Chapter 1: Motivation for a Network of Wireless Sensor Nodes

Chapter 1: Roadmap

- 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>
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<tr>
<td>Pressure</td>
<td>Pressure gauges, barometers, Baratron gauges</td>
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<tr>
<td>Optical</td>
<td>Photodiodes, phototransistors, infrared sensors, CCD sensors</td>
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<tr>
<td>Resistive</td>
<td>Resistive elements, transistors</td>
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<tr>
<td>Mechanical</td>
<td>Strain gauges, tactile sensors, piezoresistive cells</td>
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<tr>
<td>Motion, vibration</td>
<td>Accelerometers, mass at fly sensors</td>
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<tr>
<td>Position</td>
<td>GPS, ultra-precise motion sensors, inclinometers</td>
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<tr>
<td>Chemical</td>
<td>pH sensors, electrochemical sensors, infrared sensors</td>
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<tr>
<td>Electromagnetic</td>
<td>Hall-effect sensors, magnetometers</td>
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<tr>
<td>Radiation</td>
<td>Ionization detectors, gamma detectors</td>
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Other Classifications

- Power supply:
  - active sensors require external power, i.e., they emit energy (microwaves, light, sound) to trigger response or detect change in energy of transmitted signal (e.g., electromagnetic proximity sensor)
  - passive sensors detect energy in the environment and derive their power from this energy input (e.g., passive infrared sensor)
- Electrical phenomenon:
  - resistive sensors use changes in electrical resistivity (\( \rho \)) based on physical properties such as temperature (resistance \( R = \rho l / A \))
  - capacitive sensors use changes in capacitor dimensions or permittivity (\( \varepsilon \)) based on physical properties (capacitance \( C = \varepsilon A / d \))
  - inductive sensors rely on the principle of inductance (electromagnetic force is induced by fluctuating current)
  - piezoelectric sensors rely on materials (crystals, ceramics) that generate a displacement of charges in response to mechanical deformation
Example: Wheatstone Bridge Circuit

\[ V_{\text{out}} = V_{CC} \times \left( \frac{R_x R_3}{R_1 R_3 + R_2 R_x - R_1 R_2} \right) \]

- R1, R2, and R3 known (R2 adjustable)
- Rx is unknown

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

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]
  - Sensirion [www.sensirion.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 versus 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
      \[ E_{CPU} = E_{switch} + E_{leak} = C_{total} \cdot V_{dd}^2 + V_{dd} \cdot I_{leak} \cdot \Delta t \]
  - 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 to 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**: $P_r \propto P_t \frac{d^2}{d^4}$
    - limits radio range
  - 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 due to 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 sensor makes routing decisions based on limited local information
    - routes may be nonoptimal, but route establishment management may 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

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<thead>
<tr>
<th>Traditional Networks</th>
<th>Wireless Sensor Networks</th>
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<tbody>
<tr>
<td>General-purpose design serving many applications</td>
<td>Single-purpose design serving one specific application</td>
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<tr>
<td>Typical primary design concern is network performance and scalability</td>
<td>Energy is the main constraint in the design of all node and network components</td>
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<td>Networks are designed and engineered according to plan</td>
<td>Deployment, network structure, and resource use are often ad-hoc, emergent planning</td>
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<tr>
<td>Devices and networks operate in controlled and mild environments</td>
<td>Sensor networks often operate in environments with harsh conditions</td>
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<tr>
<td>Maintenance and repair are relatively easy to achieve</td>
<td>Physical access to sensor nodes is often difficult or even impossible</td>
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<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 feasible, distributed and coordinated management is possible</td>
<td>Most decisions are made locally without the support of a central manager</td>
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