Sensors and Wireless Sensor Networks

Roadmap

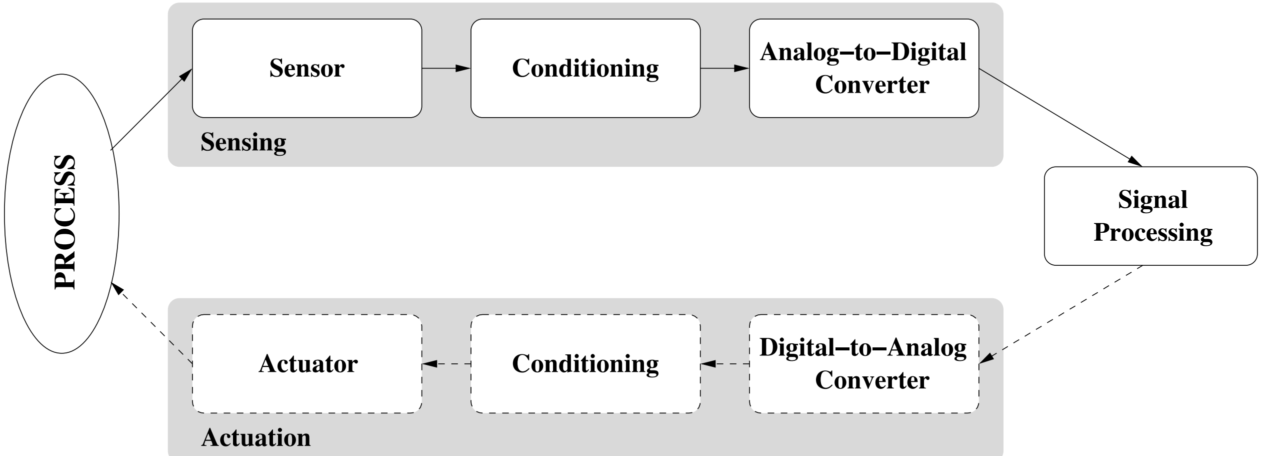
- Motivation for a Network of Wireless Sensor Nodes
  - Definitions and background
  - Challenges and constraints
  - Overview of topics covered

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)



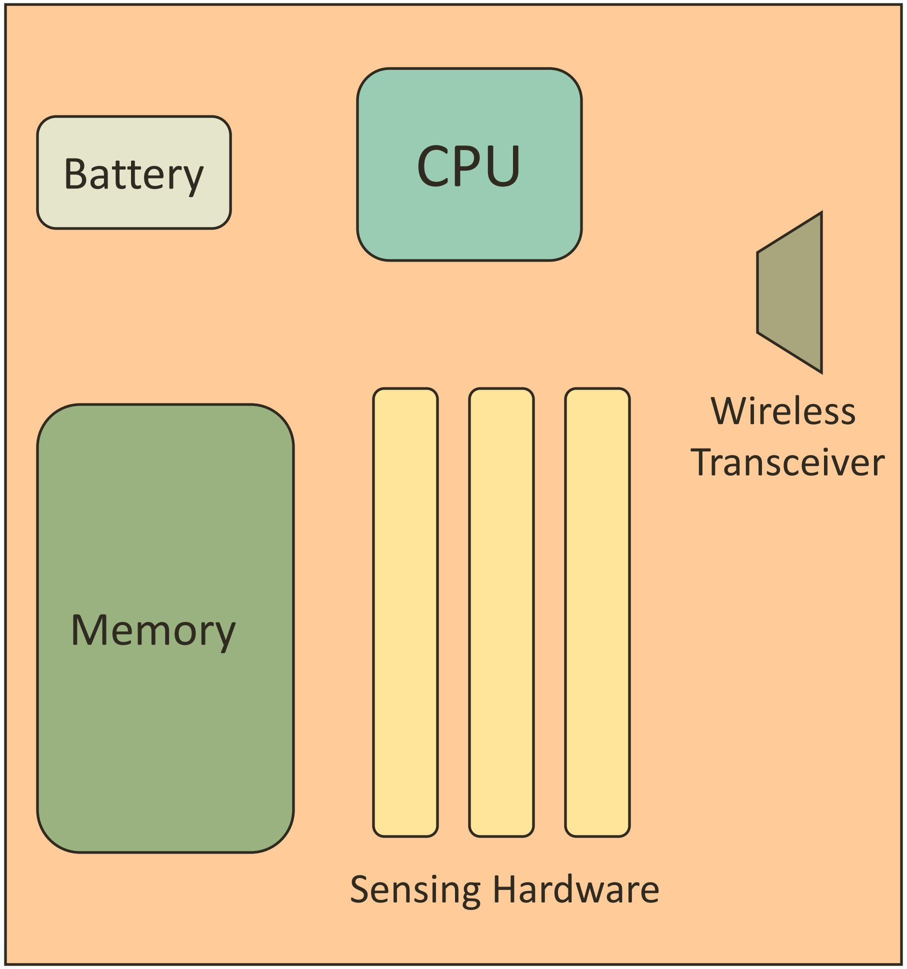
- Sensors capture phenomena in the physical world (process, system, plant)
- Signal conditioning prepare captured signals for further use (amplification, attenuation, filtering of unwanted frequencies, etc.)
- Analog-to-digital conversion (ADC) translates analog signal into digital signal
- Digital signal 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

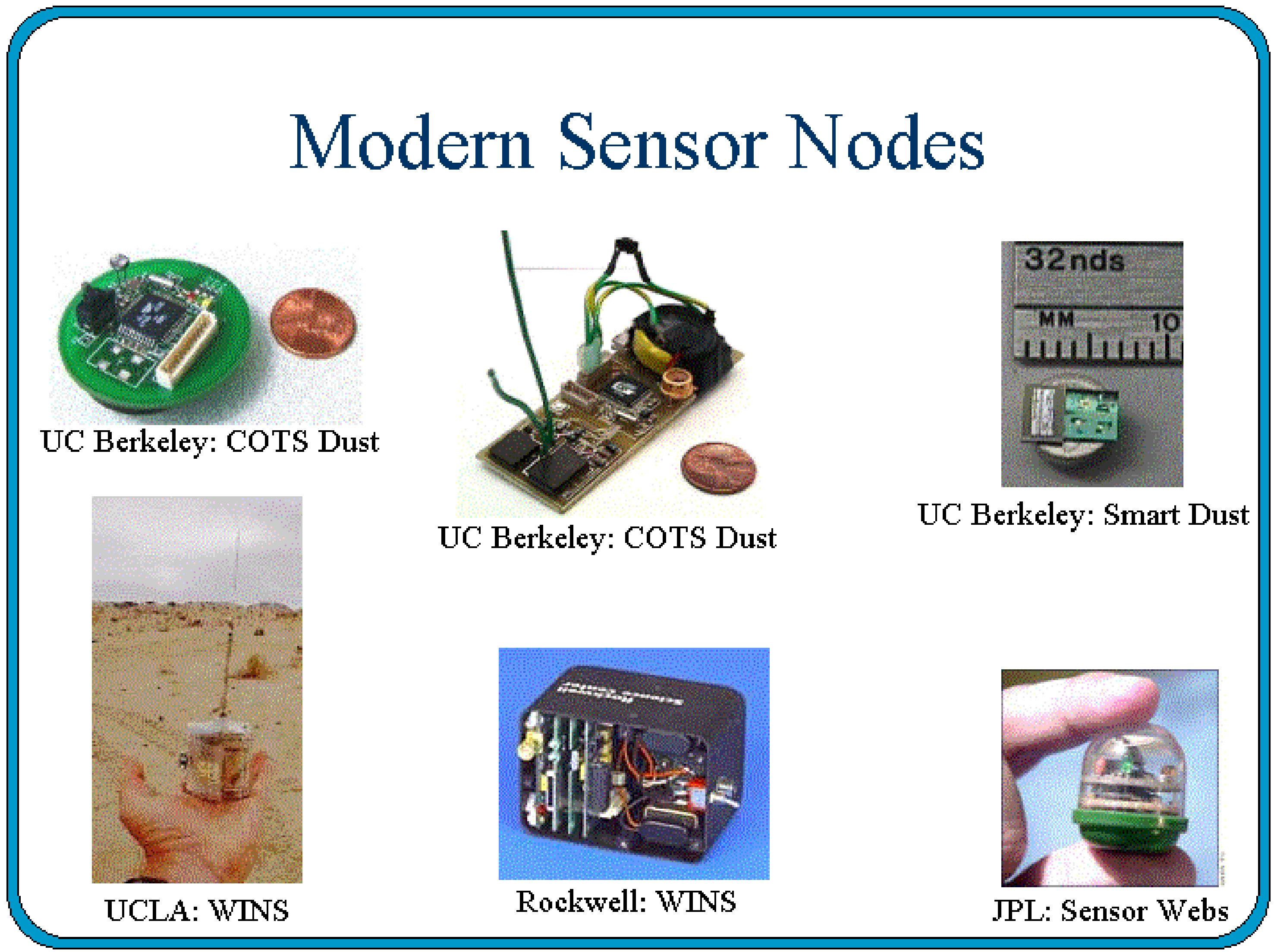
Type	Examples
Temperature	Thermistors, thermocouples
Pressure	Pressure gauges, barometers, ionization gauges
Optical	Photodiodes, phototransistors, infrared sensors, CCD sensors
Acoustic	Piezoelectric resonators, microphones
Mechanical	Strain gauges, tactile sensors, capacitive diaphragms, piezoresistive 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

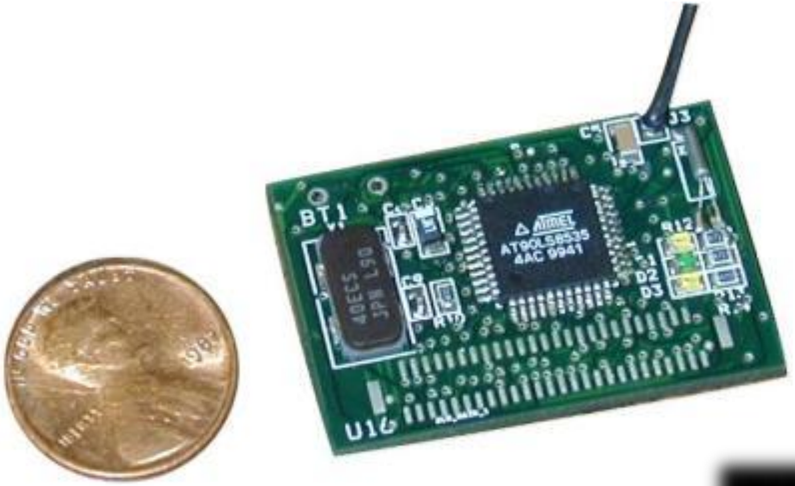


- Enabled by recent advances in MEMS technology
- Integrated Wireless Transceiver
- Limited in
  - Energy
  - Computation
  - Storage
  - Transmission range
  - Bandwidth

Sensors


Modern Sensor Nodes
UC Berkeley: COTS Dust
UC Berkeley: COTS Dust
UC Berkeley: Smart Dust
UCLA: WINS
Rockwell: WINS
JPL: Sensor Webs

Sensor Nodes

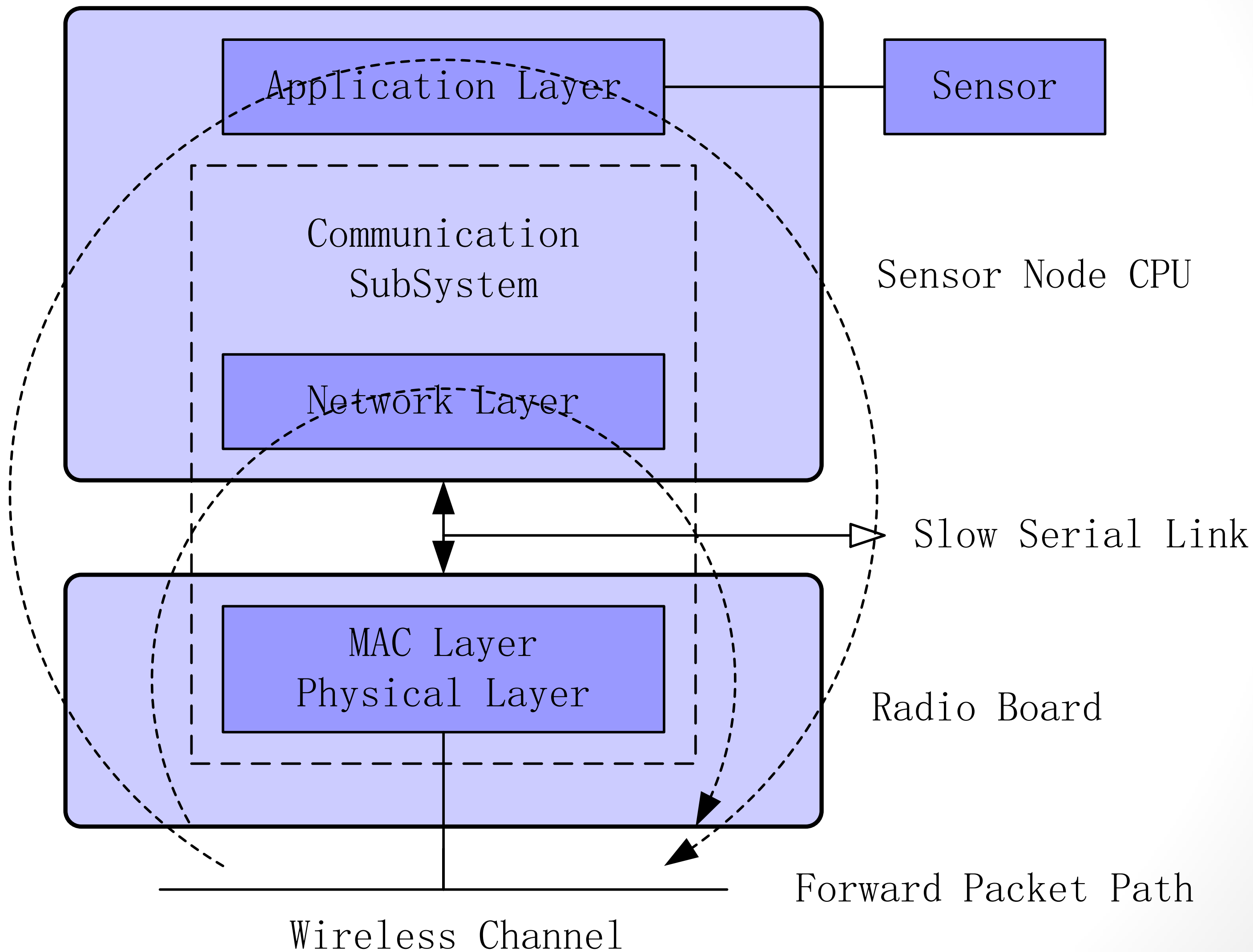


Sensors (contd.)

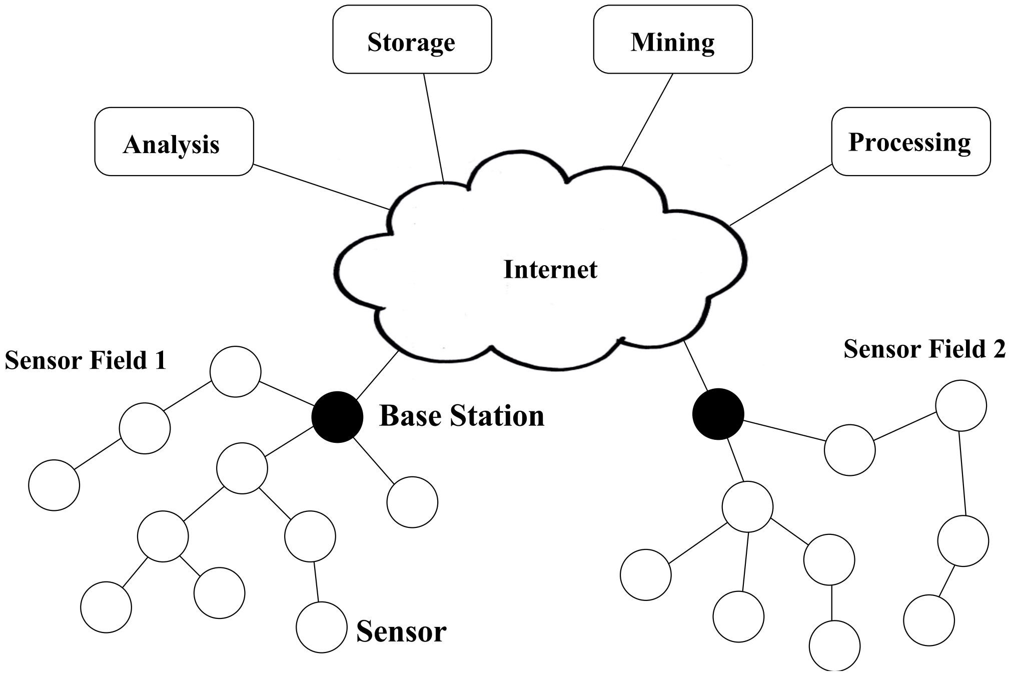
- The overall architecture of a sensor node consists of:
  - The sensor node processing subsystem running on sensor node main CPU
  - The sensor subsystem and
  - The communication subsystem
- The processor and radio board includes:
  - TI MSP430 microcontroller with 10kB RAM
  - 16-bit RISC with 48K 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

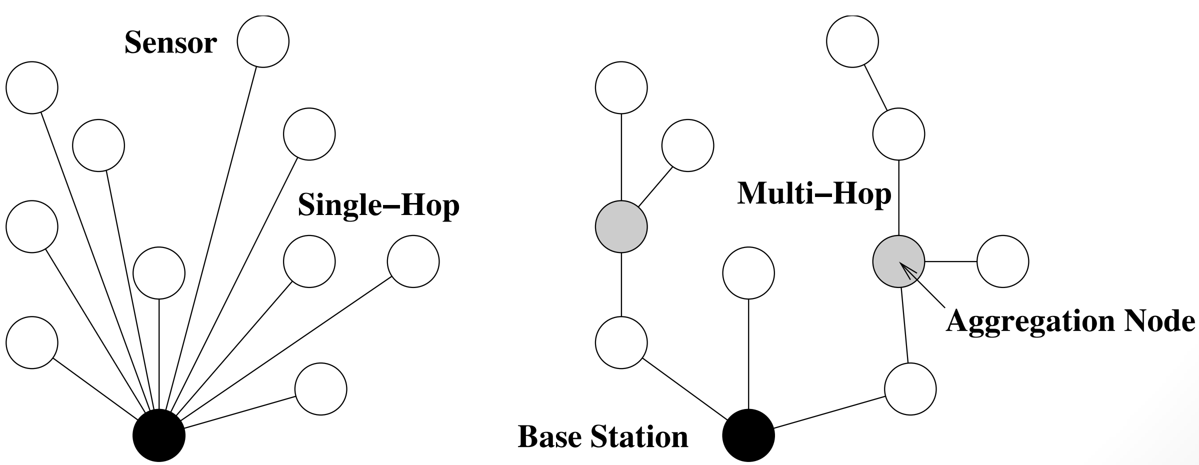
- Recent commercial efforts
  - Crossbow (www.xbow.com)
  - Sensoria (www.sensoria.com)
  - Worldsens (worldsens.citi.insa-lyon.fr)
  - Dust Networks (www.dustnetworks.com)
  - Ember Corporation (www.ember.com)

