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

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

UC Berkeley: COTS 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
Mica2 Wireless Sensors

New MicaZ follows IEEE 802.15.4 Zigbee standard with direct sequence spread spectrum radio and 256kbps data rate.

MTS310 Sensor Boards
- Acceleration,
- Magnetic,
- Light,
- Temperature,
- Acoustic,
- Sounder

Adapted from Crossbow web site
Overall Architecture of a Sensor Node

Application Layer
Network Layer
MAC Layer
Physical Layer
Communication SubSystem
Wireless Channel
Slow Serial Link
Sensor Node CPU
Radio Board
Forward Packet Path
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) or a sink node, which propagates the information to remote devices for storage, analysis, and processing.
Common Network Architecture

- Sensor nodes are responsible for:
  - Detection of events
  - Observation of environments
  - Relaying of third party messages

- Information is generally gathered at sinks:
  - Sinks are responsible for higher level processing and decision making
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)
- UC-Berkeley
  - Smart Dust project (1999)
  - Concept of “motes”: extremely small sensor nodes
- Berkeley Wireless Research Center (BWRC)
  - PicoRadio project (2000)
- MIT
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

\[
E_{CPU} = E_{\text{switch}} + E_{\text{leakage}} = C_{\text{total}} \times V_{dd}^2 + V_{dd} \times I_{\text{leak}} \times \Delta t
\]
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
# Comparison of Energy Sources

<table>
<thead>
<tr>
<th></th>
<th>Power (Energy) Density</th>
<th>Source of Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batteries (Zinc-Air)</td>
<td>1050 - 1560 mWh/cm$^3$ (1.4 V)</td>
<td>Published data from manufacturers</td>
</tr>
<tr>
<td>Batteries (Lithium ion)</td>
<td>300 mWh/cm$^3$ (3 - 4 V)</td>
<td>Published data from manufacturers</td>
</tr>
<tr>
<td>Solar (Outdoors)</td>
<td>15 mW/cm$^2$ - direct sun</td>
<td>Published data and testing.</td>
</tr>
<tr>
<td></td>
<td>0.15 mW/cm$^2$ - cloudy day.</td>
<td></td>
</tr>
<tr>
<td>Solar (Indoor)</td>
<td>.006 mW/cm$^2$ - my desk</td>
<td>Testing</td>
</tr>
<tr>
<td></td>
<td>0.57 mW/cm$^2$ - 12 in. under a 60W bulb</td>
<td></td>
</tr>
<tr>
<td>Vibrations</td>
<td>0.001 - 0.1 mW/cm$^3$</td>
<td>Simulations and Testing</td>
</tr>
<tr>
<td>Acoustic Noise</td>
<td>3E-6 mW/cm$^2$ at 75 Db sound level</td>
<td>Direct Calculations from Acoustic Theory</td>
</tr>
<tr>
<td></td>
<td>9.6E-4 mW/cm$^2$ at 100 Db sound level</td>
<td></td>
</tr>
<tr>
<td>Passive Human Powered</td>
<td>1.8 mW (Shoe inserts &gt;&gt; 1 cm$^2$)</td>
<td>Published Study.</td>
</tr>
<tr>
<td>Thermal Conversion</td>
<td>0.0018 mW - 10 deg. C gradient</td>
<td>Published Study.</td>
</tr>
<tr>
<td>Nuclear Reaction</td>
<td>80 mW/cm$^3$</td>
<td>Published Data.</td>
</tr>
<tr>
<td></td>
<td>1E6 mWh/cm$^3$</td>
<td></td>
</tr>
<tr>
<td>Fuel Cells</td>
<td>300 - 500 mW/cm$^3$</td>
<td>Published Data.</td>
</tr>
<tr>
<td></td>
<td>~4000 mWh/cm$^3$</td>
<td></td>
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</tbody>
</table>

With aggressive energy management, ENS might live off the environment.

