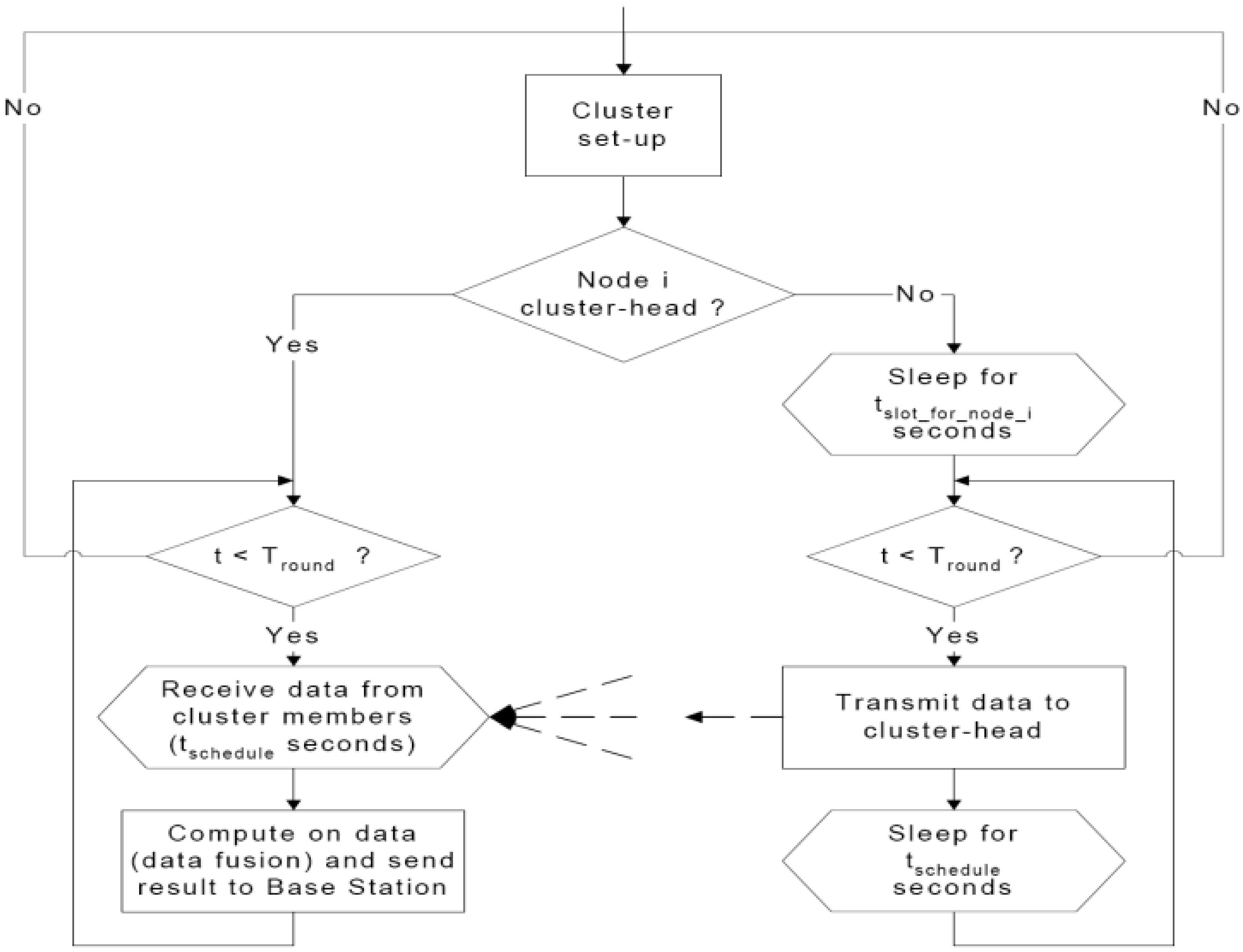
Steady-State Phase



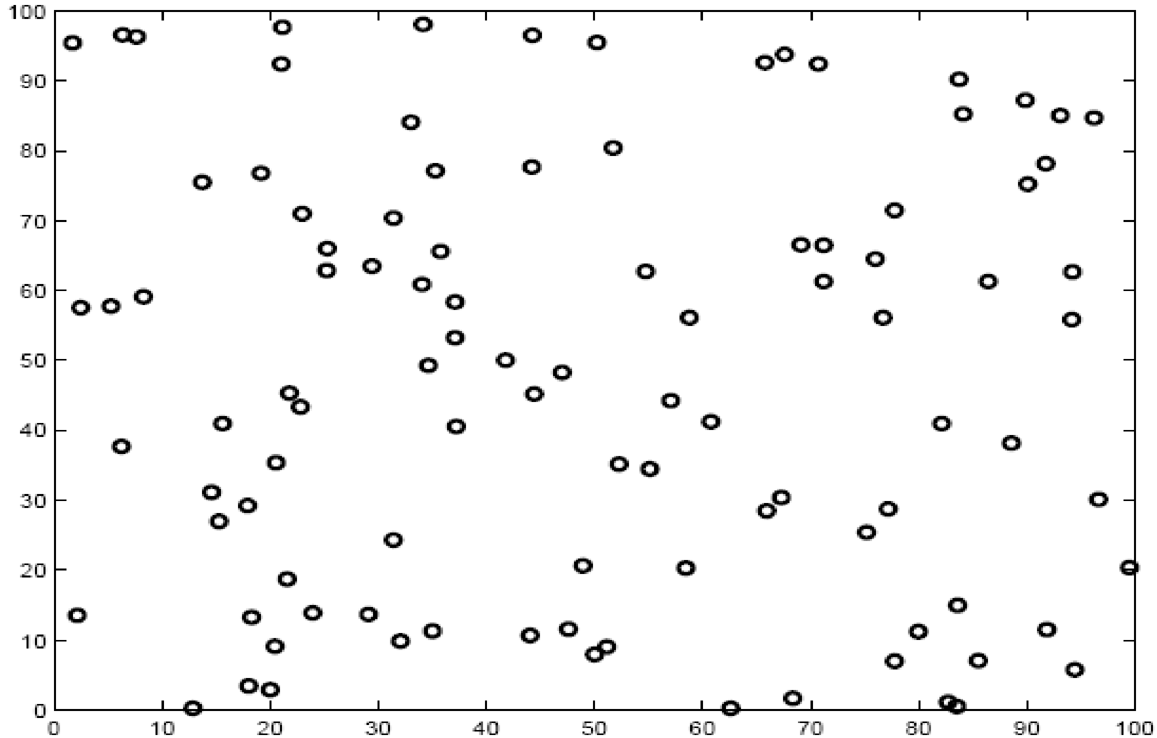
Timeline showing LEACH operation

- Assumptions
  - Nodes are all time synchronized and start the setup phase at same time
    - BS sends out synchronized pulses to the nodes
  - Cluster Head must be awake all the time
- To reduce inter-cluster interference, each cluster in LEACH communicates using direct-sequence spread spectrum (DSSS)
- Data is sent from the cluster head nodes to the BS using a fixed spreading code and CSMA

Flow Chart for Steady Phase



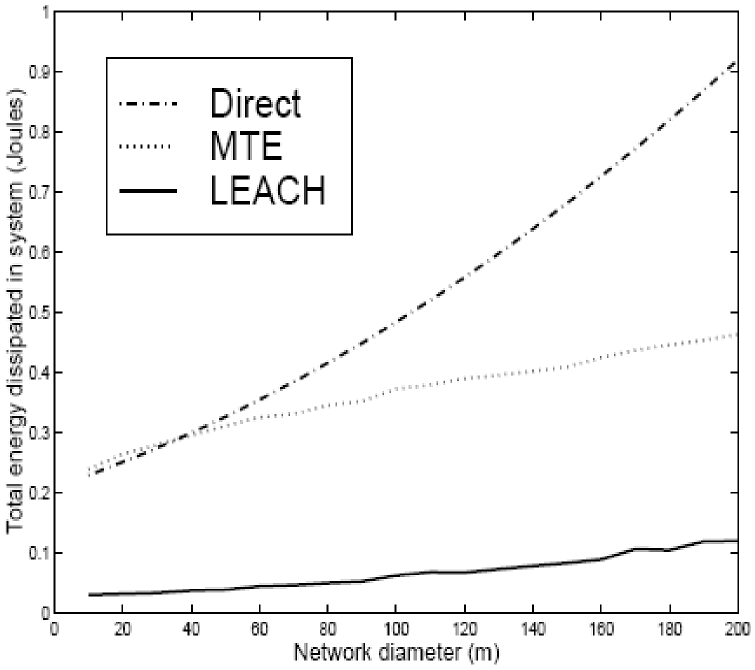
LEACH Simulation



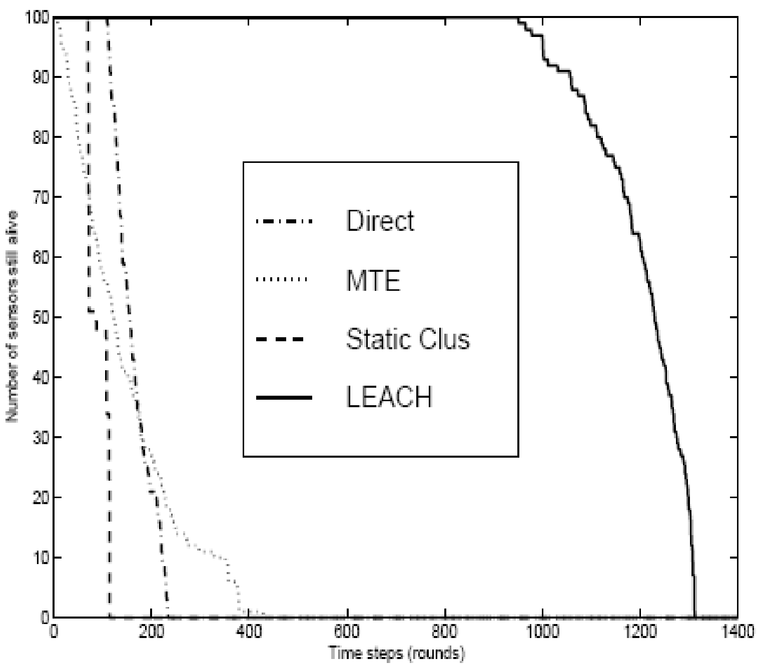
100 node random test network

Nodes	100
Network size	100 m $\times$ 100 m
Base station location	(50, 175)
Radio propagation speed	3×10^8 m/s
Processing delay	50 μs
Radio speed	1 Mbps
Data size	500 bytes

LEACH – Simulation Result



Energy dissipation



System Lifetime

LEACH Conclusion

- Advantages
  - Completely distributed
  - No global knowledge of the network
  - Increases the lifetime of the network

- Disadvantages
  - Uses single-hop routing within cluster → **not** applicable to networks in large regions
  - Dynamic clustering brings extra overhead (advertisements, etc.)
  - The paper assumes all the nodes begin with same energy – this assumption may not be realistic