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
  - Underground Mining

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/

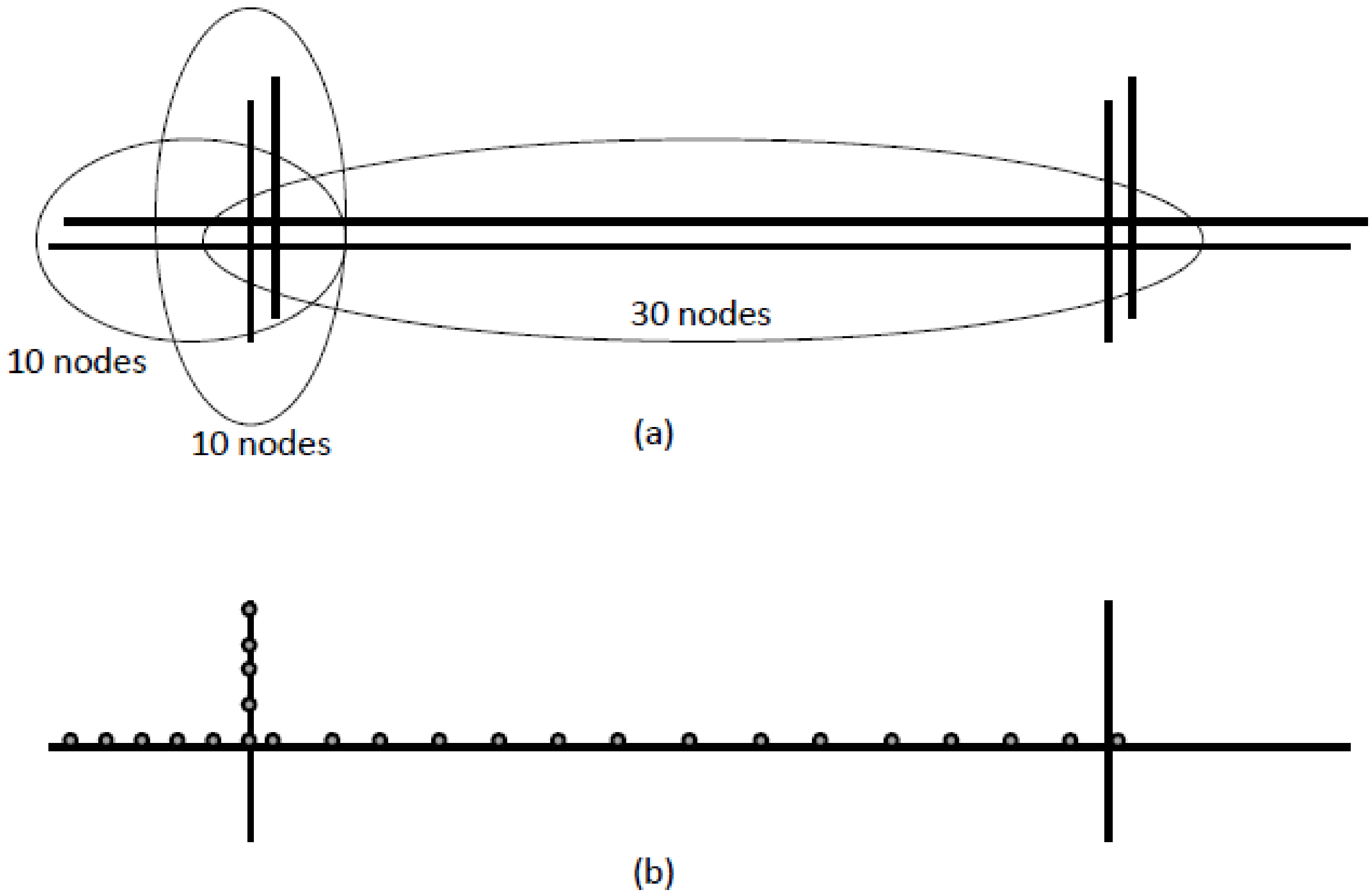


Figure: The deployment scenario on the Golden Gate Bridge

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
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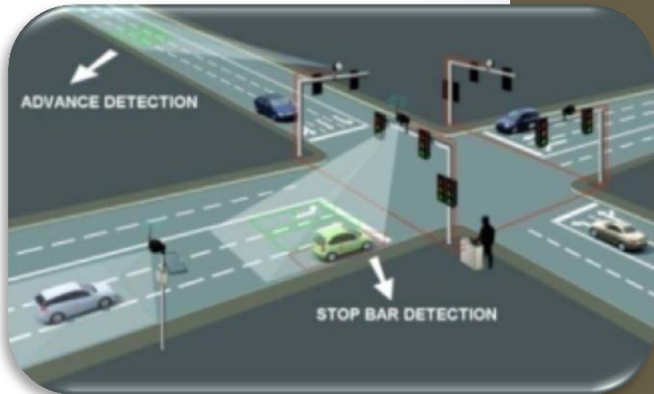
Traffic Control

- 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

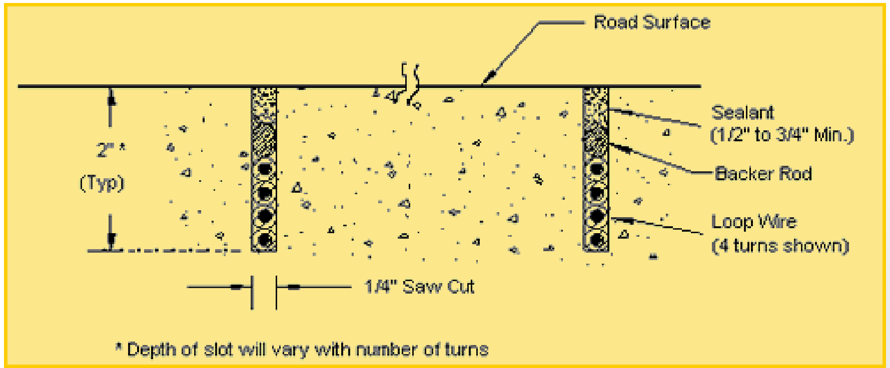


Traffic Control

- 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

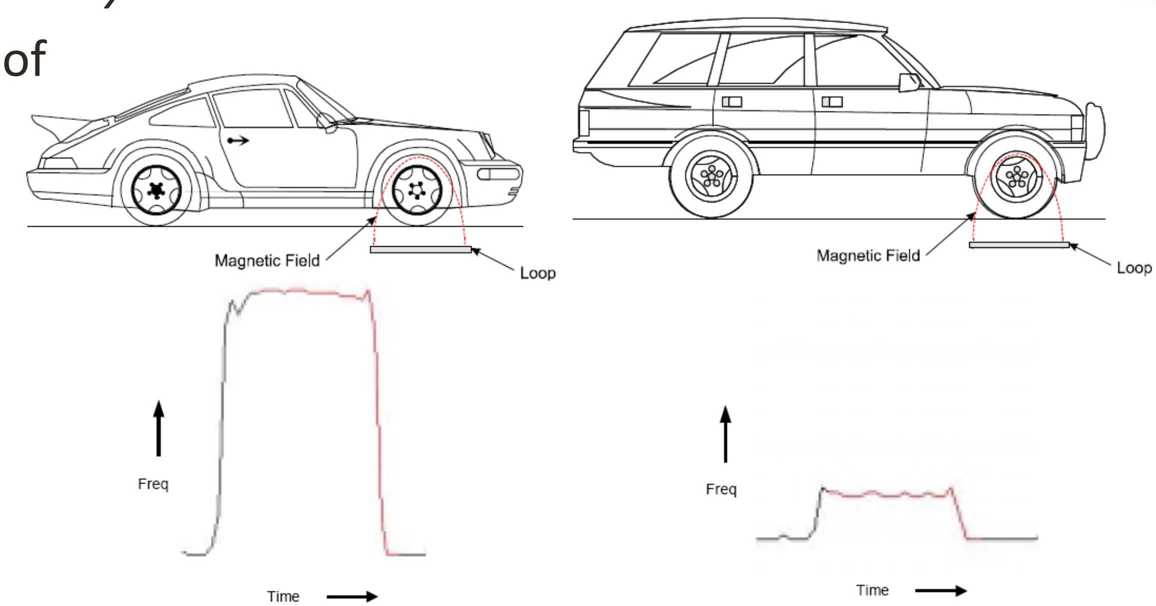
The Sensing Task

- 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

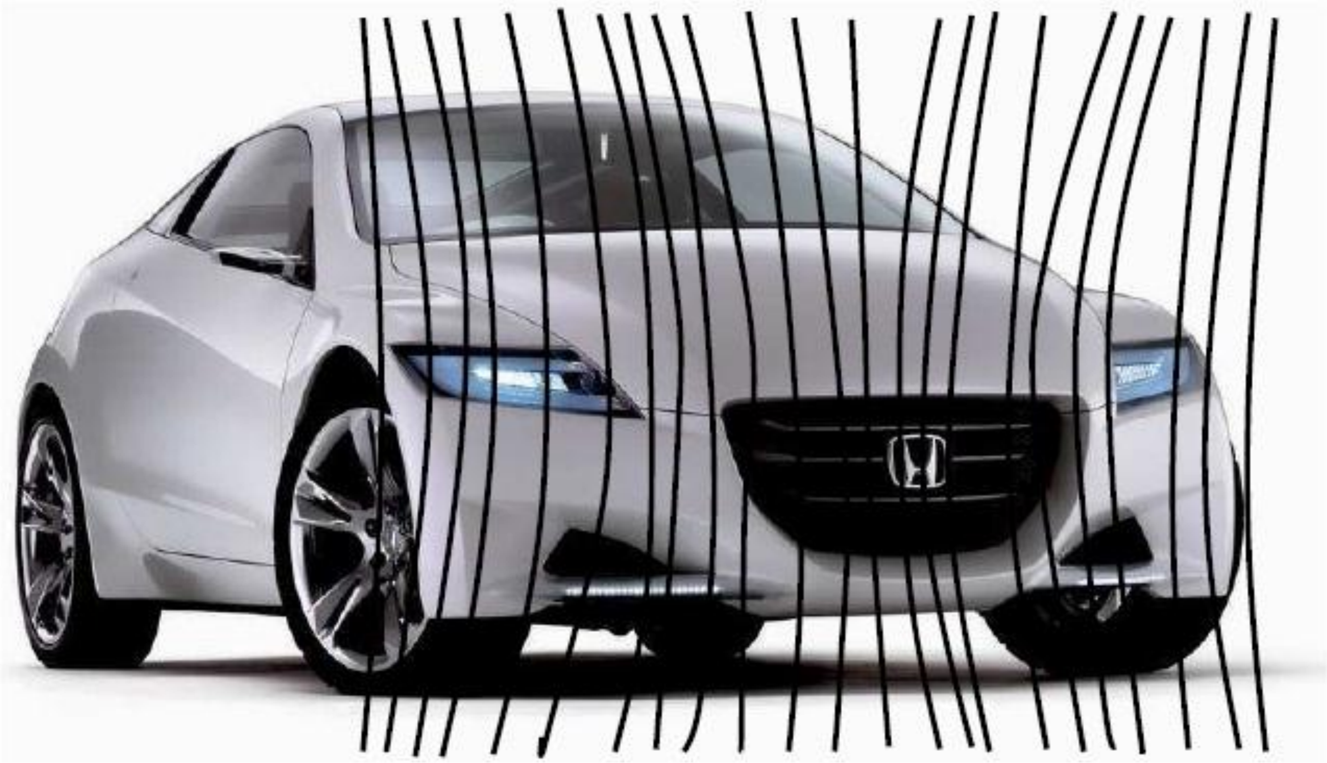


Figure: Detection of a moving vehicle with an ARM magnetic sensor (Caruso and Withanawasam 1999)

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

Knaian (2000)

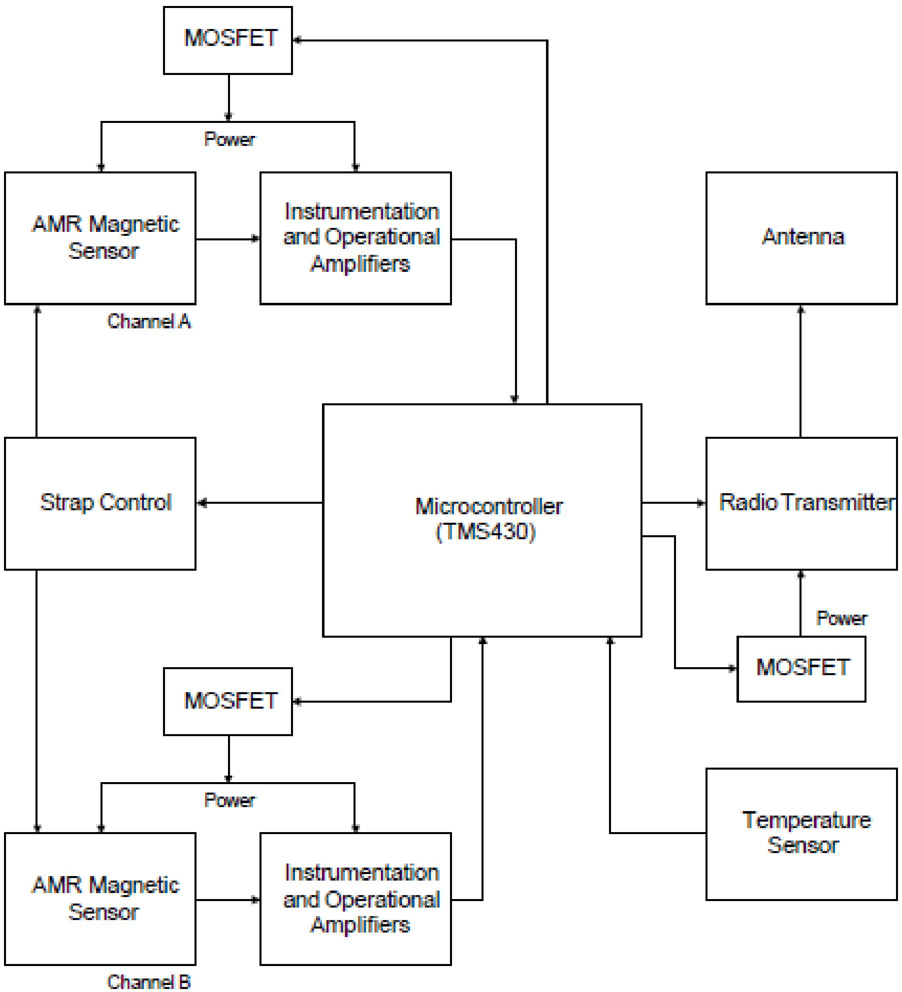


Figure: Block diagram of the MIT node for traffic monitoring (Knaian 2000)

Knaian (2000)

- Proposes wireless sensor networks for traffic monitoring in urban areas
- The node consists of
  - *Two AMR magnetic sensors* to detect vehicular activities
    - By observing the disturbance in the Earth's magnetic field the vehicular creates
    - The vehicle pulls field lines away from the sensor when it approaches it
    - Then towards the sensor when it drives away from it
  - *A temperature sensor* to monitor road condition (snow, ice, or water)

http://resenv.media.mit.edu/pubs/theses/AraKnaian-Thesis.pdf

Knaian (2000)

- To measure the speed of a vehicle, the node waits until it detects an excursion from the predefined baseline and then starts sampling at a frequency of 2KHz
  - Two AMR magnetic sensors are placed *one at the front* of the node and *the other at the back* - they are shifted in time
  - The node *waits* for the signal from the rear sensor to cross the baseline
  - Then it begins to *count* the number of *samples* until the signal from the forward sensor crosses the baseline
  - From this count, it *computes* the *speed* of the passing vehicle

Arora et al. (2004)

- Deploys *90 sensor nodes* to detect the movement of vehicles and people (e.g., soldiers)
  - *78* of the nodes were *magnetic sensor nodes* that were deployed in a 60×25 square foot area
  - *12 radar sensor nodes* were overlaid on the network
- These nodes form a *self-organizing* network which connects itself to a remote computer via a base station and a long haul radio repeater

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  - Structural Health Monitoring
  - Traffic Control
  - **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

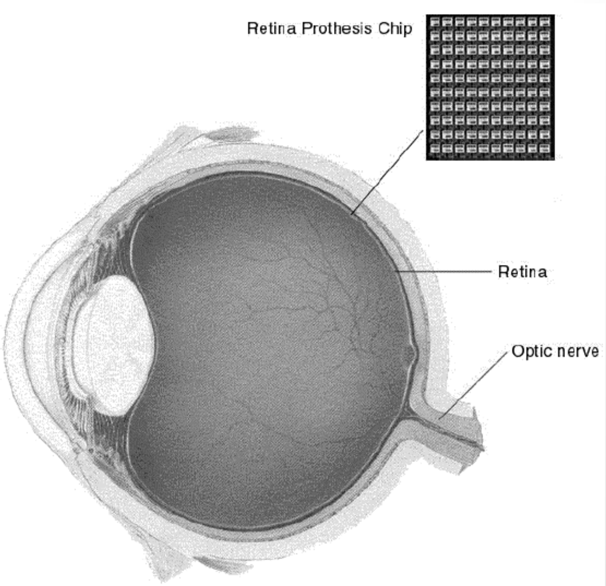
- To deal with these problems, researchers proposed comprehensible solutions that involve the following tasks:
  - building *pervasive systems* that *provide* patients with *rich information* about diseases and their prevention mechanisms
  - seamless integration of health infrastructures with *emergency 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

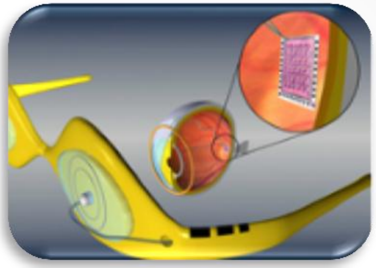
- Pulse oxygen saturation sensors
- Blood pressure sensors
- Electrocardiogram (ECG)
- Electromyogram (EMG) for measuring muscle activities
- Temperature sensors (core body temperature and skin temperature)
- Respiration sensors
- Blood flow sensors
- Blood oxygen level sensor

Artificial Retina

- Schwiebert et al. (2001) developed a micro-sensor array that can be *implanted in the eye* as an artificial retina to assist people with visual impairments
- The system consists of *an integrated circuit* and *an array of sensors*
- An integrated circuit
  - is coated with a *biologically inert substance*
  - is *a multiplexer* with on-chip switches and pads to support a 10 × 10 grid of connections; it operates at 40KHz
  - has an *embedded transceiver* for wired and wireless communications
  - each *connection* in the chip interfaces a sensor through an aluminum probe surface



Artificial Retina



- An array of sensors
  - each sensor is *a micro-bump*, sufficiently *small and light*
  - the *distance* between adjacent micro-bumps is approximately *70 microns*
  - the sensors *produce electrical signals* proportional to the light reflected from an object being perceived
  - the *ganglia* and additional tissues *transform the electrical energy* into *a chemical energy*
  - the chemical energy is *transformed* into *optical signals* and *communicated to the brain* through the optical nerves
  - the *magnitude and wave shape* of the transformed energy *corresponds to* the response of *a normal retina to light stimulation*

Artificial Retina

- The system is *a full duplex system*, allowing communication in a reverse direction - the sensor array can be used for *reception* and *transmission* in a feedback loop
  - in addition to the transformation of electrical signals into optical signals
  - *neurological signals* from the ganglia can *be picked up* by the micro-sensors and *transmitted* out of the sensing system *to an external signal processor*
- Two types of wireless communications are foreseen