Source: UC Berkeley
Energy Management Issues

• Actuation energy is the highest
  • Strategy: ultra-low-power “sentinel” nodes
    • Wake-up or command movement of mobile nodes
• Communication energy is the next important issue
  • Strategy: energy-aware data communication
    • Adapt the instantaneous performance to meet the timing and error rate constraints, while minimizing energy/bit
• Processor and sensor energy usually less important
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

<table>
<thead>
<tr>
<th>Traditional Networks</th>
<th>Wireless Sensor Networks</th>
</tr>
</thead>
<tbody>
<tr>
<td>General-purpose design; serving many applications</td>
<td>Single-purpose design; serving one specific application</td>
</tr>
<tr>
<td>Typical primary design concerns are network performance and latencies; energy is not a primary concern</td>
<td>Energy is the main constraint in the design of all node and network components</td>
</tr>
<tr>
<td>Networks are designed and engineered according to plans</td>
<td>Deployment, network structure, and resource use are often ad-hoc (without planning)</td>
</tr>
<tr>
<td>Devices and networks operate in controlled and mild environments</td>
<td>Sensor networks often operate in environments with harsh conditions</td>
</tr>
<tr>
<td>Maintenance and repair are common and networks are typically easy to access</td>
<td>Physical access to sensor nodes is often difficult or even impossible</td>
</tr>
<tr>
<td>Component failure is addressed through maintenance and repair</td>
<td>Component failure is expected and addressed in the design of the network</td>
</tr>
<tr>
<td>Obtaining global network knowledge is typically feasible and centralized management is possible</td>
<td>Most decisions are made localized without the support of a central manager</td>
</tr>
</tbody>
</table>
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 $\rightarrow$ everyday
    - Labor-intensive, tedious, inconsistent, and subjective
  - Basic inspections $\rightarrow$ at least once a year
  - Detailed inspection $\rightarrow$ at least every five years on selected bridges
  - Special inspections $\rightarrow$ according to technical needs
    - The rest require sophisticated tools $\rightarrow$ 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

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

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

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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)

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
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
Roadmap

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  ▪ 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
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 $10 \times 10$ 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 \textit{full duplex system}, allowing communication in a reverse direction - the sensor array can be used for \textit{reception} and \textit{transmission} in a feedback loop
  - in addition to the transformation of electrical signals into optical signals
  - \textit{neurological signals} from the ganglia can be \textit{picked up} by the micro-sensors and \textit{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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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
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

- 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
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
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.

- 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

- 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% O₂; little CO₂; no CH₄)
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
- Coverage and Connectivity Issues in Sensor Networks
  - Coverage
  - Connectivity
A Sensor Node

Memory (Application)

Processor

Sensor
Actuator
Network Interface

Transmission range

Sensing range
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 & $R_t > 2R_s$
  Region is covered $\rightarrow$ sensors are connected
Problem Space

- coverage
  - barrier coverage
  - blanket coverage
- connectivity
  - probabilistic
    - per-node
  - algorithmic
    - homo
    - heterogeneous
    - k-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

1-connected
2-connected
3-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? $P(\text{network connected}) \to 1$, as $N \to \infty$
An Alternative View

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

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

  - 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)
$\Theta(\log n)$ Neighbors Needed for Connectivity

- $N$: number of nodes (or area). $K$: number of neighbors.

- Xue & Kumar (2002):
  - If $K < 0.074 \log N$, almost sure disconnected
  - If $K > 5.1774 \log N$, almost sure connected

- 2004, improved to $0.3043 \log N$ and $0.5139 \log N$
Applying Result to Power Control
(Bettstetter, MobiHoc’02)

• Nodes deployed randomly
• Given: number of nodes n, node density $\lambda$, transmission range $R$
• $P = \text{Probability}\left(\text{every node has at least k neighbors}\right)$ can be calculated

• Adjust $R$ so that $P \approx 1$
• With this transmission range, network is k-connected with high probability
Application 1

- N = 500 nodes
- A = 1000m x 1000m
- 3-connected required
- R = ?

