Outline

- What technology for what applications?
- WSNs characteristics and design issues, with special focus on:
  - Power management
  - Reliable data collection
  - Hybrid architectures
- Are there size limitations?
- Conclusion
- Based on slides by Prof JP Hubaux, EPFL, and Dr. Lama Nachman, Intel

Cold Chain Management

- Supermarket chains need to track the storage temperature of perishable goods in their warehouses and stores.
- Tens if not hundreds of fridges should be monitored in real-time
- Whenever the temperature of a monitored item goes above a threshold
  - An alarm is raised and an attendant is warned (pager, sms)
  - The refrigeration system is turned on
- History of data is kept in the system for legal purpose
- Similar concept can be applied to pressure and temperature monitoring in production chains, containers, pipelines

Home automation

- Temperature management:
  - Monitor heating and cooling of a building in an integrated way
  - Temperature in different rooms is monitored centrally
  - A power consumption profile is to be drawn in order to save energy in the future
- Lighting management:
  - Detect human presence in a room to automatically switch lights on and off
  - Responds to manual activation/deactivation of switches
  - Tracks movement to anticipate the activation of light-switches on the path of a person
- Similar concept can be applied to
  - Intrusion detection

Precision Agriculture management

- Farming decisions depend on environmental data (typically photosynthesis):
  - Solar radiation
  - Temperature
  - Humidity
  - Soil moisture
- These data evolve continuously over time and space
- A farmer’s means of action to influence crop yield:
  - Irrigation
  - Fertilization
  - Pesticide treatment
- To be optimal, these actions should be highly localized (homogenous parcels can be as small as one hectare or less)
- Environmental impact is also to be taken into account
  - Salinization of soils, groundwater depletion, well contamination, etc.

WaterSense

- Goal: Help define and implement farming strategies for farmers in a situation of water scarcity.
  - Crop assessment
  - Water conservation measures
  - Time of farming operations
  - Real-time monitoring of the field conditions
- Desired Outcome: farming decision support system based on environmental data
Earthquake detection

- The occurrence of an earthquake can be detected automatically by accelerometers.
- Earthquake speed: around 5-10 km/s.
- If the epicenter of an earthquake is in an unpopulated area 200 km from a city center, instantaneous detection can give a warning up to 30 sec before the shockwave hits the city.
- If a proper municipal actuation network is in place:
  - Sirens go off
  - Traffic lights go to red
  - Elevators open at the nearest floor
  - Pipeline valves are shut
- Even a warning of a few seconds can reduce the effects of the earthquake.
- Similar concept can be applied to:
  - Forest fire, landslides, etc.

Ubiquitous Computing

Economic Forecast

- Industrial Monitoring (35% – 45%)
  - Monitor and control production chain
  - Storage management
  - Monitor and control distribution
- Building Monitoring and Control (20 – 30%)
  - Fire, intrusion
- Access control
- Home Automation (15 – 25%)
  - Energy management
  - Remote control of appliances
- Automated Meter Reading (10-20%)
  - Water meter, electricity meter, etc.
- Environmental Monitoring (5%)
  - Agriculture
  - Wildlife monitoring

Other areas:
- Performance monitoring in sports
- Patient monitoring in health and medicine
- Sensor going wireless in vehicular networks

WSN Characteristics and Design Issues

- Characteristics
  - Distributed data collection
  - Many-to-one (rarely peer-to-peer)
  - Limited mobility
  - Data collection (time and space resolution)
  - Event detection
  - Minimal intrusiveness
- Design issues
  - Low-cost (hardware and communication)
  - Extended life-time
  - Reliable communication
  - Efficient integrated data processing
  - Hybrid network infrastructure
  - Security

Example of a Low Power Transceiver: Tinynode™

- 868 MHz multi-channel transceiver
- 8 MHz µ-Controller
- 10 KB RAM
- 48 KB Program space
- 512 External Flash
- 115 kbps data rate
- 3V supply voltage
- Current consumption
  - Transmit 25 mA
  - Receive 14 mA
  - Sleep < 1 µA
- -121 dBm sensitivity
- Radio range 200m (outdoor)
- 39 MHz quartz reference

Design Issue: Low-cost

- Hardware
  - Low-cost radio
  - Low cost internal clock
  - Limited storage and processing capabilities
  - Not tamper-proof
- Communication
  - Cannot rely on existing pay-per-use cellular infrastructure
### Design Issue: Power Management

- Energy-efficient routing
- Minimum-cost spanning tree
- Load-balancing
- Mobility
- In-network aggregation
- Medium-access control

### Simple Model for Energy Consumption

**Equation:**

\[ E_{\text{Tx}}(k, d) = E_{\text{elec}}^* k + E_{\text{amp}}^* k \cdot d^a \]