Artificial Retina

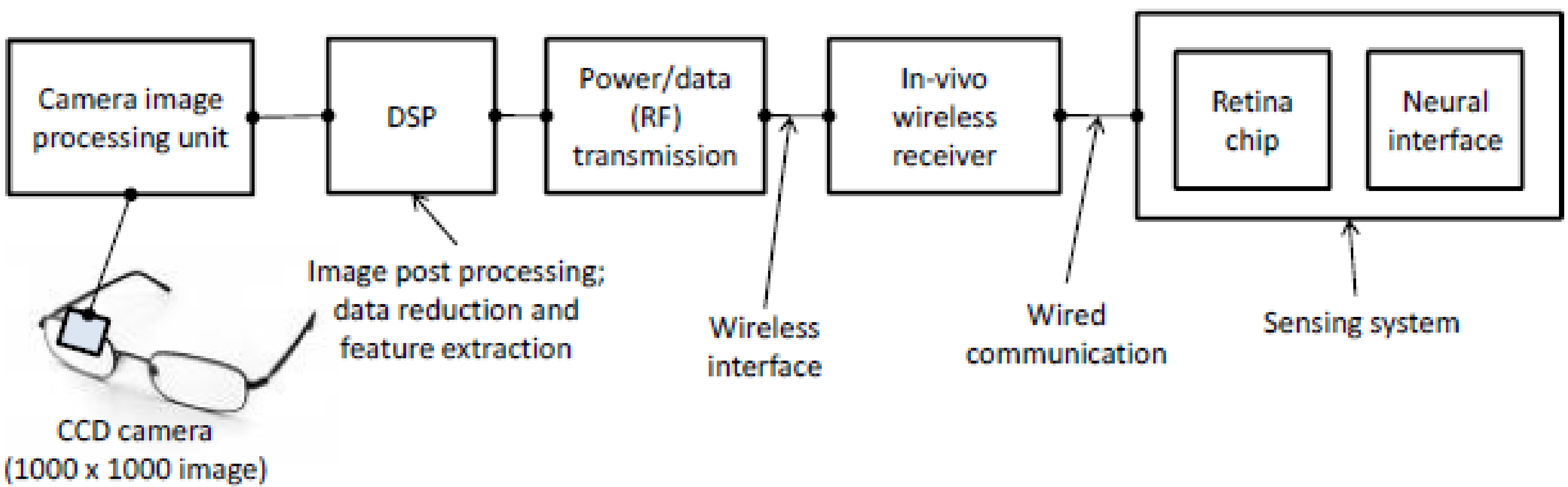


Figure: The processing components of the artificial retina (Schwiebert et al. 2001)

Artificial Retina

- Above figure illustrates the signal processing steps of the artificial retina
  - a *camera* embedded in a pair of spectacles *directs its output to* a real-time *DSP*
  - *DSP - data reduction and processing*
  - the camera can be combined with a laser pointer for automatic focusing
  - *the output* of the DSP *is compressed* and *transmitted* through a wireless link to the *implanted sensor array*
  - the sensor array decodes the image and produces a corresponding electrical signal

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  - Structural Health Monitoring
  - Traffic Control
  - Health Care
  - **Pipeline Monitoring**
  - Precision Agriculture
  - Underground Mining

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

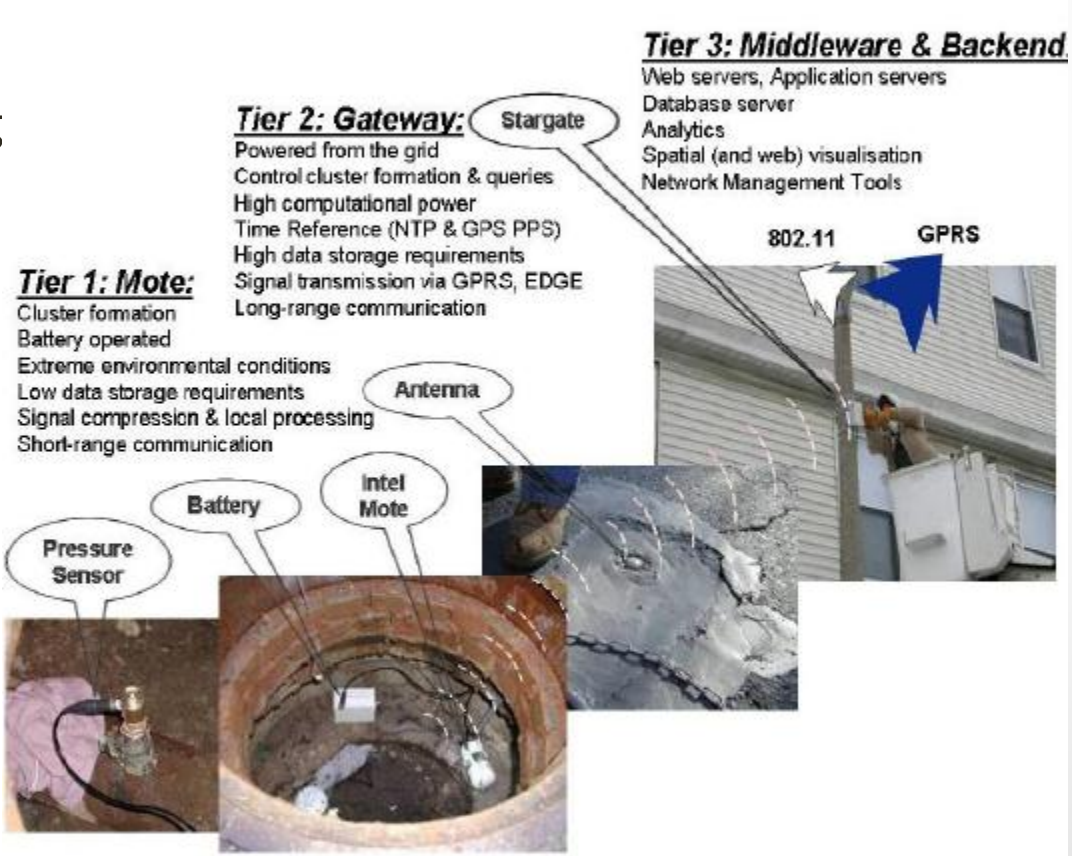
- To detect leakages, it is vital to *understand the characteristics* of the substance *the pipelines transport*
  - fluid pipelines generate a hot-spot at the location of the leak
  - gas pipelines generate a cold-spot due to the gas pressure relaxation
  - fluid travels at a higher propagation velocity 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



Three different settings

- First setting:
  - pressure and pH sensors are installed on a 12 inch cast-iron pipe
  - pressure sensor is a modified version of the OEM piezoresistive silicon sensor
  - pressure data is collected every 5 minutes at a rate of 100 Hz for a period of 5s
  - a pH sensor is a glass electrode with an Ag/AgCl reference cell
  - pH data is collected every 5 minute for a period of 10s at a rate of 100 Hz
  - the sensor nodes use a Bluetooth transceiver for wireless communication

Three different settings

- Second setting:
  - a pressure sensor measures the pressure in 8 inch cast iron pipe
  - the data are collected every 5 minutes for a period of 5 s at a sampling rate of 300 Hz
  - for this setting the raw data was transmitted to a remote gateway

Three Different Settings

- Third setting:
  - the water level of a combined sewer outflow collector is monitored
  - two pressure transducers (low-power device, < 10 mW) were placed at the bottom of the collector
  - an ultrasonic sensor (high-power device, < 550 mW) was placed on top of the collector
  - efficient power consumption:
    - pressure sensors are employed for periodic monitoring
    - when the difference of pressure sensors and the ultrasonic sensor exceeds a certain threshold; or
    - when the water level exceeds the weir height
    - the ultrasonic sensor is required to verify the readings from the pressure sensors

Three Different Settings

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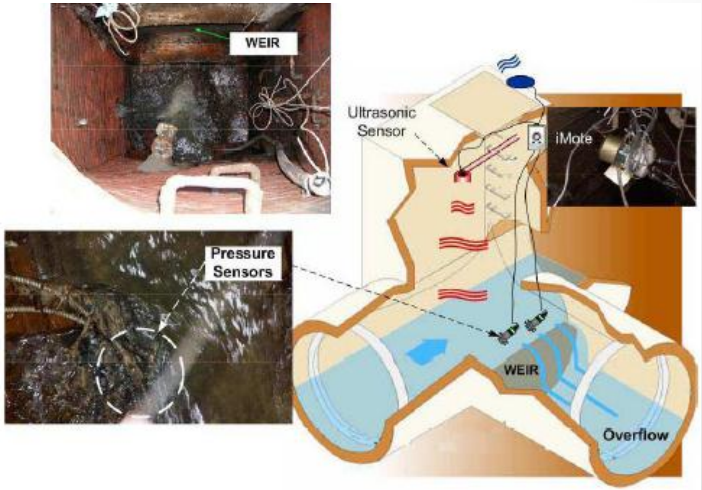


Roadmap

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

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
  - Structural Health Monitoring
  - Traffic Control
  - Health Care
  - Pipeline Monitoring
  - Precision Agriculture
  - **Underground Mining**

Underground Mining

- Motivation:
  - one of *the most dangerous* work *environments* in the world
  - incident of August 3, 2007 at the Crandall Canyon mine, Utah, USA
    - six miners were trapped inside the coal mine
    - their precise *location was not known*
    - the owners of the mine claimed a natural earthquake was the cause while scientists suspect the mine operations caused seismic spikes
    - a *costly* and irksome *rescue* attempt went underway
    - 6.4 cm and 26 cm holes into the mine cavity where drilled, through which
      - an omnidirectional *microphone* and a *video camera* were lowered down
      - An *air sample* was taken – (20% O_2; little CO_2; no CH_4)

Underground Mining

- This evidence caused a mixed anticipation
  - if the miners were alive, the amount of O_2 was sufficient enough to sustain life for some additional days
  - the absence of methane gave hope that there would be no immediate danger of explosion
  - however, the absence of CO_2 and the evidence from the camera and the microphone undermined the expectation of finding the lost persons alive
- *More than six labor-intensive days* were required to collect the above evidence
- Unfortunately, the rescue mission had to be suspended
  - additional seismic shift in the mountain – this fact strengthened the proposition that man-made causes produced the first incident
- *Three rescuers were killed* and *several were injured*

Sources of Accidents

- *Seismic shifts* not the only danger
- *Explosions sparked* by methane gas and coal-dusts
  - methane from coalification process
  - inadequate ventilation
  - methane from fallen coal
  - methane from the mining faces
  - methane from the walls and ceilings of coal and rock roadways
  - methane from gob of coal mine
- High density coal dust ➔ CO can not disperse into the air ➔ poisonous gas

The Sensing Tasks

- *Four tasks:*
  - locate individuals
  - locate collapsed holes
  - measure and forecast seismic shifts
  - measure the concentration of gases
- *Challenges* (extreme hostile environment for radio communication)
  - turns and twists of underground tunnels ➔ impossible to maintain a line-of-sight communication link ➔ signals being highly reflected, refracted, and scattered
  - high percentage of humidity ➔ signal absorption and attenuation is extremely high

Roadmap

- Motivation for a Network of Wireless Sensor Nodes
- Applications
- 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

Data-centric Protocols

- In many applications of sensor networks, it is not feasible to assign global identifiers to each node
- Data-centric protocols are query-based
- Sink sends queries to certain regions and waits data from sensors located in that region
- Attribute-based naming is necessary to specify properties of data

Data-centric Routing

- Sensor networks can be considered as a virtual database
- Implement query-processing operators in the sensor network
- Queries are flooded through the network (or sent to a representative set of nodes)
- In response, nodes generate tuples and send matching tuples towards the origin of the query
- Intermediate nodes may merge responses or aggregate

Data-centric Protocols

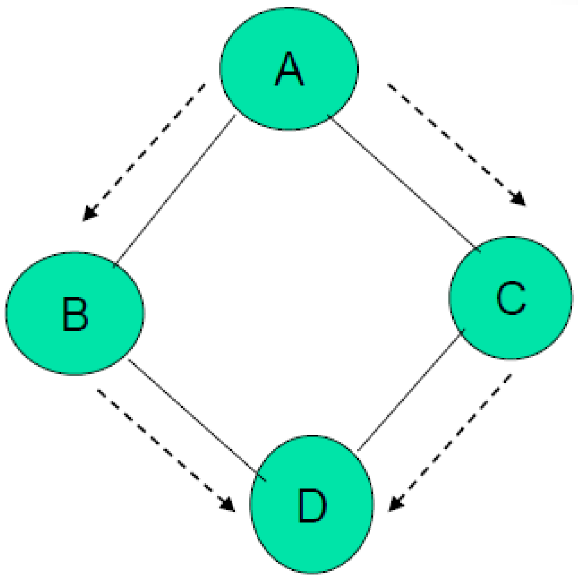
- Flooding
- Gossiping
- Sensor Protocols for Information via Negotiation (SPIN)
- Directed Diffusion
- Energy-aware Routing
- Rumor Routing
- Gradient-Based Routing (GBR)
- Constrained Anisotropic Diffusion Routing (CADR)
- COUGAR
- ACtive QUery forwarding In sensoR nEtworks (ACQUIRE)

Data-centric Protocols

- **Flooding**
  - Sensor broadcasts every packet it receives
  - Relay of packet till the destination or maximum number of hops
  - No topology maintenance or routing
- **Gossiping**
  - Enhanced version of flooding
  - Sends received packet to a randomly selected neighbor

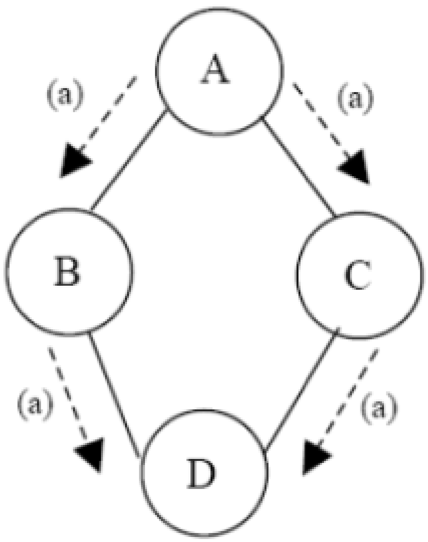
Classic Flooding Problems

- **Implosion Problem:**
  - A starts by flooding its data to all of its neighbors
  - Two copies of the data eventually end at node D
  - The system wastes energy and bandwidth
- **Overlap Problem:**
  - Two sensors cover an overlapping graphic region
  - Node receives two copies of the Data
- **Resource Blinding:**
  - Resources do not modify their activities based on the amount of energy they have

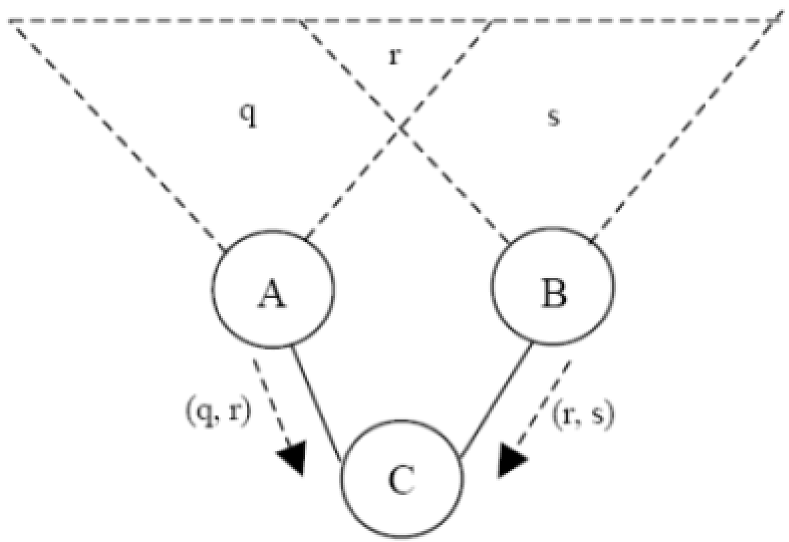


Data-centric Protocols –Flooding, Gossiping Problems

- Problems of Implosion, Overlap, Resource Blindness



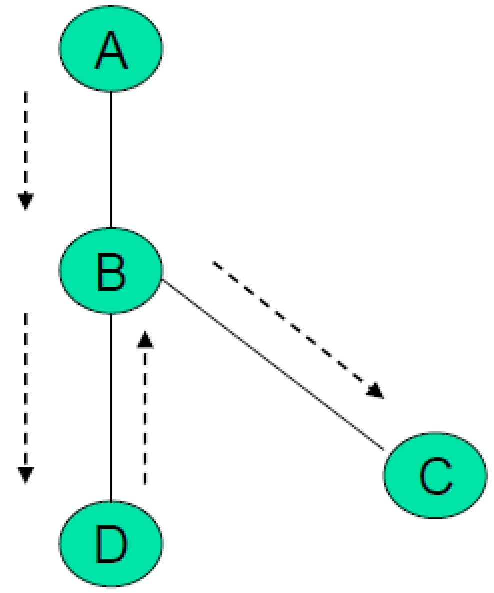
Implosion Problem



Overlap Problem

Gossiping

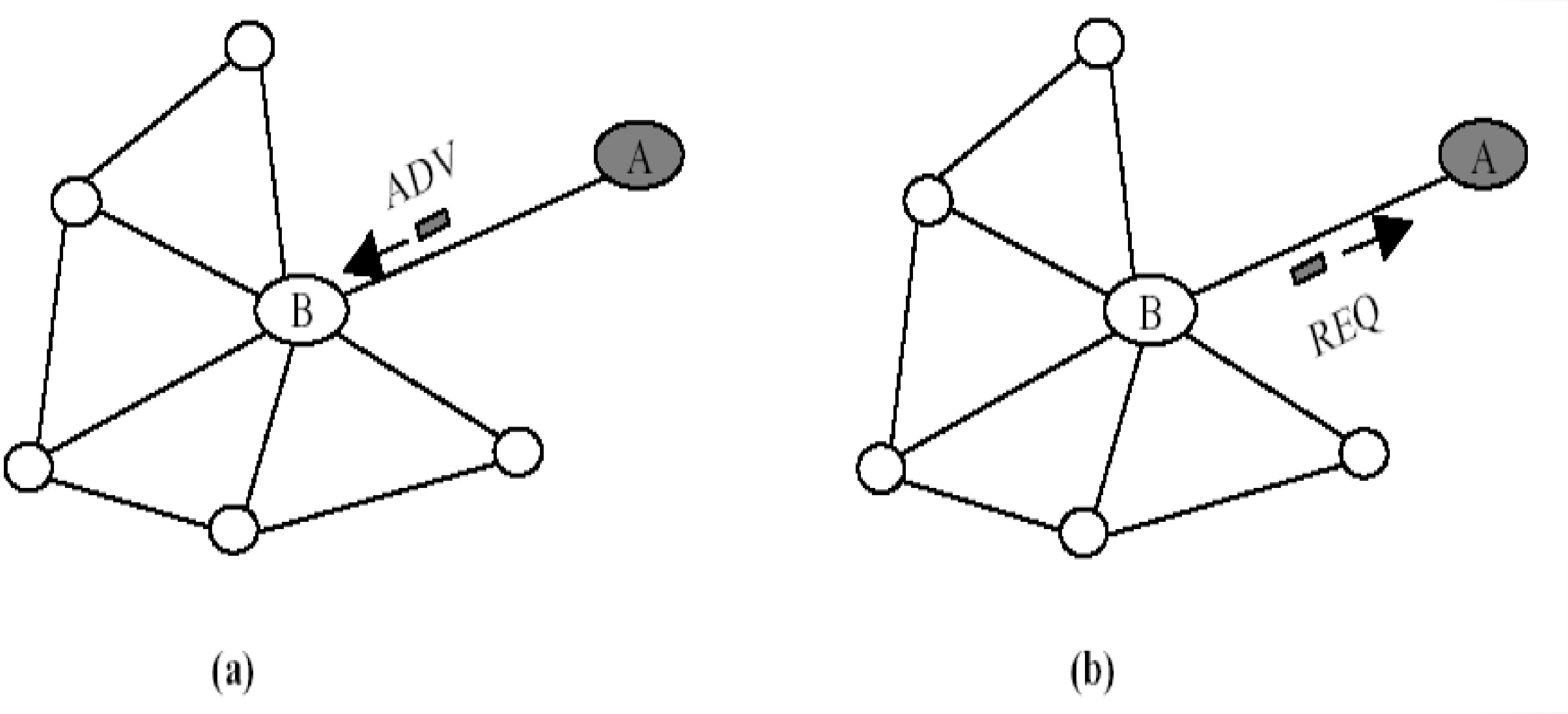
- An alternative to the classic flooding
- Uses randomization to conserve energy
- Each node only forwards data on to one neighbor
  - Is selected randomly
- After node D receives the data, it must forward the data back to sender (B)
  - Otherwise the data would never reach node C