- With R = 100 m, G has degree 3 with probability 0.99
- Thus, G is 3-connected with high probability
Application 2: How Many Sensors to Deploy?

- $A = 1000\text{m} \times 1000\text{m}$
- $R = 50\text{ m}$
- 3-connected required
- $N = ?$

Choose $N$ such that $P(\ G \text{ has degree 3} )$ is sufficiently high.
Problem Space

coverage

connectivity

probabilistic

algorithmic

per-node

homo

homo

heterogeneous

barrier coverage

blanket coverage

k-connected
Algorithmic Approach
• Gmax: network with maximum transmission range
• Gmax: assumed to be connected
• Construct a connected subgraph of Gmax
  • With certain desired properties
  • Distributed & localized algorithms
• Use the subgraph for routing
• Adjust power to reach just the desired neighbor
• What subgraphs?
What Subgraphs?

- \( G_{\text{max}}(V) \): Network with max trans range
- \( \text{RNG}(V) \): Relative neighborhood graph
- \( \text{GG}(V) \): Gabriel graph
- \( \text{YG}(V) \): Yao graph
- \( \text{DG}(V) \): Delaunay graph
- \( \text{LMST}(V) \): Local minimum spanning tree graph
Desired Properties of Proximity Graphs

- $PG \cap G_{\text{max}}$ is connected (if $G_{\text{max}}$ is)
- $PG$ is sparse, having $\Theta(n)$ edges
- Bounded degree
  - Degree $\text{RNG, GG, YG} \leq n - 1$ (not bounded)
  - Degree of LMST $\leq 6$
- Small stretch factor
- Others
Coverage Issues
Simple Coverage Problem

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

Wake-up rate?

Sleep → Wake up → Go to Work?

- Yes → Work
- No → Sleep
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
- \( \lambda = \) average # of wake-ups per unit time
Wake-Up Rates

\[ f(t) = \lambda \exp(-\lambda t) \]

\[ f(t) = \lambda' \exp(-\lambda't) \]

\[ A + B: \quad f(t) = (\lambda + \lambda') \exp(- (\lambda + \lambda') t) \]
Adjust Wake-Up Rates

- Working node knows
  - Desired total wake-up rate $\lambda_d$
  - Measured total wake-up rate $\lambda_m$
- When a node wakes up, adjusts its $\lambda$ by
  \[ \lambda := \lambda \left( \frac{\lambda_d}{\lambda_m} \right) \]
Go to Work or Return to Sleep?

- Depends on whether there is a working node nearby

Go back to sleep

$R_p$

Go to work
Is the Resulting Network Covered or Connected?

- If $R_t \geq (1 + \sqrt{5}) R_p$ and ... then $P(\text{connected}) \rightarrow 1$

- Simulation results show good coverage
OGDC: Optimal Geographical Density Control

• “Maintaining Sensing Coverage and Connectivity in Large sensor networks”
  • Honghai Zhang and Jennifer Hou
  • MobiCom’03
Basic Idea of OGDC

- Minimize the number of working nodes
- Minimize the total amount of overlap
Minimum Overlap

Optimal distance = $\sqrt{3} \ R$
Minimum Overlap
Near-Optimal
OGDC: the Protocol

- Time is divided into rounds
- In each round, each node runs this protocol to decide whether to be active or not

1. Select a starting node. Turn it on and broadcast a power-on message
2. Select a node closest to the optimal position. Turn it on and broadcast a power-on message. Repeat this
Selecting Starting Nodes

- Each node volunteers with a probability $p$.
- Backs off for a random amount of time.
- If hears nothing during the back-off time, then sends a message carrying
  - Sender’s position
  - Desired direction
Select the Next Working Node

- On receiving a message from a starting node
- Each node computes its deviation D from the optimal position.
- Sets a back-off timer proportional to D.
- When timer expires, sends a power-on message.