**Equation:**

\[ E_{\text{Rx}}(k) = E_{\text{elec}}^* k \]

**Typical values:**

- \( a = 2 \ldots 6 \)
- \( E_{\text{elec}}^* = 50 \text{ nJ/bit} \)
- \( E_{\text{amp}}^* = 100 \text{ pJ/bit/m} \)

### Energy-efficient Routing: Example

Transmitting a single \( k \)-bit message from node \( A \) (located at distance \( d \) from Sink) to Sink:

**Direct transmission:**

\[ E_{\text{direct}} = E_{\text{Tx}}(k, d = n*r) = E_{\text{elec}}^* k + E_{\text{amp}}^* k \cdot (nr)^a \]

**Multihop transmission:**

\[ E_{\text{multihop}} = n(E_{\text{elec}}^* k + E_{\text{amp}}^* k \cdot r^a) + (n-1)E_{\text{elec}}^* k = k((2n-1)E_{\text{elec}}^* + E_{\text{amp}}^* nr^a) \]

### Minimum Energy in a Wireless Network

- **Problem:** For an arbitrary configuration of nodes, find (in a fully distributed way) the minimum cost spanning tree to and from a given sink node
- **Assumptions**
  - Each node knows its own location (e.g., using GPS)
  - The power decreases with distance according to a power law with a known and uniform exponent \( a \)
  - Each node can communicate with another node located at an arbitrary distance
  - Nodes do not move
  - Slightly different power model

### Distributed Network Protocol

- **Finds the minimum power topology for a stationary set of nodes with a single sink**
- **Assumption:** Each node is equipped with a GPS-receiver and transmits its position to its neighbors
- **The protocol proceeds in 2 phases:**
  1. Each node computes its own enclosure
  2. Each node computes its optimal cost distribution
**Load-balancing**

- Assumption: in a multi-hop many-to-one sensor network, the data collection follows a spanning tree.
- Power consumption due to transmission/reception grows exponentially from the leaves to the root of the tree.
- Consequence: the power sources of the nodes close to the sink deplete faster. Since they relay all the network’s traffic, they pull the network lifetime down.

**In-network Data Aggregation**

- To mitigate cost of forwarding, compute relevant statistics along the way: mean, max, min, median etc.
- Forwarding nodes aggregate the data they receive with their own and send one message instead of relaying an exponentially growing number of messages.
- Issues:
  - Location-based information (which nodes sent what) is lost
  - Distributed computation of statistics
    - mean: node needs to know both the mean values and the sizes of samples to aggregate correctly
    - median: only an approximated computation is possible
- Especially useful in a query-based data collection system
  - Queries regard a known subset of nodes
  - Aggregation function can be specified

**Medium-Access Control**

- MAC attributes:
  - Collision avoidance
  - Energy efficiency
  - Scalability and adaptivity
- Nodes transmit very intermittently, but once a transmission is taking place, we must ensure that the intended receiver gets it.
- Current-consumption in receive state or in radio-on idle state are comparable
- Idle state (idle listening) is a dominant factor in power consumption

Goal is to put nodes to sleep most of the time, and wake them up only to receive a packet.

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For detailed information, refer to [this resource](http://research.com/ru.edu/people/estrin/resources/conferences/2002jun-Ye-Estrin-Energy.pdf)

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**Synchronous MACs**

- TDMA (similar to cellular networks)

![Frame 1 and Frame 2 diagram]

- Shortcomings:
  - Necessity to organize nodes in clusters and cluster hierarchies
  - High control traffic cost
- Possible solution:
  - Each node maintains two schedules
    - Its parent schedule
    - The schedule it sets for its children
    - Beacons are used to compensate for clock drifts
Shortcomings

- Transmitting a packet is very expensive
- Overhearing is expensive
- Relaying packets is expensive (multihop)

Simple Improvement:
- Aggregating packets before sending them
  - In low duty cycle data collection network, gain may be substantial
  - Price to pay: real-time

Design Issue: Reliable data collection

- Many-to-one communication paradigm
- Multi-hop communication
- Nodes select one parent to send their data packets (tree topology)

MintRoute: A Data Collection Tree Routing Protocol

- Distance-vector routing protocol: one routing path per node
- A shortest path: Minimum number of transmissions
- The base station send periodic beacons that are broadcast by each node after incrementing a hop count
- Node select beacons with lowest hop count from the ones it received, and adds its sender among a list of potential parents
- Neighboring nodes exchange periodic beacons for link quality evaluation (gaps within the sequence # of packets → packet losses)
- Nodes select their parent based on hop count, link quality and load.
- Volatile routing topology → load balancing
- Cycle avoidance: Link quality must not vary too rapidly