SPIN: Sensor Protocols for Information Negotiation

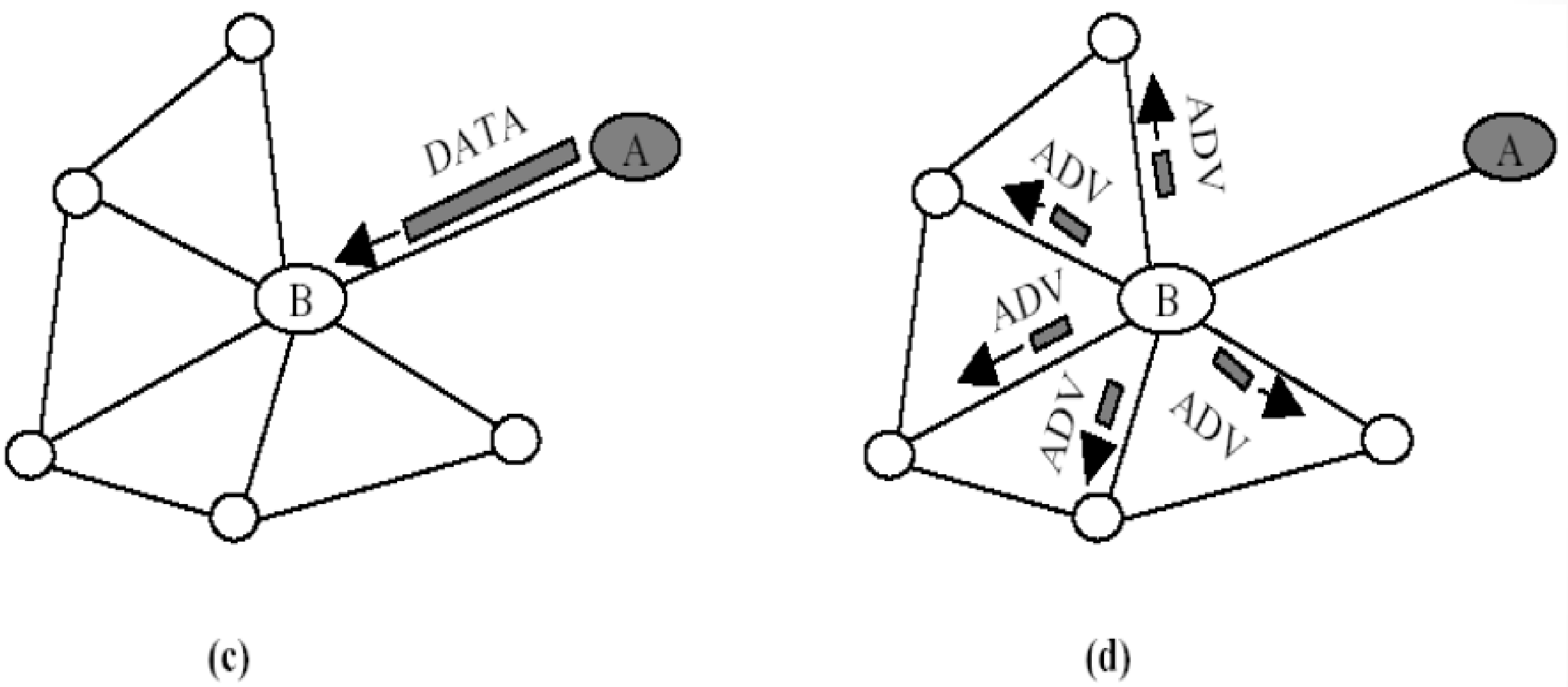
- One of the most dominant form of routing in the wireless sensor networks
- Name data, using meta-data
  - Meta Data for each sensor data
  - Same senor data -> same meta-data
  - Different sensor data -> different meta-data
- Size of meta-data << Size of actual data
- There is no standard meta-data format and it is assumed to be application specific
- Uses three types of messages:
  - ADV –advertise data
  - REQ –request for data
  - DATA –data message, contains actual sensor data

SPIN Protocol Example



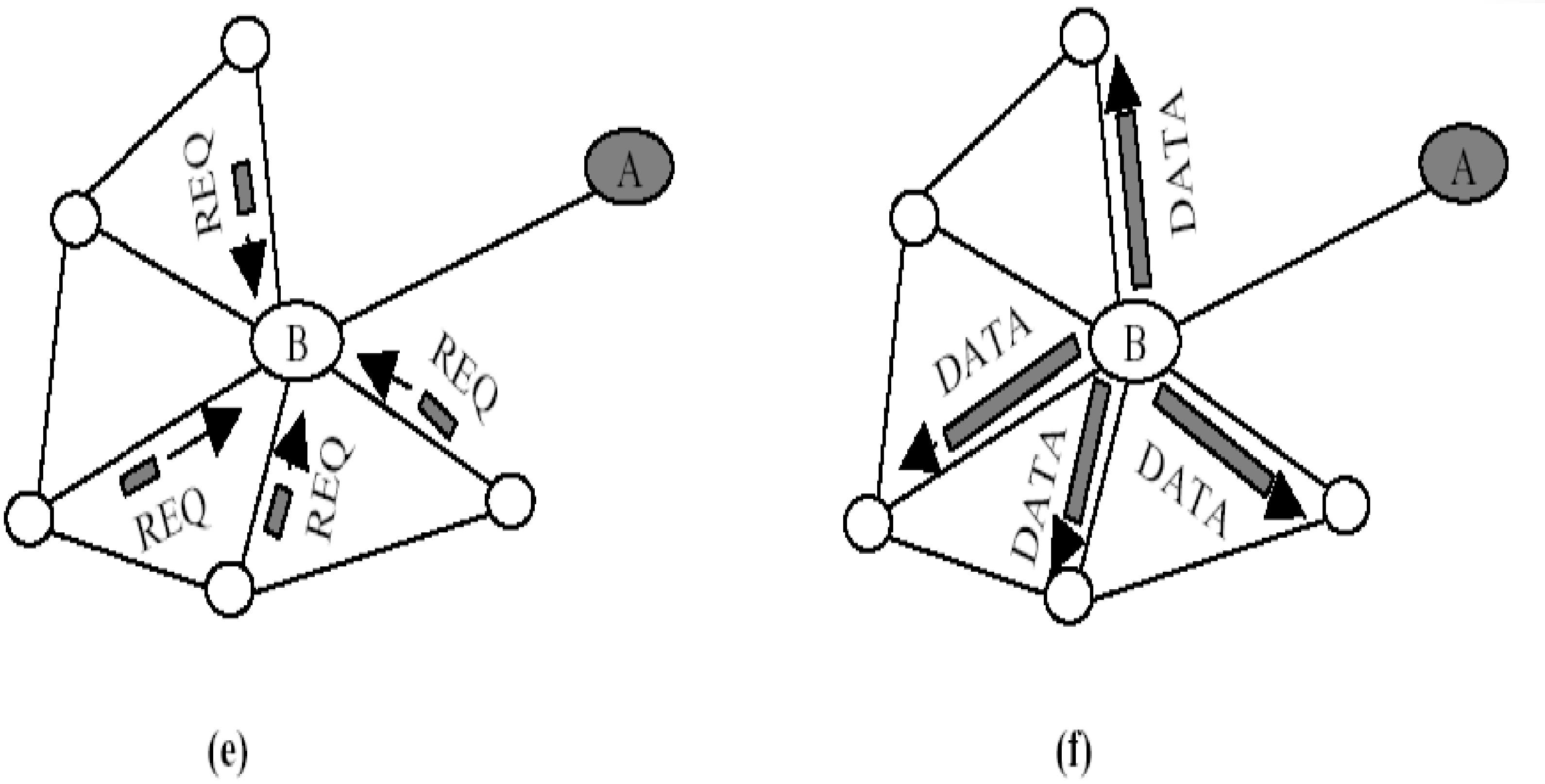
- A sends an ADV message to B
- B sends a REQ listing all of the data it would like to acquire

SPIN Protocol Example



- If node B had its own data, it could aggregate this with the data of node A and advertise

SPIN Protocol Example



- Nodes need not respond to every message

Data-centric Protocols -SPIN

- Topological changes are localized -Each node needs to know only its neighbors
- SPIN halves the redundant data in comparison to flooding
- Cannot guarantee data delivery
- SPIN **NOT** good for applications that need reliable data delivery

SPIN1 and SPIN2

SPIN1: Three way handshaking protocol

- ADV, REQ, DATA.

- Each sensor node has resource manager
  - Keeps track of resource consumption
  - Applications probe the manager before any activity
  - Cut down activity to save energy

SPIN2: energy constraint

- Adds energy-conservative heuristic to the SPIN1 protocol.
- Node initiates three stage protocol, only if it has enough energy to complete it.
- If below energy threshold, node can still receive messages, cannot send/recv DATA messages

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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

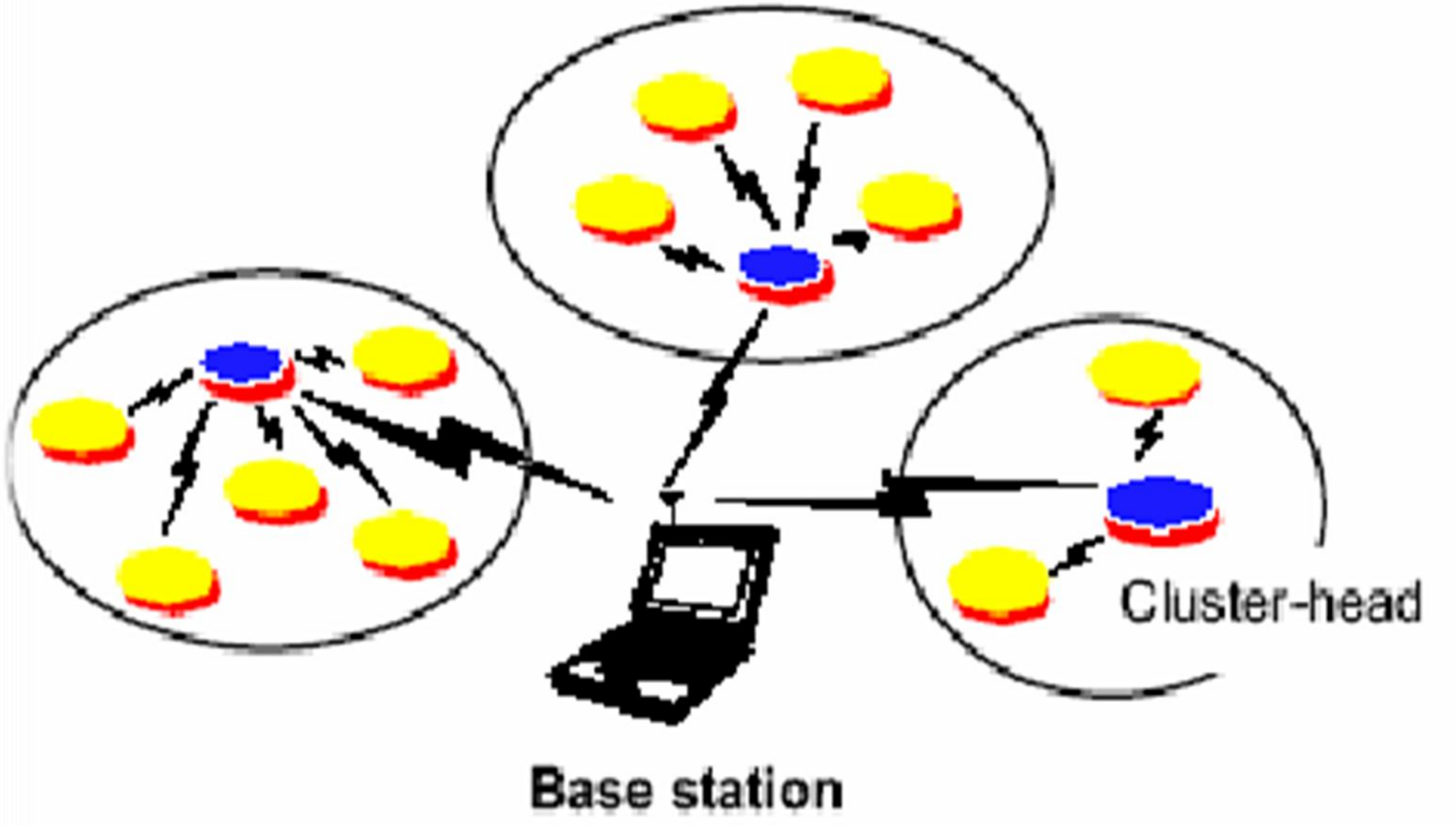
Hierarchical Protocols

- 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

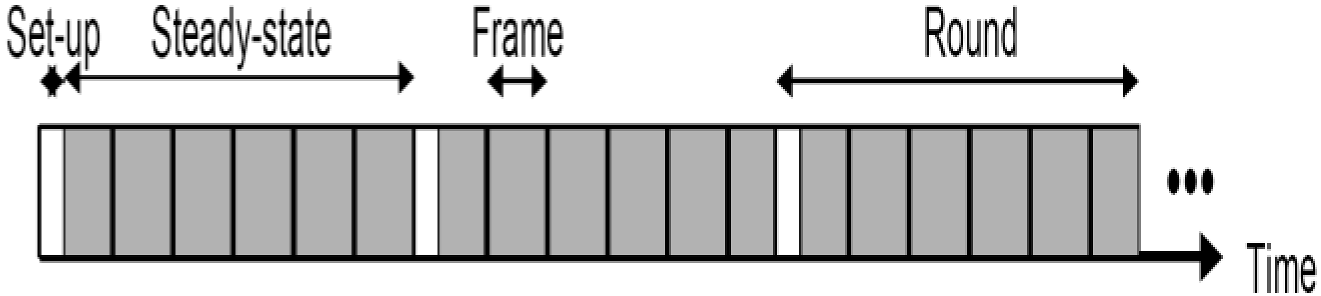
- One of the first hierarchical routing protocols
- Forms clusters of the sensor nodes based on received signal strength
- Self-organizing, adaptive clustering protocol
- *Dynamic* cluster formation
- Local cluster heads route the information of the cluster to the sink
- Data processing & aggregation 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