- On receiving a power-on message from a non-starting node
\[ T_{c1} = \begin{cases} 
  t_0(c((\sqrt{3}r_s - d)^2 + (d\Delta\alpha)^2) + u), & \text{if } d \leq \sqrt{3}r_s; \\
  t_0(c((\sqrt{3}r_s - d)^2 + (d\Delta\alpha)^2 + \ell) + u), & \text{otherwise}, \end{cases} \]
Coverage Issues

K-covered?

density control

PEAS  OGDC

How many sensors are needed?
How Many Sensors to Deploy?

- A similar question for k-connectivity

- Depends on:
  - Deployment method
  - Sensing range
  - Desired properties
  - Sensor failure rate
  - Others
Unreliable Sensor Grid: Coverage and Connectivity, INFOCOM 2003

- Active
- Dead
- $p$: probability (active)
- $r$: sensing range
- Necessary and sufficient condition for area to be covered?

$N$ nodes
## Conditions for Asymptotic Coverage

<table>
<thead>
<tr>
<th>Necessary:</th>
<th>[ \lim_{n \to \infty} \frac{np \cdot \pi r^2}{\log n} \geq 1 ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sufficient:</td>
<td>[ \lim_{n \to \infty} \frac{np \cdot \pi r^2}{\log n} &gt; 4 ]</td>
</tr>
</tbody>
</table>

\[ np \cdot \pi r^2 = \text{expected # of active sensors in a sensing disk.} \]

N nodes
On k-Coverage in a Mostly Sleeping Sensor Network, Mobicom’04

<table>
<thead>
<tr>
<th>Condition</th>
<th>Equation</th>
</tr>
</thead>
</table>
| Almost sure k-covered:                        | \[
\lim_{n \to \infty} \frac{np \cdot \pi r^2}{\log np} > 1
\]                                                                   |
| Almost sure not k-covered:                    | \[
\lim_{n \to \infty} \frac{np \cdot \pi r^2}{\log np} < 1
\]                                                                   |
| Covered or not covered depending on how it approaches 1 | \[
\lim_{n \to \infty} \frac{np \cdot \pi r^2}{\log np} = 1
\]                                                                   |
Critical Value

- $M$: average # of active sensors in each sensing disk.
- $M > \log(np)$: almost sure covered.
- $M < \log(np)$: almost sure not covered.

Infocom’03: $\log n$  $4 \log n$

N nodes
Poisson or Uniform Distribution

- Similar critical conditions hold.
Application of Critical Condition

- P: probability of being active
- R: sensing range
- N: number of sensors?

Theorem. Let $n$ sensors be deployed uniformly over a unit square region. If

$$\frac{np\pi r^2}{\log np} \geq 1 + \frac{\sqrt{\log \log(np) + k \log \log(np)}}{\log(np)}$$

for sufficiently large $n$, then the unit square region is almost always $k$-covered.
Problem Space
Blanket vs. Barrier Coverage

• Blanket coverage
  • Every point in the area is covered (or k-covered)

• Barrier coverage
  • Every crossing path is k-covered
Recent Results

• Algorithms to determine if a region is $k$-barrier covered.

• How many sensors are needed to provide $k$-barrier coverage with high probability?
Is a Belt Region K-Barrier Covered?

- Construct a graph $G(V, E)$
  - $V$: sensor nodes, plus two dummy nodes $L, R$
  - $E$: edge $(u,v)$ if their sensing disks overlap
- Region is $k$-barrier covered iff $L$ and $R$ are $k$-connected in $G$. 
Donut-Shaped Region

- K-barrier covered iff $G$ has $k$ essential cycles
Critical Condition for K-Barrier Coverage

- Almost sure k-covered:
  \[
  \lim_{s \to \infty} \frac{2npr}{s \log np} > 1
  \]

- Almost sure not k-covered:
  \[
  \lim_{s \to \infty} \frac{2npr}{s \log np} > 1
  \]
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
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 sensor 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
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
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 to 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
Setup Phase

- At the beginning of each round, each node advertises its 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 broadcast 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