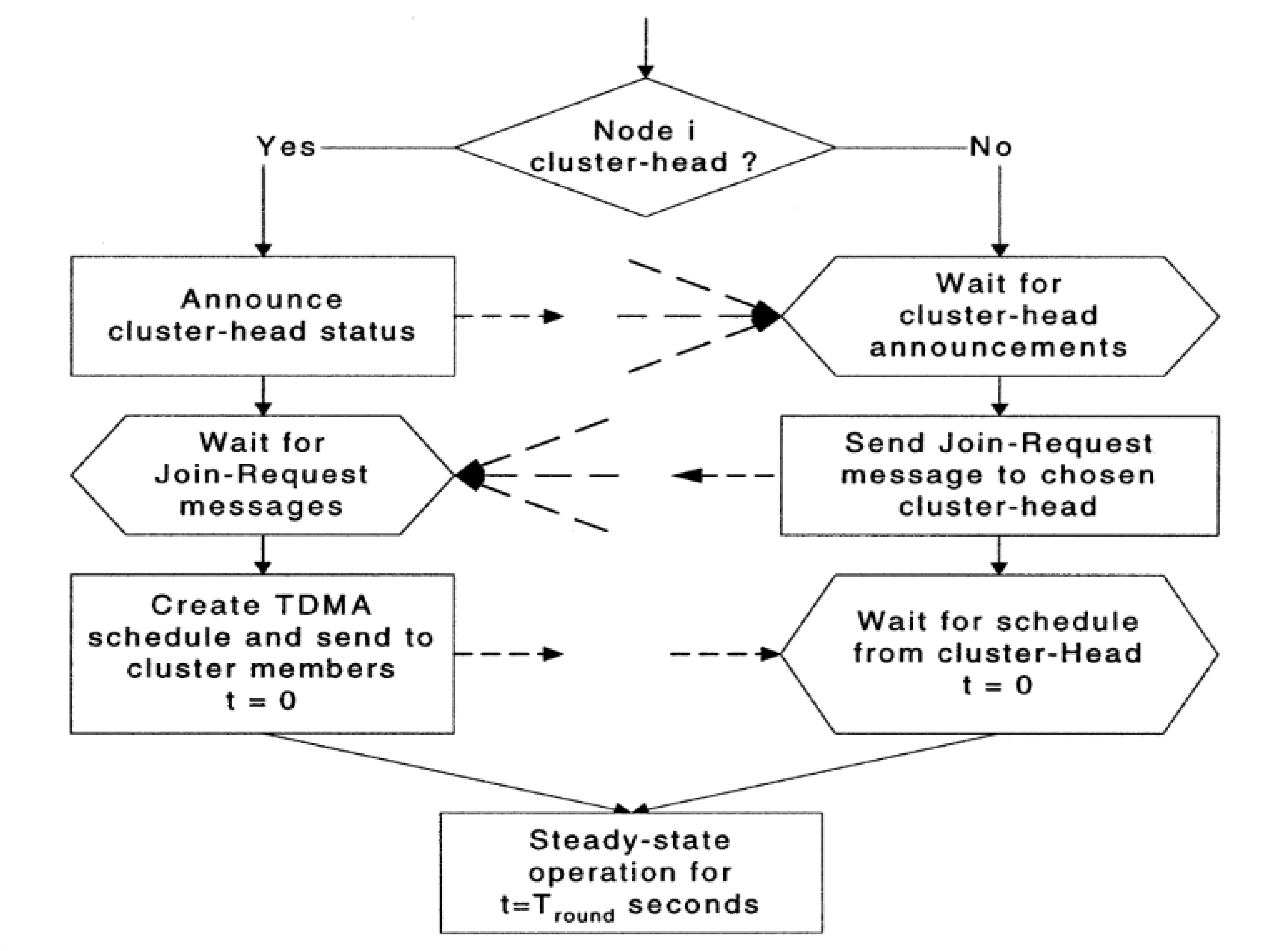


Timeline showing LEACH operation

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

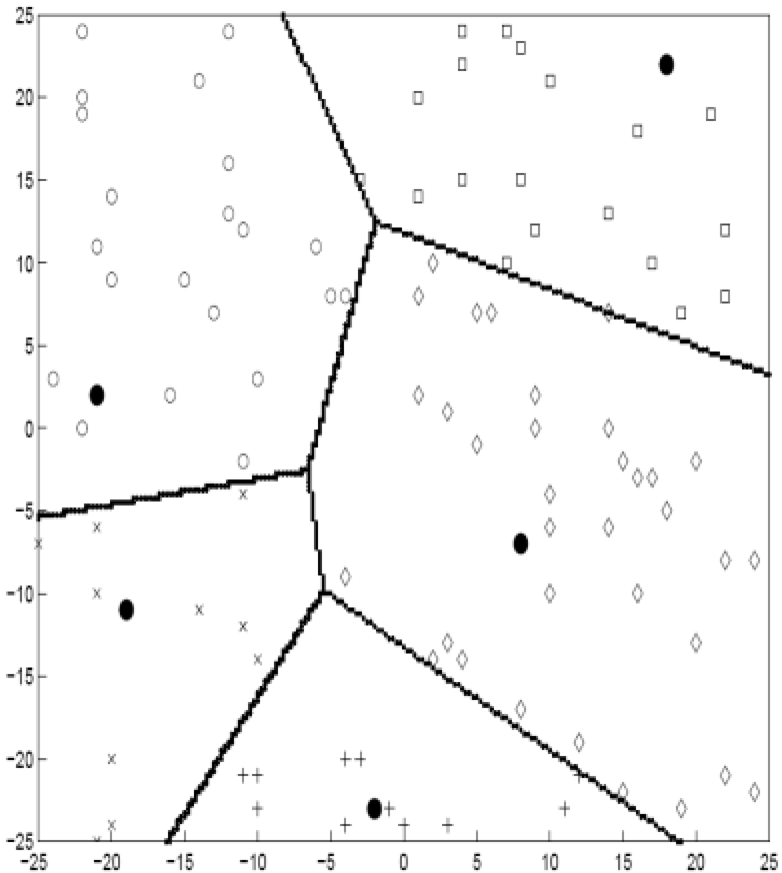
Cluster Head Selection Algorithm

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

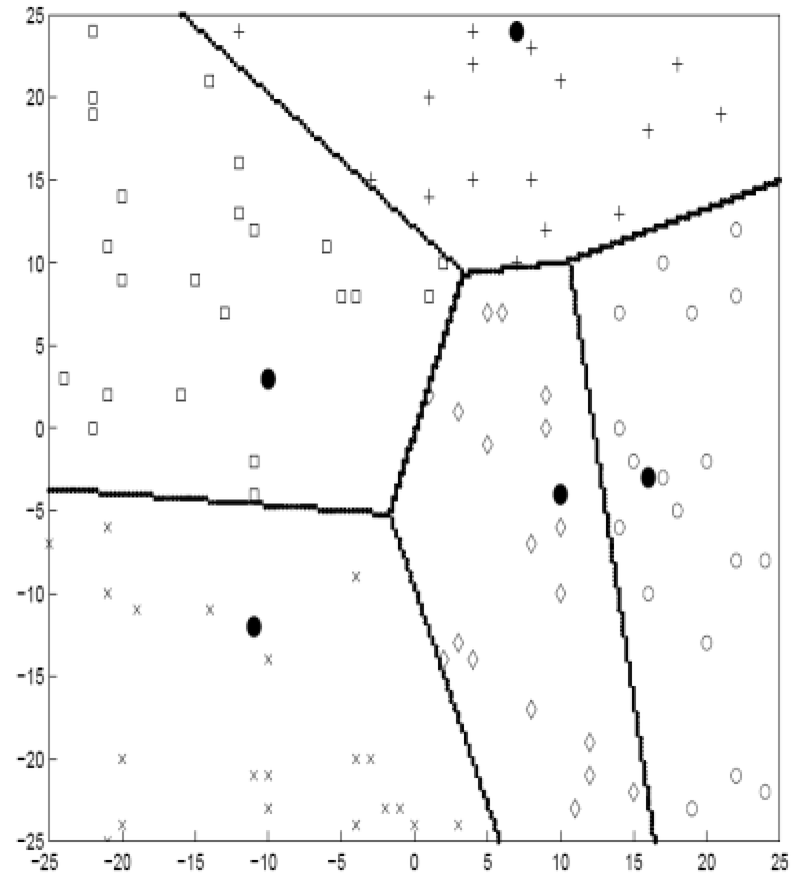
$$P_i(t) = \begin{cases} \frac{k}{N-k*(r \bmod \frac{N}{k})} & : \quad C_i(t) = 1 \\ 0 & : \quad C_i(t) = 0 \end{cases} \qquad (2)$$

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

Dynamic Cluster Formation

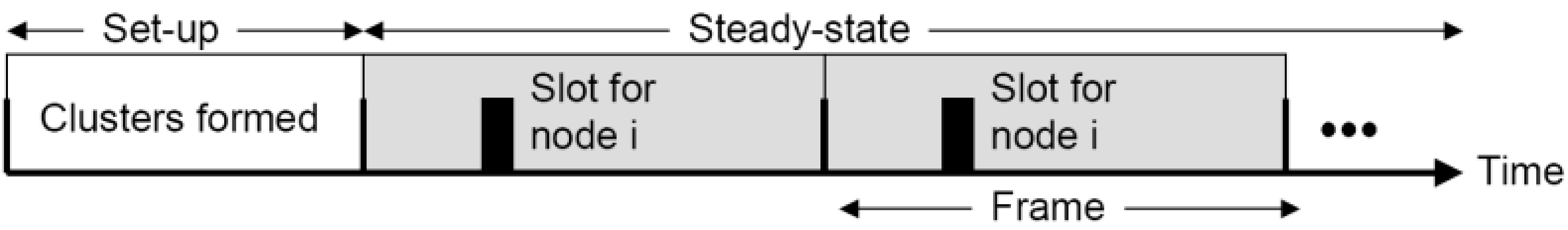


Clusters at time t



Clusters at time t+d

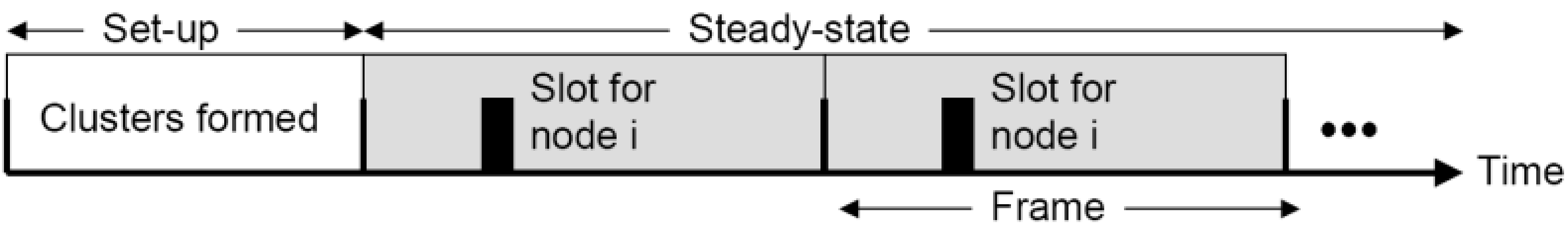
Steady-State Phase



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

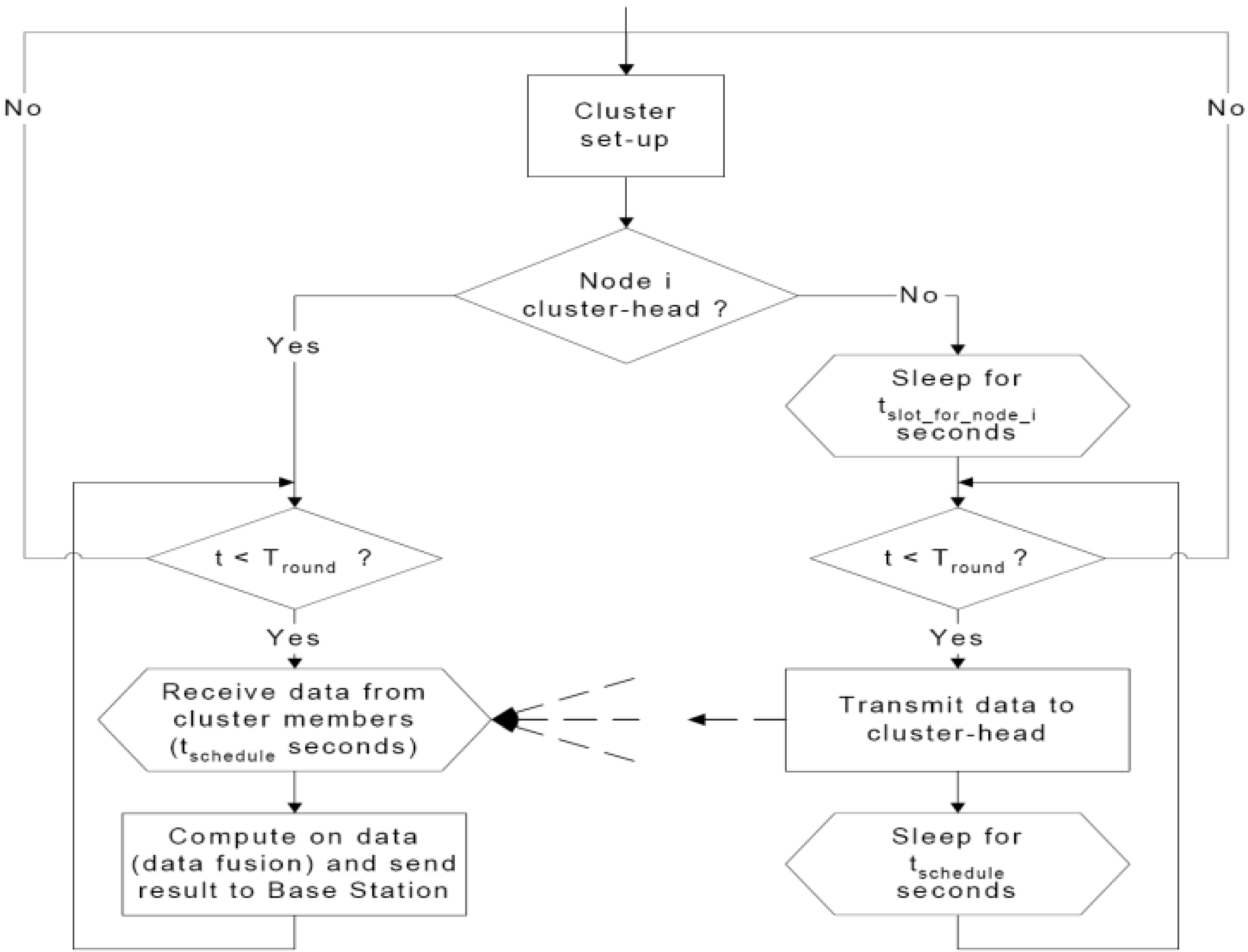
Steady-State Phase



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

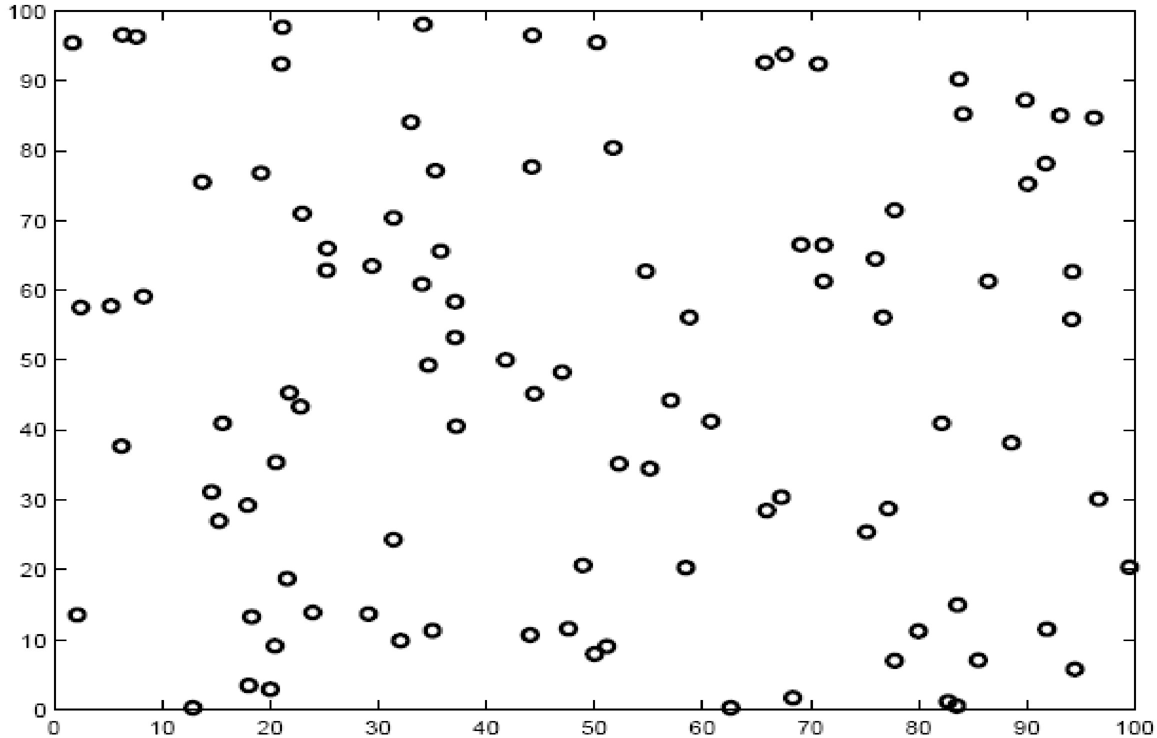
Flow Chart for Steady Phase



LEACH-C: BS Cluster Formation

- LEACH doesn’t guarantee cluster head spread in the network
- Centralized clustering algorithm for cluster formation
- Uniform distribution of Cluster Heads through out the network
- Uses same steady-state protocol as LEACH
- Set-up phase
  - Each node specifies its location (using GPS) and energy level to the BS
  - BS runs an *optimization algorithm* to determine the cluster’s for that round
  - BS determines optimal clusters and broadcasts a message containing cluster head ID for each node

LEACH Simulation



100 node random test network

Nodes	100
Network size	100 m × 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

Existing Routing Protocols

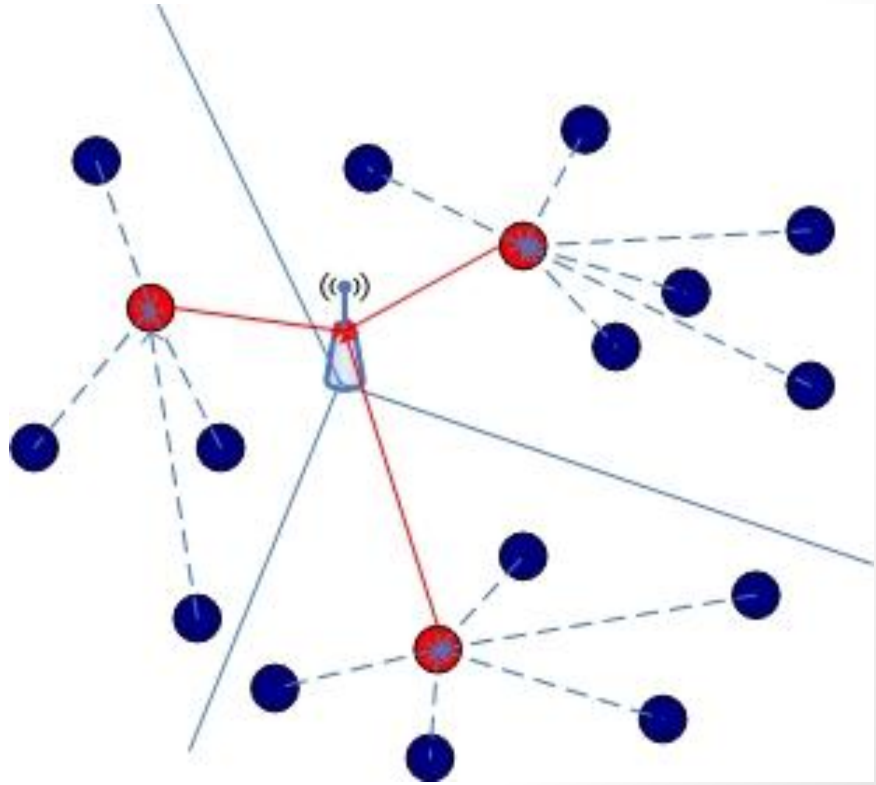
- LEACH is compared against three other routing protocols:
  - Direct-Transmission
    - Single-hop
  - Minimum-Transmission Energy
    - Multi-hop
  - Static Clustering
    - Multi-hop

Direct-Transmission vs. Minimum Transmission Energy (MTE)

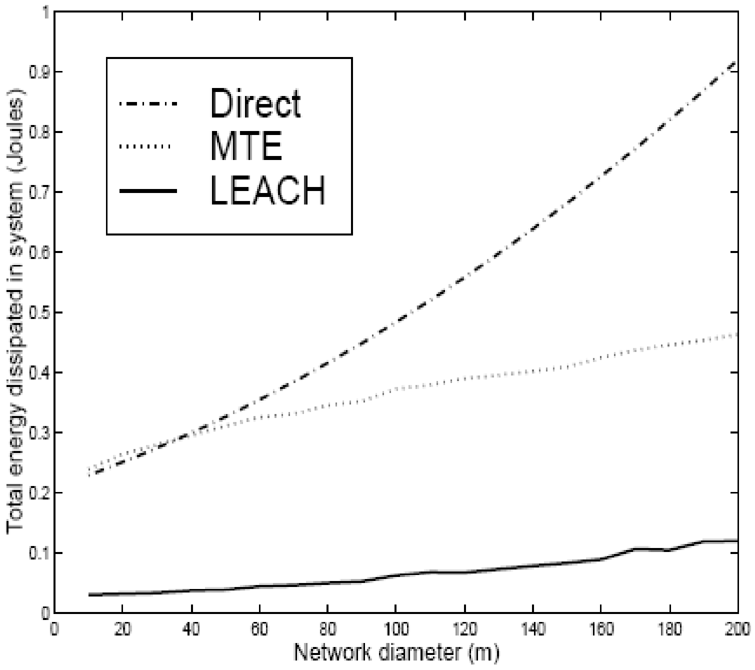
- DT
  - Each sensor node transmits directly to the sink, regardless of distance
  - Most efficient when there is a small coverage area and/or high receive cost
- MTE
  - Traffic is routed through intermediate nodes
    - Node chosen by transmit amplifier cost
    - Receive cost often ignored
  - Most efficient when the average transmission distance is large and E_{elec} is low

Static Clustering

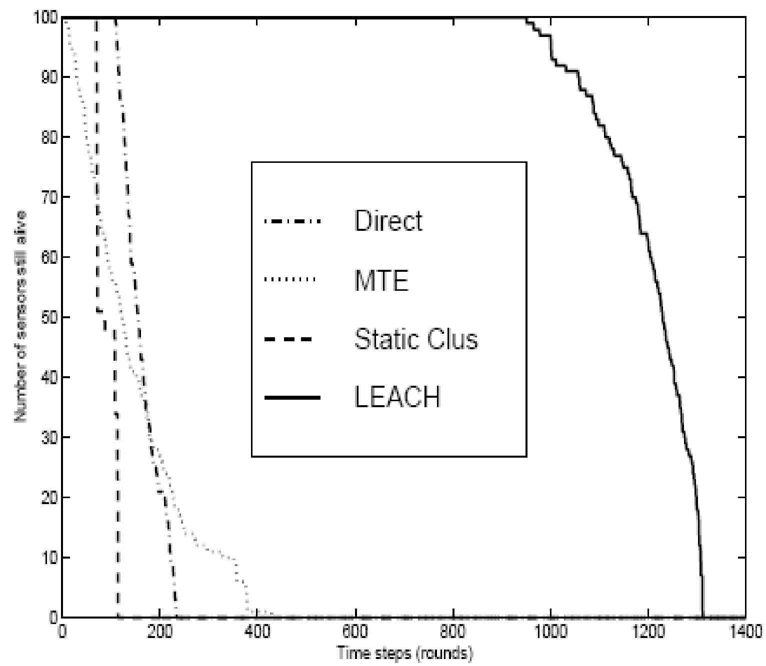
- Indirect upstream traffic routing
- Cluster members transmit to a cluster head
  - TDMA
- Cluster head transmits to the sink
  - Not energy-limited
- Does not apply to homogenous environments



LEACH – Simulation Result

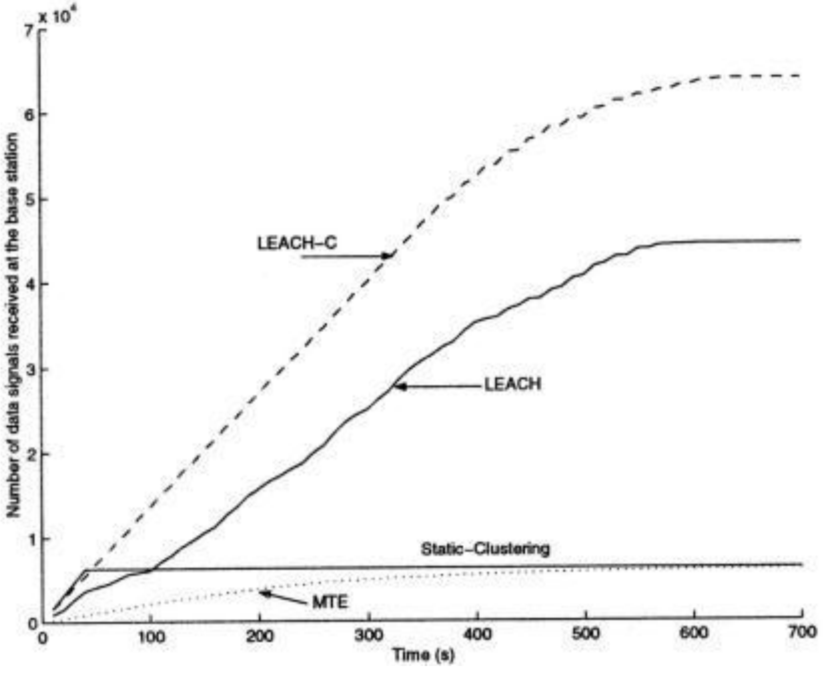


Energy dissipation

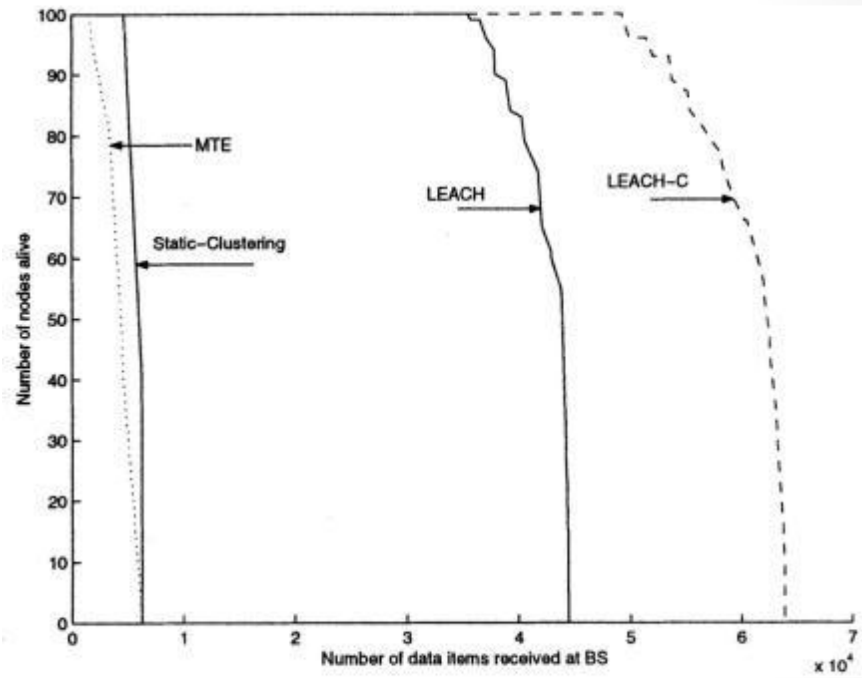


System Lifetime

LEACH-C : Simulation Result



Total amount of data received at the BS over time



Number of nodes alive per amount of data sent to the BS

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

Classification of Routing Protocols

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Location-based Protocols

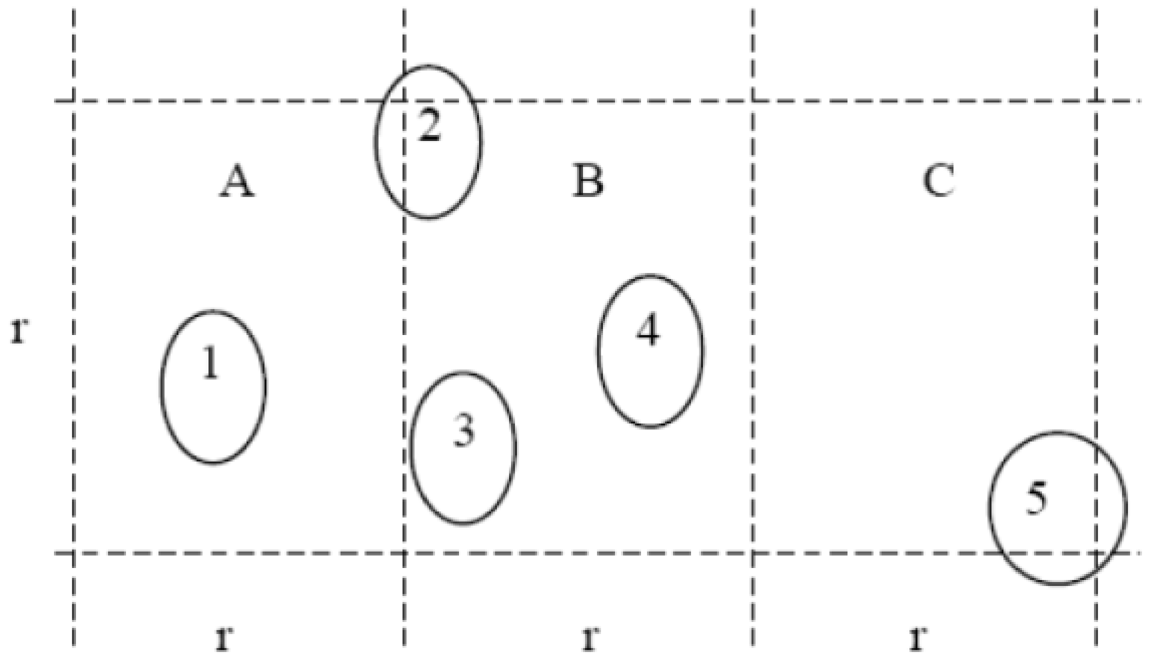
- Most of the routing protocols for sensor networks require location information for sensor nodes
- There is no addressing scheme for sensor networks like IP-addresses
- Location information can be utilized in routing data in an energy efficient way
- Protocols designed for Ad hoc networks with mobility in mind
  - Applicable to Sensor Networks as well
  - Only energy-aware protocols are considered

GAF: Geographic Adaptive Fidelity

- GAF is an energy-aware location-based routing algorithm
- GAF conserves energy by turning off unnecessary nodes in the network without affecting the level of routing fidelity
- It forms a virtual grid for the covered area
- Each node uses its GPS-indicated location to associate itself with a point in the virtual grid
- Nodes associated with the same point on the grid are considered equivalent in terms of the cost of packet routing

GAF Example

- Node 1 can reach any of 2, 3 and 4 and nodes 2, 3, and 4 can reach 5
- Therefore nodes 2, 3 and 4 are equivalent and two of them can sleep

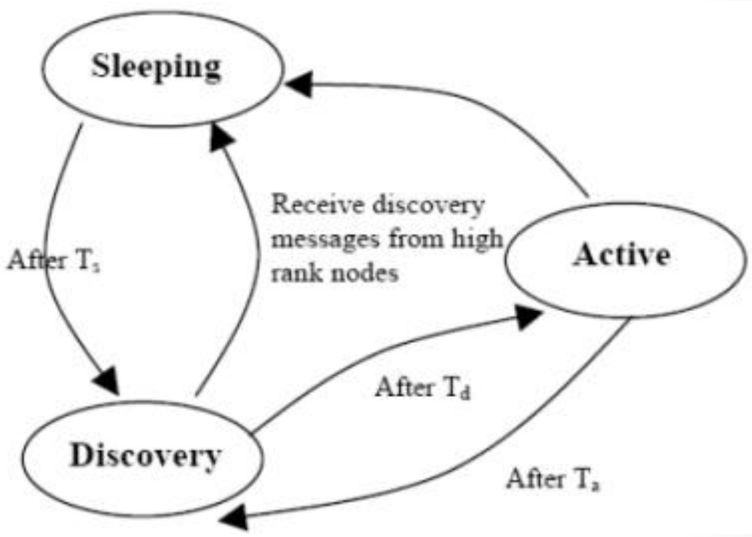


GAF States

- Three States
  - Discovery
  - Active
  - Sleep
- Discovery state is used for determining the neighbors in the grid
- Nodes change states from sleeping to active in turn so that the load is balanced
- Active reflecting participation in routing and sleep when the radio is turned off
- As good as a normal Ad hoc in terms of latency and packet loss (saving energy)

GAF State Diagram

- Each node in the grid estimates its leaving time of grid and sends this to its neighbors
- The sleeping neighbors adjust their sleeping time accordingly in order to keep the routing fidelity
- Before the leaving time of the active node expires, sleeping nodes wake up and one of them becomes active
- GAF strives to keep the network connected by keeping a representative node always in active mode for each region on its virtual grid



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

Network Flow & QoS-aware Protocols

- Network Flow:
  - Maximize traffic flow between two nodes, respecting the capacities of the links
- QoS-aware protocols:
  - Consider end-to-end delay requirements while setting up paths

Network Flow & QoS-aware Protocols

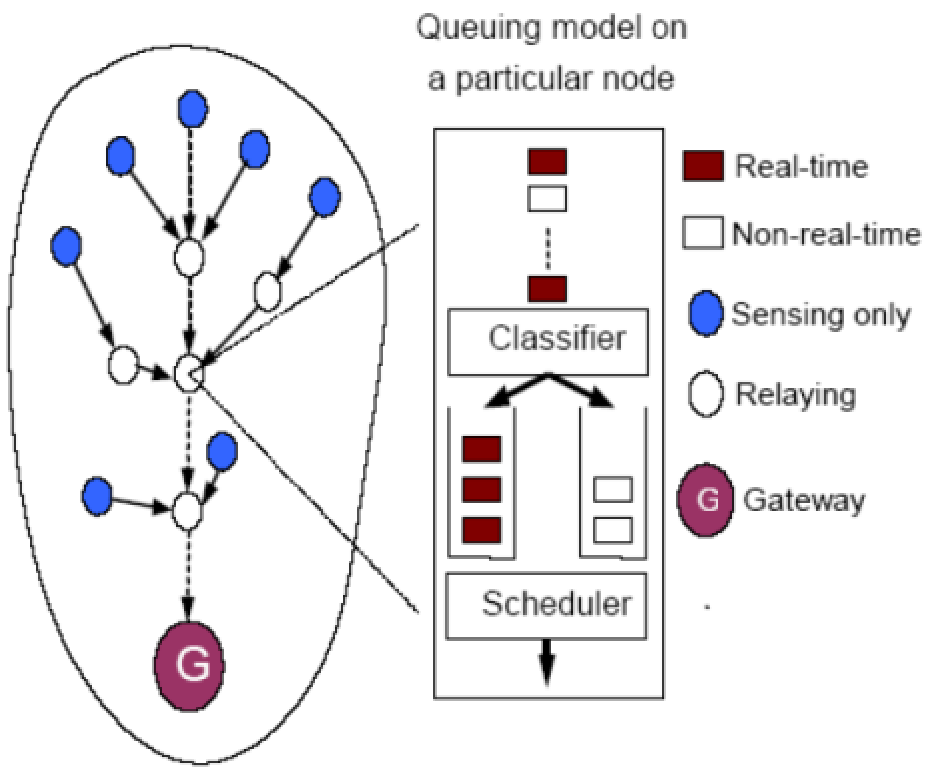
- Maximum Lifetime Energy Routing
- Maximum Lifetime Data Gathering
- Minimum Cost Forwarding
- Sequential Assignment Routing
- Energy Aware QoS Routing Protocol
- SPEED

Maximum Lifetime Energy Routing

- Maximizes network lifetime by defining link cost as a function of:
  - Remaining energy
  - Required transmission energy
- Tries to find traffic distribution (Network flow problem)
- The least cost path is one with the highest residual energy among paths

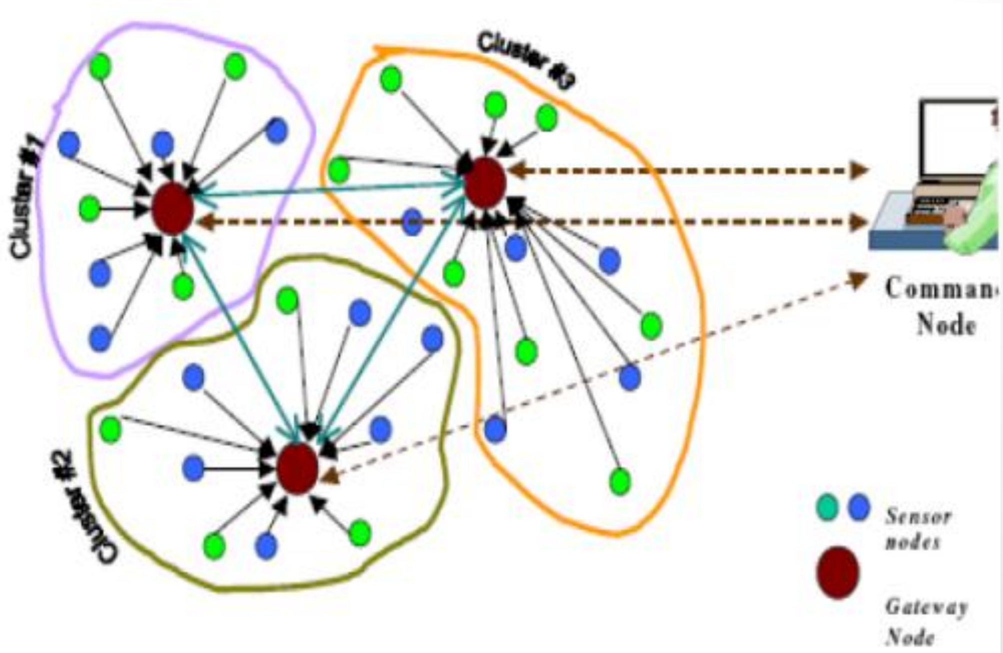
Energy Aware QoS Routing Protocol

- Finds least cost and energy efficient paths that meet the end-to-end delay during connection
  - Energy reserve, transmission energy, error rate
- Class-based queuing model used to support best-effort and real-time traffic



Energy Aware QoS Routing Protocol

- Basic settings
  - Base station
  - Gateways can communicate with each other
  - Sensor nodes in a cluster can only be accessed by the gateway managing the cluster
  - Focus on QoS routing in one cluster
  - Real-time & non-real-time traffic exist
    - Support timing constraints for RT
    - Improve throughput of non-RT traffic



Summary of Routing Protocols in WSN

Routing protocol	*Data-centric*	*Hierarchical*	*Location-based*	*QoS*	*Network-flow*	*Data aggregation*
SPIN	✓					✓
Directed Diffusion	✓					✓
Rumor Routing	✓					✓
Shah et al.	✓		✓			
GBR	✓					✓
CADR	✓					
COUGAR	✓					✓
ACQUIRE	✓					
Fe et al.					✓	
LEACH		✓				✓
TEEN&APTEEN	✓	✓				✓
PEGASIS		✓				✓
Younis et al.		✓	✓			
Subramanian et al.		✓				✓
MECN&SMECN			✓			
GAF		✓	✓			
GEAR			✓			
Chang et al.		✓			✓	
Kalpakis et al.			✓		✓	
Akkaya et al.		✓		✓		
SAR				✓		
SPEED			✓	✓		

Roadmap

- Motivation for a Network of Wireless Sensor Nodes
- Applications
- Routing Protocols for Wireless Sensor Networks
- Medium Access Control Layer
  - Characteristics of MAC Protocols in Sensor Networks
  - Various types of MAC Protocols

Characteristics of MAC Protocols in WSNs

- Most MAC protocols are built for fairness
  - everybody should get an equal amount of resources
  - no one should receive special treatment
- In a WSN, all nodes cooperate to achieve a common purpose, therefore fairness is less of a concern
- Instead, wireless nodes are mostly concerned with energy consumption
- Sensing applications may value low latency or high reliability over fairness

Energy Efficiency

- Sensor nodes must operate using finite energy sources, therefore MAC protocols must consider energy efficiency
- Common technique: dynamic power management (DPM)
  - a resource can be moved between different operational modes such as active, idle, and asleep
  - for resources such as the network, the active mode can group together multiple different modes of activity, e.g., transmitting and receiving
- Periodic traffic models are very common in WSNs
  - significant energy savings can be obtained by putting a device into a low-power sleep mode
  - fraction of time a sensor nodes spends in active mode is called the duty cycle
    - often very small due to the infrequent and brief data transmissions occurring in most sensor networks

Energy Efficiency

	RFM TR1000	RFM TR3000	MC13202	CC1000	CC2420
Data rate (kbps)	115.2	115.2	250	76.8	250
Transmit current	12mA	7.5mA	35mA	16.5mA	17.4mA
Receive current	3.8mA	3.8mA	42mA	9.6mA	18.8mA
Idle current	3.8mA	3.8mA	800μA	9.6mA	18.8mA
Standby current	0.7μA	0.7μA	102μA	96μA	426μA

Characteristics of typical radios used by state-of-the-art sensor nodes

Energy Efficiency

- Reasons for energy inefficiency
  - idle listening
  - inefficient protocol designs (e.g., large packet headers)
  - reliability features (collisions requiring retransmissions or other error control mechanisms)
  - control messages to address the hidden-terminal problem
  - choice of modulation scheme
  - choice of transmission rate
  - Over-emitting

Energy-Efficient MAC

- Expected life time of many WSN applications: Months or years
- Actual lifetime
  - AA batteries: Max. 2000 mAh
  - CC2420 radio: 18.8mA when idle but awake (RX mode)
  - 2000mAh / 18.8mA = 106.4 hours = 4.4 days

→Keep radio asleep most of the time

→Ideal duty cycle: 0.1% - 1%

Types of WSN MAC

- Scheduled contention: Nodes periodically wake up together, contend for channel, then go back to sleep
  - S-MAC, T-MAC
- Channel polling: Nodes independently wake up to sample channel
  - B-MAC, X-MAC
- TDMA (Time Division Multiple Access): Nodes maintain a schedule that dictates when to wake up and when they are allowed to transmit
  - DRAND
- Hybrid: SCP, Z-MAC, 802.15.4 (contention access period + contention free period)

S-MAC (Sensor MAC)

- A node sleeps most of the time
- Periodically wake up for short intervals to see if any node is transmitting a packet
- Low energy consumption if traffic is light
- Accept latency to extend lifetime

Combine benefits of TDMA + contention protocols

- Mainly handle the idle listening issue (dominant in sensor network)
- Long idle time when no sensing event happens

SMAC Design

- Tradeoff

Latency ↓ ⟶ Energy ↑
Fairness

- Major components in S-MAC
  - Periodic listen and sleep: avoid idle listening
  - Collision avoidance: by using RTS and CTS
  - Overhearing avoidance: by switching the radio off when transmission is not meant for that node
  - Message passing: reduce control overhead

Periodic Listen and Sleep

- Problem
  - Idle listening consumes significant energy
- Solution
  - Periodic listen and sleep

  - Turn off radio when sleeping
  - Reduce duty cycle to ~10%

Periodic Listen and Sleep

- Choosing schedule
  - The node randomly choose 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 select its own schedule, it adopts both schedules

  - Selection of sleep and listen duration is based on the application scenarios
  - Neighboring nodes are synchronized together

Contd….