1. **Node i cluster-head?**
   - **Yes**
     - Announce cluster-head status
     - Wait for Join-Request messages
     - Create TDMA schedule and send to cluster members $t = 0$
   - **No**
     - Wait for cluster-head announcements
     - Send Join-Request message to chosen cluster-head
     - Wait for schedule from cluster-Head $t = 0$

2. Steady-state operation for $t = T_{round}$ seconds
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 $k$

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

(1)

- $k = \text{number of clusters during each round}$
- $N = \text{number of nodes in the network}$
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 $t$

\[
P_i(t) = \begin{cases} 
\frac{k}{N-k*(r\ mod\ \frac{N}{k})} & : \ C_i(t) = 1 \\
0 & : \ C_i(t) = 0 
\end{cases}
\] (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 the 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

1. **Cluster set-up**
   - **Node i cluster-head?**
     - **No**
     - **Yes**
     - **t < T_{round}?**
       - **Yes**
         - Receive data from cluster members (t_{schedule} seconds)
         - Compute on data (data fusion) and send result to Base Station
       - **No**
         - Sleep for t_{slot_for_node_i} seconds
     - **t < T_{round}?**
       - **Yes**
         - Transmit data to cluster-head
       - **No**
         - Sleep for t_{schedule} seconds
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 throughout 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

<table>
<thead>
<tr>
<th>Nodes</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network size</td>
<td>100 m x 100 m</td>
</tr>
<tr>
<td>Base station location</td>
<td>(50, 175)</td>
</tr>
<tr>
<td>Radio propagation speed</td>
<td>$3 \times 10^8$ m/s</td>
</tr>
<tr>
<td>Processing delay</td>
<td>50 $\mu$s</td>
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<tr>
<td>Radio speed</td>
<td>1 Mbps</td>
</tr>
<tr>
<td>Data size</td>
<td>500 bytes</td>
</tr>
</tbody>
</table>
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

- **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
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

<table>
<thead>
<tr>
<th>Routing protocol</th>
<th>Data-centric</th>
<th>Hierarchical</th>
<th>Location-based</th>
<th>QoS</th>
<th>Network-flow</th>
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Roadmap

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

<table>
<thead>
<tr>
<th></th>
<th>RFM TR1000</th>
<th>RFM TR3000</th>
<th>MC13202</th>
<th>CC1000</th>
<th>CC2420</th>
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</thead>
<tbody>
<tr>
<td>Data rate (kbps)</td>
<td>115.2</td>
<td>115.2</td>
<td>250</td>
<td>76.8</td>
<td>250</td>
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<tr>
<td>Transmit current</td>
<td>12mA</td>
<td>7.5mA</td>
<td>35mA</td>
<td>16.5mA</td>
<td>17.4mA</td>
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<td>Receive current</td>
<td>3.8mA</td>
<td>3.8mA</td>
<td>42mA</td>
<td>9.6mA</td>
<td>18.8mA</td>
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<td>800μA</td>
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<td>18.8mA</td>
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<td>Standby current</td>
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<td>0.7μA</td>
<td>102μA</td>
<td>96μA</td>
<td>426μA</td>
</tr>
</tbody>
</table>

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)
  - $2000\text{mAh} / 18.8\text{mA} = 106.4 \text{ hours} = 4.4 \text{ days}$

  ➔ 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
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
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

Channel Utilization vs. # of Contenders

- CSMA
- TDMA
- IDEAL
Z-MAC: Basic Objective

Can you do hybrid contention resolution?

<table>
<thead>
<tr>
<th>MAC</th>
<th>Channel Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Contention</td>
</tr>
<tr>
<td>CSMA</td>
<td>High</td>
</tr>
<tr>
<td>TDMA</td>
<td>Low</td>
</tr>
</tbody>
</table>

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
  • 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
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
- 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 $s_i$th 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 $[0, T_0]$.
  - whereas other nodes choose their back-off values from the range $[T_0, T_{no}]$. 
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
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.