- Nodes exchange schedules by broadcast
- Multiple neighbors contend for the medium
- Once transmission starts, it does not stop until completed

Choosing and Maintaining Schedules

- Each node maintains a schedule table
- Initial schedule is established
  - Synchronizer
  - Follower

- Rules for joining a new node

Maintaining Synchronization

- Needed to prevent clock drift
- Periodic updating using a SYNC packet

Sender Node ID	**Next-Sleep Time**

SYNC Packet

- Receivers adjust their timer counters
- Listen interval divided into two parts

  Each part further divided into time slots

Timing Relationship

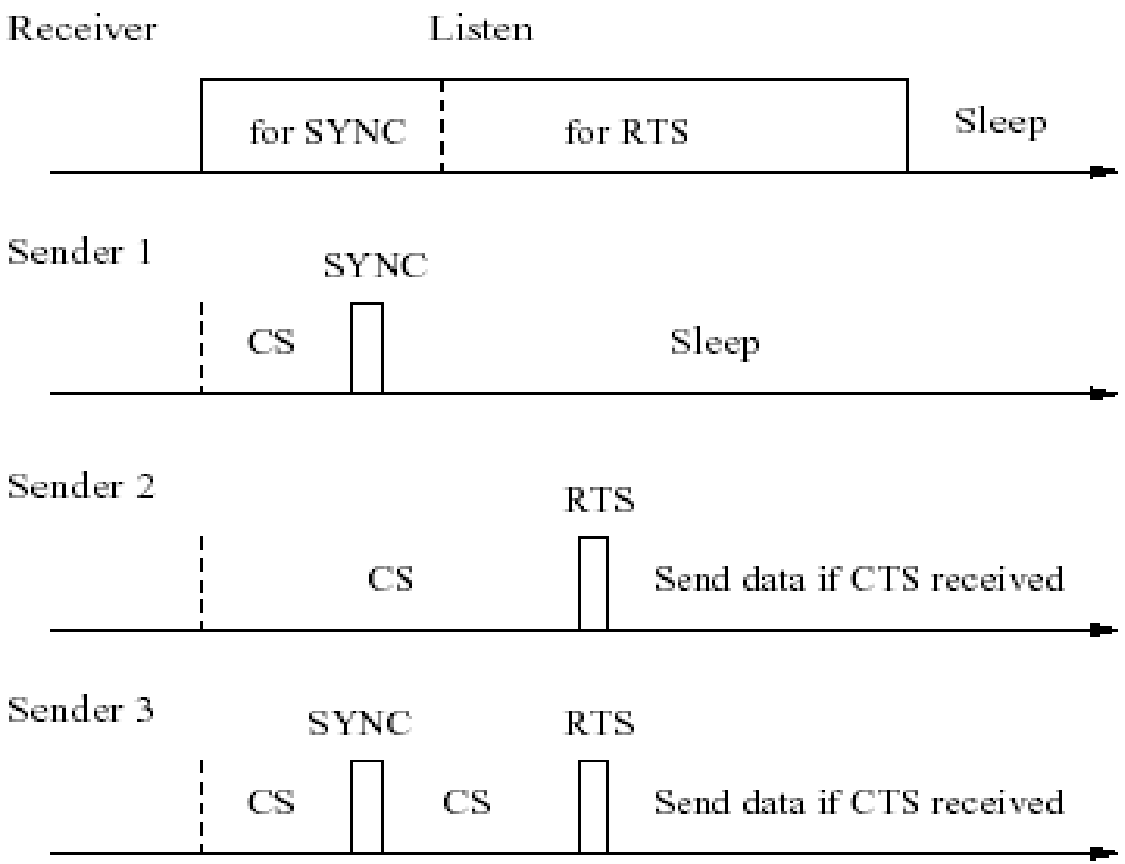
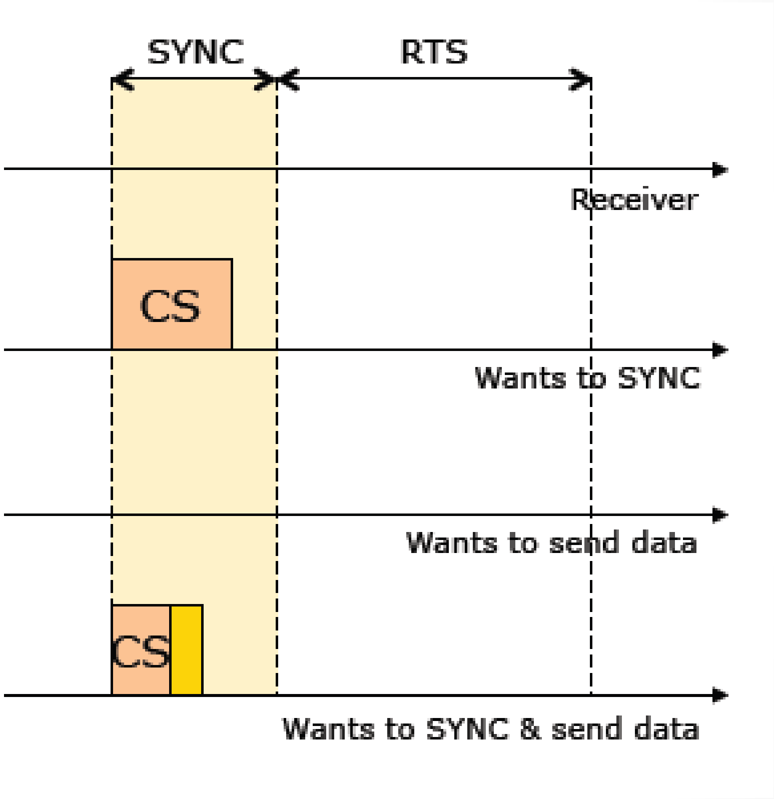


Fig. 3. Timing relationship between a receiver and different senders. CS stands for carrier sense.

SMAC

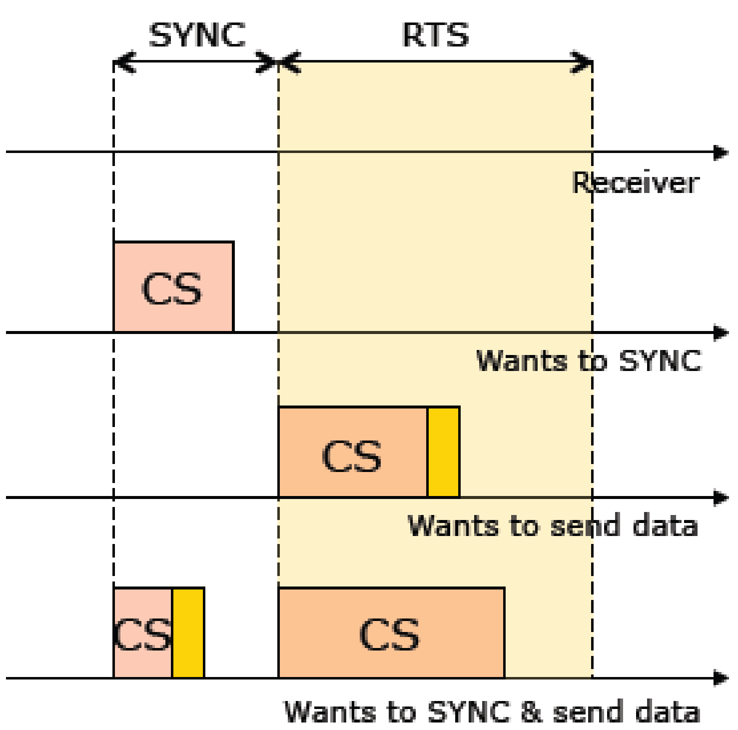
- Awake time consists of two parts: SYNC and RTS
- A node periodically send SYNC packet to synchronize clocks
- CSMA/CA for channel contention



CS: Carrier Sense

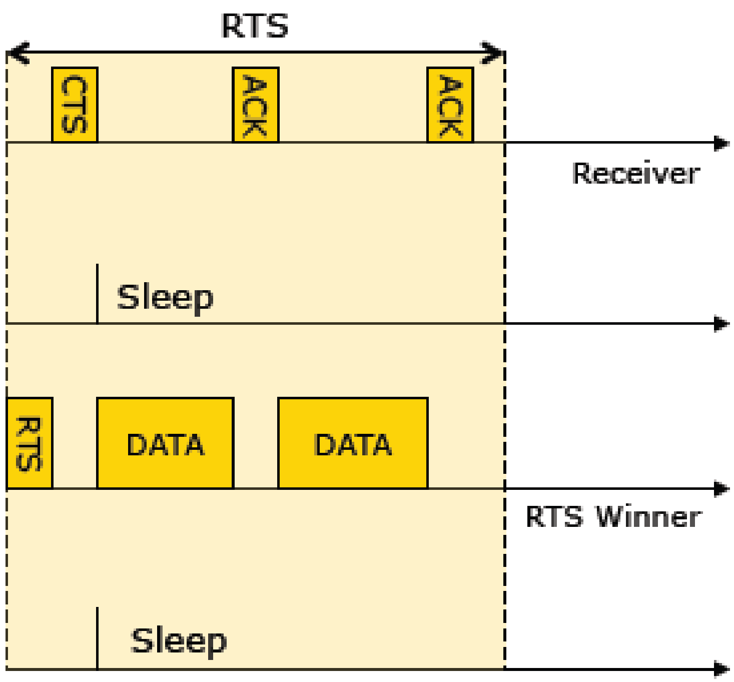
S-MAC

- RTS is section used to transmit data
- CSMA/CA followed by RTS/CTS



S-MAC

- CTS for somebody else → Sleep
- Sender does one RTS/CTS and then sends data for the rest of the frame
  - Prefer application performance to node level fairness
- ACK every data packet
  - Packet fragmentation for higher reliability



Collision Avoidance

- Similar to IEEE 802.11 using RTS/CTS mechanism
- Perform virtual and physical carrier sense before transmission
- RTS/CTS addresses the hidden terminal problem
- NAV –indicates how long the remaining transmission will be.

Overhearing Avoidance

- Interfering nodes go to sleep after they hear the RTS or CTS packet
- The medium is busy when the NAV value is not zero
- All immediate neighbors of sender and receiver should go to sleep

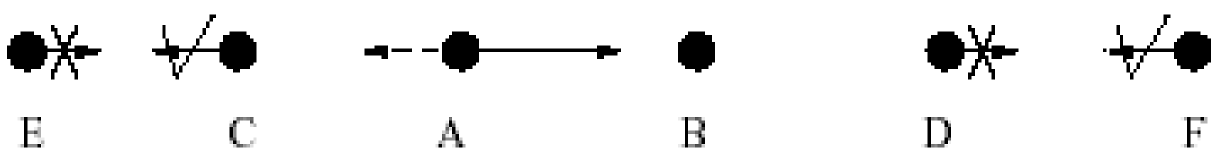


Fig. 4. Who should sleep when node A is transmitting to B?

S-MAC (Sensor-Networks)

- 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)

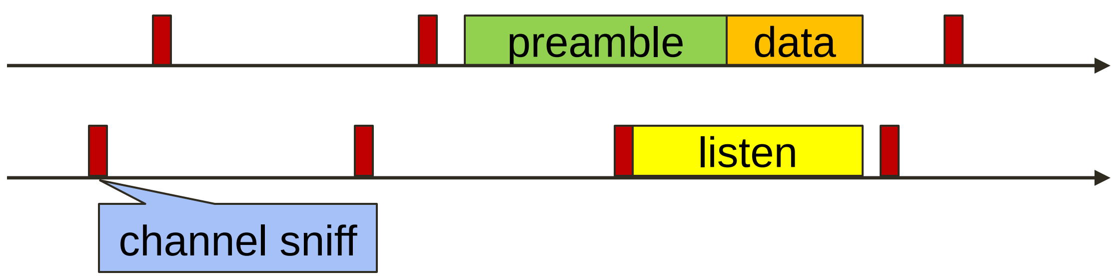
Pros and Cons of S-MAC

- More power conserving than standard CSMA/CA
- During the listening interval, everyone needs to stay awake unless someone transmits
  - Waste energy when network traffic is light
- Time sync overhead
- RTS/CTS/ACK overhead
- Complex to implement

Low Power Listening (B-MAC)

- Nodes wake up for a short period and check for channel activity
  - Return to sleep if no activity detected

- If a sender wants to transmit a message, it sends a long preamble to make sure that the receiver is listening for the packet
  - preamble has the size of a sleep interval



- Very robust
  - No synchronization required
  - Instant recovery after channel disruption

Pros and Cons of B-MAC

- No need for everybody to stay awake when there is no traffic
  - Just wake up for preamble sampling and go back to sleep
- Better power conservation, latency and throughput than S-MAC
- Simpler to implement

- Low duty cycle → longer preamble
  - Little cost to receiver yet higher cost to sender
  - Longer delay
  - More contention

X-MAC

- A Short Preamble MAC Protocol for Duty-Cycled Wireless Sensor Networks
- Builds on the foundations of asynchronous duty cycled MAC protocols

Q. Why is it needed?

A. Low power listening (LPL) long preamble protocols suffer from:

- Overhearing
- Excessive preamble => increased per hop latency
- Incompatibility with packetizing radios

X-MAC's proposal:

- Stream of short preambles with target ID
- Strobed preamble (short preamble + short wait time)

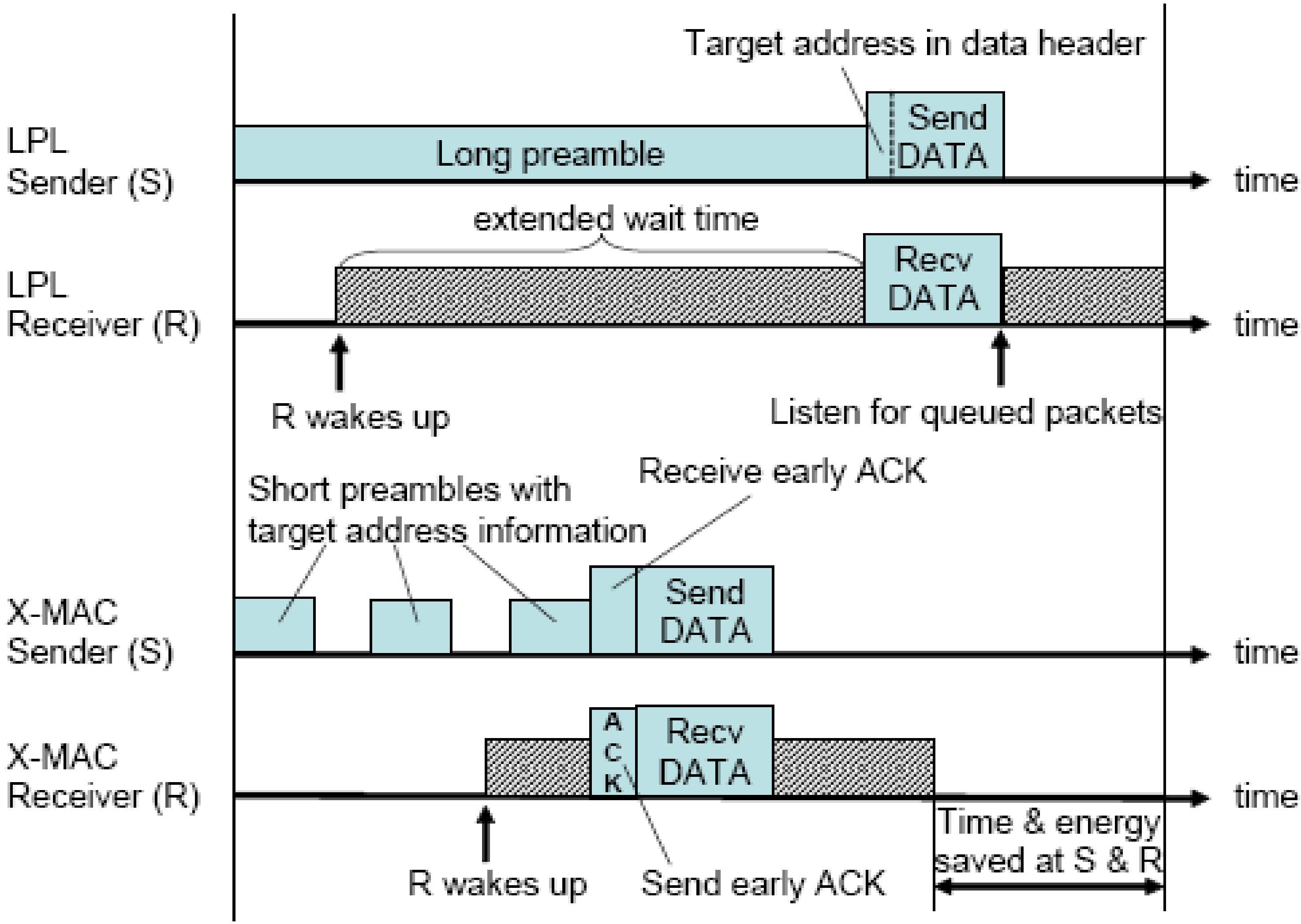


Figure 1. Comparison of the timelines between LPL's extended preamble and X-MAC's short preamble approach.

Overhearing Problem

LPL protocols:

- Non-target receivers remain awake till the end of the extended preamble
- High density of senders => almost the entire WSN may be awake

X-MAC:

- Non-target receivers go to sleep if target ID does not match
- Energy expenditure not affected much by the density of senders

Excessive Preamble Problem

LPL protocols:

- Long preambles waste sender's energy
- Receiver wakes up half-way but sender does not come to know
- Sender sends data packet after the long preamble
- Subsequent transmitters to the same receiver waste energy sending the preamble to an awake receiver

X-MAC:

- Strobed preambles help conserve energy
- Receiver sends early ACK in the gap between preambles
- Sender sends data packet as soon as it gets the ACK
- Subsequent transmitters hear the ACK; send data without preamble after a random back-off

Adaptation to Traffic Load

- Variable traffic loads

  => pre-determined sleep and awake schedules will be sub-optimal
- Some topologies may have nodes with differing traffic loads, e.g. tree topology
- Need to approximate sender and receiver sleep times depending on traffic loads

Duty Cycle Under No Contention

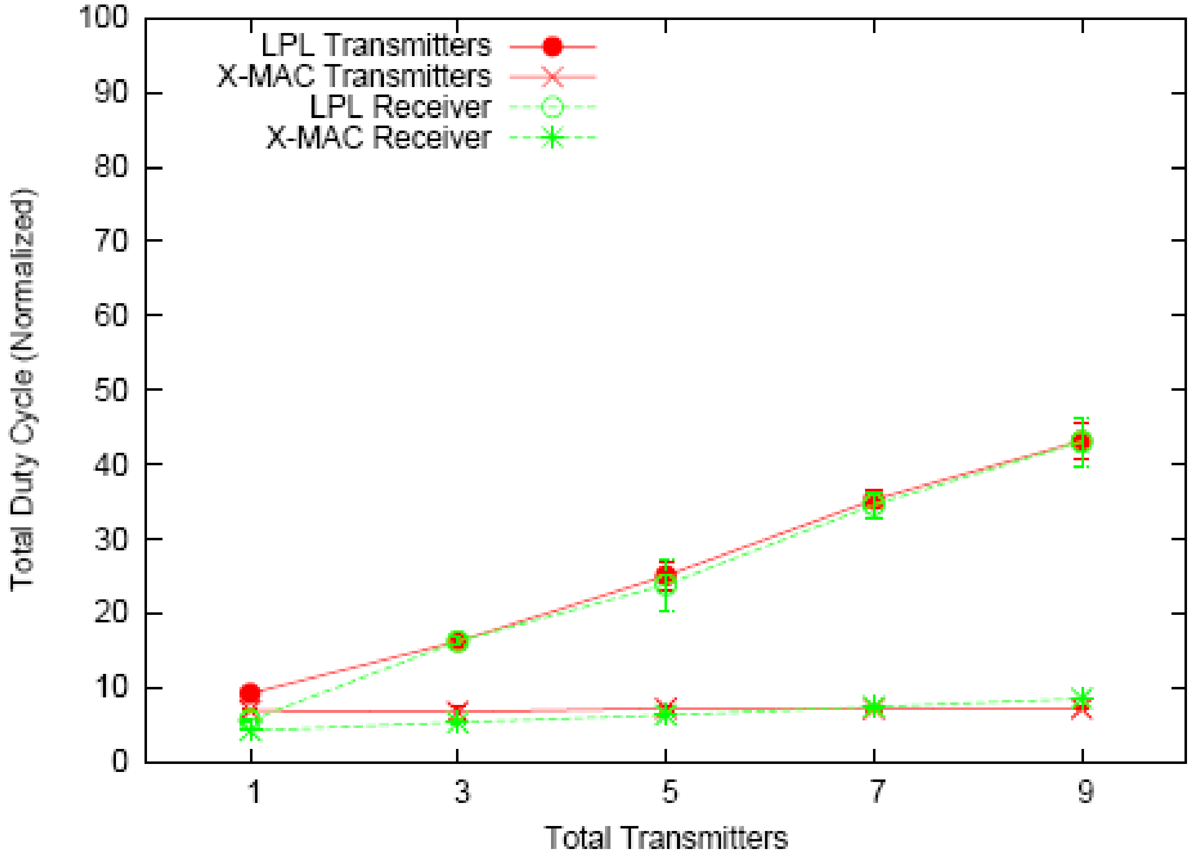


Figure 7. Duty cycles of non-contending senders and receiver and as a function of network density.

Duty Cycle Under Contention

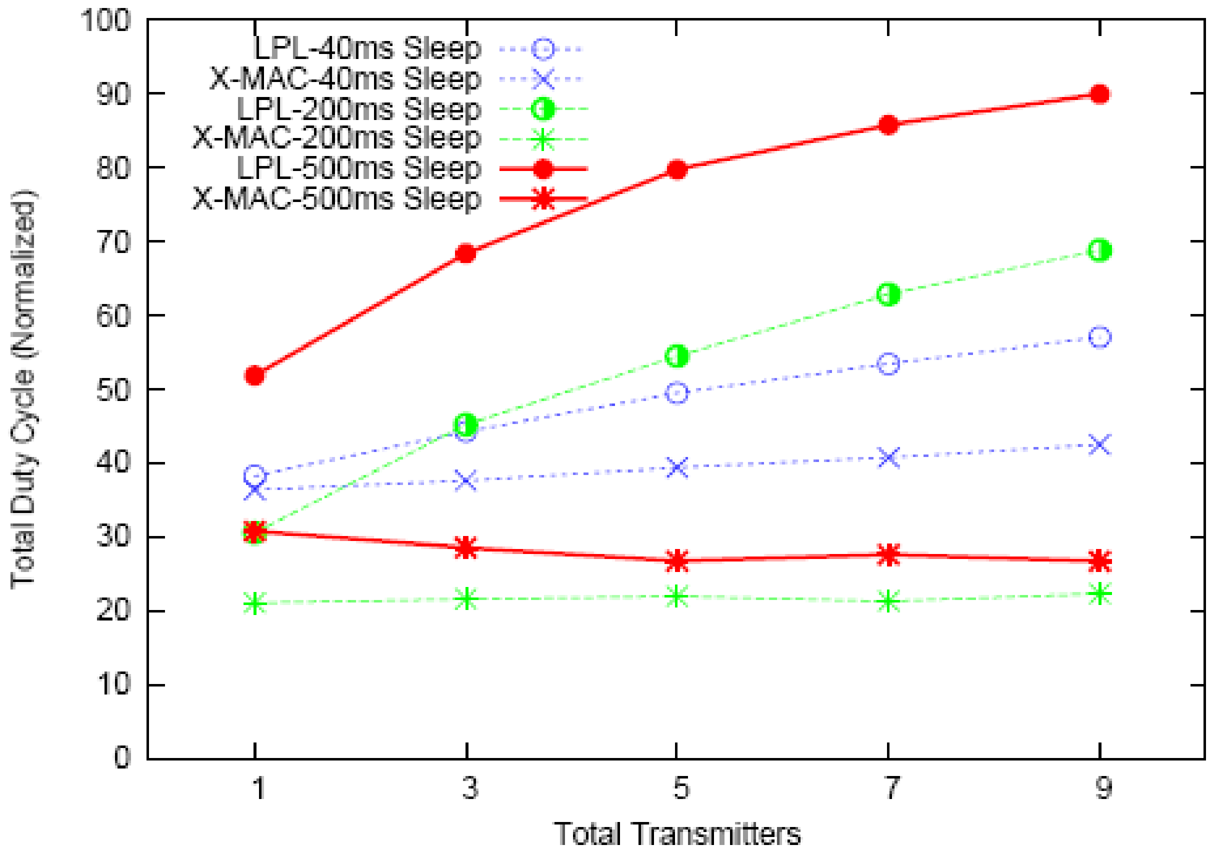


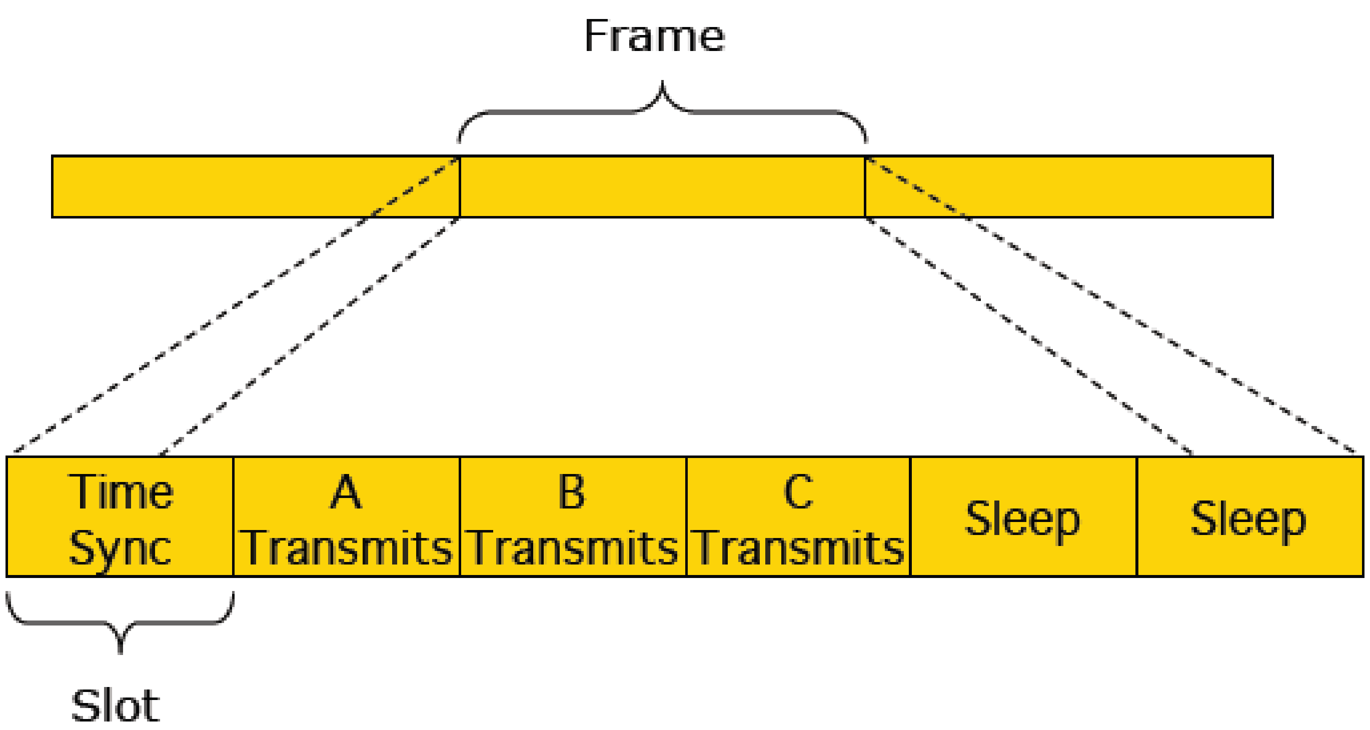
Figure 9. Duty cycle of contending senders, 1 packet per second.

Thoughts on X-MAC

- Better than B-MAC in terms of latency, throughput and power consumption
- Energy consumption due to overhearing reduced
- Simple to implement

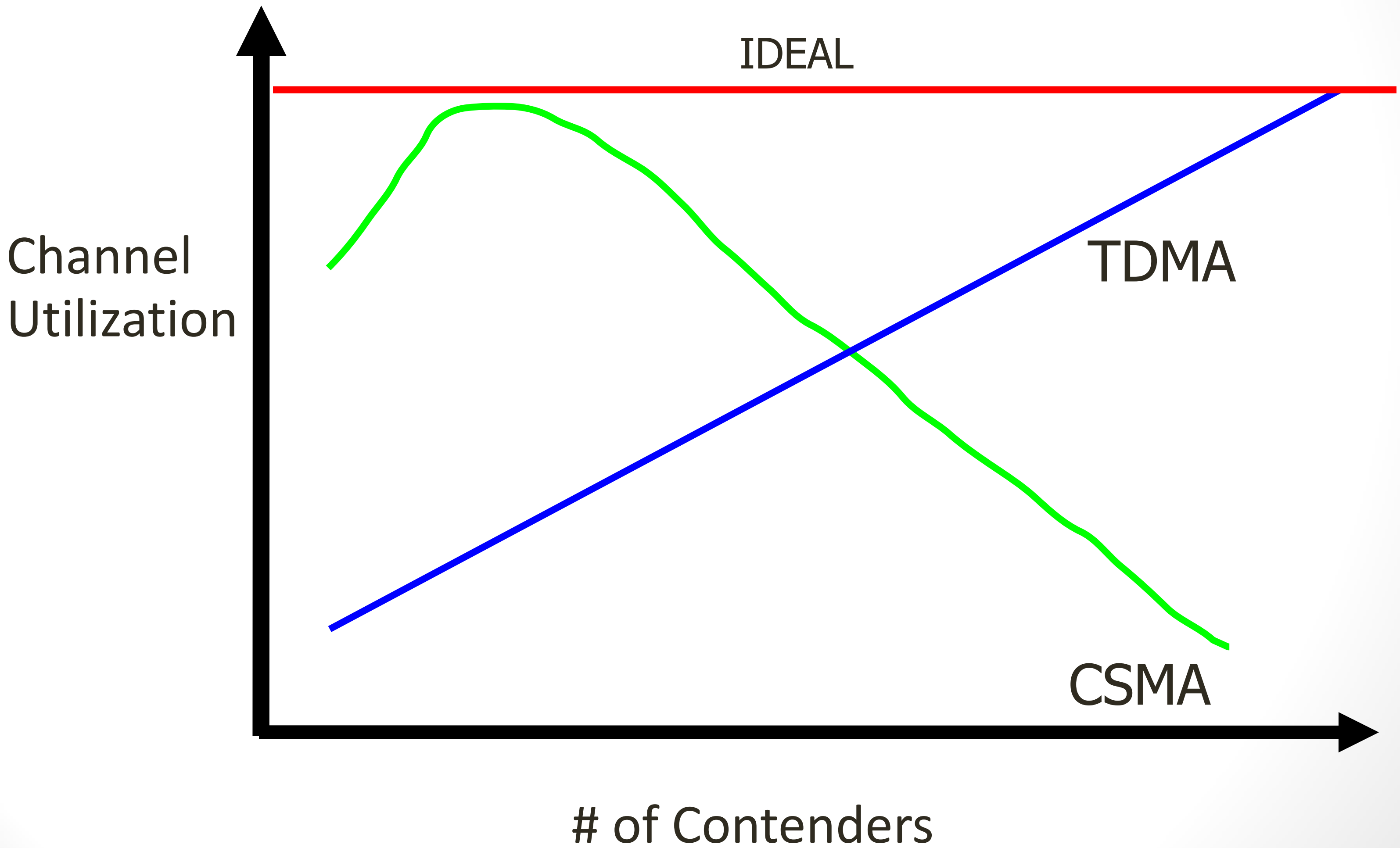
- On average the preamble size is reduced by half compared to B-MAC → Still considerable overhead

TDMA



- Predictable delay, throughput and duty cycle
- Little packet losses due to contention
- Scheduling and time sync are difficult
- Slots are wasted when a node has nothing to send

Effective Throughput
CSMA vs. TDMA



Z-MAC: Basic Objective

Can you do hybrid contention resolution?

MAC	Channel Utilization	
	Low Contention	High Contention
CSMA	High	Low
TDMA	Low	High

Z-MAC

- Combine best of both
- Eliminate worst of both

ZMAC - Basic Idea

- Each node owns a time slot
  - A node may transmit at any time slot
  - However, the owner has the higher priority to transmit data than the non-owners (contention window size)
  - When a slot is not in use by its owner, non-owners can steal the slot

- Z-MAC behaves like CSMA under low contention and like TDMA under high contention
- Basic idea: uses CSMA as the baseline MAC scheme, but uses a TDMA schedule as a hint to enhance contention resolution

Zebra MAC (Z-MAC)

- When a node starts up, it enters a setup phase to allow it
  - to discover its neighbors
  - to obtain its slot in the TDMA frame
  - Rather long setup phase for neighbor discovery, slot assignment, local frame exchange, and global time sync
- Every node periodically broadcasts a message containing a list of its neighbors
  - Through this process, a node learns about its 1-hop and 2-hop neighbors
  - This information is used as input to a distributed slot assignment protocol (provides each node with time slots)
  - Ensures a schedule where no two nodes within an 2-hop neighborhood will be assigned the same slot

Zebra MAC (Z-MAC)

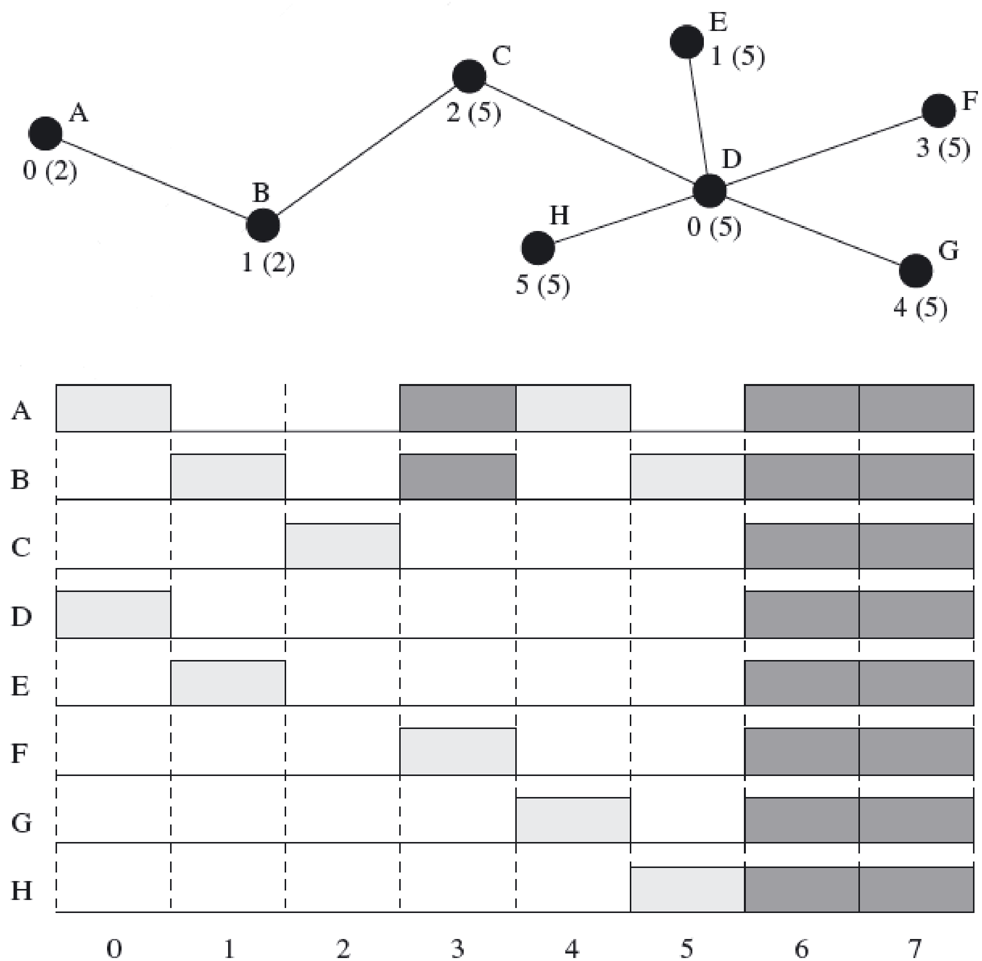
- Z-MAC allows nodes to select the periodicity of their assigned slots where different nodes can have different periods (time frames or TF)
- The advantage of this approach is that it is not necessary to propagate a maximum slot number (MSN) to the entire network
- The protocol can adapt slot allocations locally
  - assume that node *i* is assigned slot s_i
  - and F_i represents the MSN within the node's 2-hop neighborhood
  - then: *i*'s TF is set to be 2^a
    - a is a positive integer that satisfies $2^{a-1} \leq F_i < 2^{a-1}$
  - node *i* then uses the s_ith slot in every 2^a time frame

E.g., 5 neighbors, you choose a = 3, and your slots are 1,9,17, …

Zebra MAC (Z-MAC)

- Example with eight nodes
  - Number indicates the assigned slot for each node
  - Number in parenthesis is F_i
  - Bottom part of the figure shows the corresponding schedule for all nodes
    - light-shaded slots are the ones used for transmissions
    - dark-shaded slots are the empty slots that are not used by any 1-hop or 2-hop neighbors
  - If a global time frame is used, the chosen time frame size will be 6
    - nodes A and B will be allowed to use their slots only once every 6 slots even though their frame sizes are 2 each

Zebra MAC (Z-MAC)



Zebra MAC (Z-MAC)

- In Z-MAC, these nodes can use frame size 4
  - increases the concurrency in the channel usage
  - reduces message delays
- The resulting schedule shows that some slots are not assigned to any node
  - specifically slots 6 and 7
- In a global time frame, a frame size could have been chosen that reduces the number of empty slots
- However, Z-MAC allows nodes to compete for these “extra” slots using CSMA

Zebra MAC (Z-MAC)

- After the schedule has been determined, every node forwards its frame size and slot number to its 1-hop and 2-hop neighbors
- Even though slots are owned by nodes, Z-MAC uses CSMA to determine who may transmit
- However, slot owners are given preference
  - by using a random back-off value chosen from the range $[0, T_o]$
  - whereas other nodes choose their back-off values from the range $[T_o, T_{no}]$

Zebra MAC (Z-MAC)

- Z-MAC also uses explicit contention notification (ECN) to which it has a message
  - Where each node decides to whether to send an ECN message to a neighbor based on its local estimate of the contention level (e.g., determined using the packet loss rate or channel noise level)
  - This neighbor then broadcasts the ECN to its own neighbors, which then enter a high contention level (HCL) mode
  - A node in the HCL mode only transmits data in its own slots or slots belonging to its 1-hop neighbors
    - thereby reducing the contention between 2-hop neighbors
  - It returns to a *low contention level* (LCL) mode if it has not received any ECN messages for a certain amount of time

Zebra MAC (Z-MAC)

- Summary
  - Z-MAC adopts characteristics found in both TDMA and CSMA protocols
  - allowing it to quickly adapt to changing traffic conditions
  - under light traffic loads Z-MAC behaves more like CSMA
  - under heavy traffic loads contention for slots is reduced
  - Z-MAC requires an explicit setup phase (consumes both time and energy)
  - while ECN messages be used to reduce the contention locally
    - these messages add more traffic to an already busy network and take time to propagate
    - thereby causing delays in the adaptation to a more TDMA-like behavior

Summary

- The choice of a medium access protocol has a substantial impact on the performance and energy-efficiency of a WSN
- MAC protocols should also be designed to accommodate changes in network topology and traffic characteristics
- Latency, throughput, and fairness among competing nodes determined or affected by the characteristics of the MAC layer