MintRoute: Root Beaconing

MintRoute: Link Estimation

Design Issue: Data Processing

- Challenge: develop a tool that makes it convenient to query any wireless sensor network
- Cope with
  - Data heterogeneity
  - Geographic distribution
  - Platform diversity
  - Etc...
- Web-based interface to
  - Add/remove instances of sensor networks
  - Display data
  - Export data
  - Send queries
- Example: http://gsn.sourceforge.net/
Design Issue: Hybrid Network Architecture

- Deployment can be in remote areas
- The sink needs to communicate the data to the user
- Pervasive computing means pervasiveness of access to data
- Multi-tier architectures are necessary

2-tier Architecture with 802.11 Bridge

Delay Tolerant Network with Data Mules

- Clusters are not directly connected to the server
- Cluster heads store data from the cluster nodes
- "Data mules" collect the data periodically
  - Cars, robots, etc.
- When a cluster-head detects a mule, it uploads to it the data it had in store

How Large is Too Large?

- Largest Scale demonstration
  - Excal: Ohio State University, DARPA-NEST project
    - Intrusion detection application (perimeter, pipeline, border, etc)
    - Demonstrated 3 tier WSN consisting of 1000 XSM motes, 250 stargate nodes, Dec 2004
    - 3rd tier controls stargates, each stargate controls 20-50 motes
    - 1.3 km x 0.5 km, 45 m spacing
    - Demo that lasted for a few days
- Examples of long term POCs (double digit motes)
  - Habitat monitoring on Great Duck Island, UCB
  - Golden gate bridge, UCB
  - Condition based maintenance on BP oil tanker and in fab, Intel/Crossbow/Rockwell/BP
  - Water Pipeline Monitoring, Intel
  - Vineyard monitoring in Montepaldi farm, Good Food Project

Condition-Based Management

- Use vibration signatures to identify problems with equipment
- Manual data collection common today
  - ~4000 sensor points in a fabrication plant
  - ~200 KB of raw data per sensor point Lower operating costs
- Reduced manual labor
- Increased fault coverage
- Prototype in Intel Fab and BP oil tanker
  - Compare data quality and reliability to manual system
    - 25 node deployment
      - 6 Vibration/Temp channels per node
      - Tachometer
How large can deployed sensor networks feasibly grow?

- Multi-tier is the typical approach to scaling
  - Multi-tier architecture divides the scaling problem into manageable segments
  - Segmented networks (2nd tier aggregation, high throughput apps)
    - Static allocation of networks simplifies the scalability problem but complicates the management problem
    - Dynamic allocation of networks is more appealing
- Clusters on the orders of 10-50 nodes are adequate for most applications
  - In most industrial applications, having access to power for 2nd tier nodes is realistic (or at least intermittent power sufficient to charge a battery)
  - Outdoor deployments can also leverage solar power for recharging 2nd tier batteries
  - Pipeline monitoring applications look different, will probably need higher scaling

Conclusion Sensor Networks

- WSNs are an emerging technology which is poised to grow exponentially in the coming years
- This new communication paradigm introduces a new set of design constraints
  - They must be extremely low-cost
    - Both to purchase and to operate
  - They must be extremely energy efficient since their lifetime is potentially years
    - Hardware design
    - Routing and topology mechanisms
    - Specialized Medium Access Control mechanisms
  - Despite their low-cost and power management features, they must implement reliable communication protocols
  - They must integrate versatile middleware and provide data processing
  - They will often rely on a hybrid network infrastructure

Load balancing

- Power consumption increases at least linearly when nodes are closer to the sink
- Typical case is much worse

Sensor Node architecture

- A sensor node can be an information source, a sink and a router
- Autonomous low-power
- Combine sensing, signal conditioning, signal processing, control and communication capabilities
Properties

Notation: For a particular transmit node \( i \), we will denote \((x_i, y_i) \in R_{\text{net}}\) by \( R(i) \).

Distance properties of relay nodes:
Let \( i \) be the transmit node, \( r \) the relay node, and \( j \) the receive node. If \( R(i) \cap R(j) \neq \emptyset \), then:

- \( d_r < d_j \)
- \( d_r > d_r \)

Enclosure

The enclosure of a transmit node \( i \) is defined as the nonempty solution \( \theta_i \) to the set of equations:

\[
\theta_i = \bigcap_{k \in \Theta(i)} R_k \cap D_i
\]

\( R(i) \) is the set of neighbors of node \( i \)
\( D_i \) is the deployment region
\( \Theta(i) \) denotes the complement of \( \Theta(i) \)

\( N(i) = \{ w \in N \mid (x_k, y_k) \in \theta_i, n = k \} \)

The enclosure graph of a set of nodes \( N \) is the graph whose vertex set is \( N \) and whose edge set is

\[
E = \bigcup_{i \in N} \bigcup_{n \in N(i)} \{(i, n), (n, i)\}
\]

where \( \sigma_{in} \) is the directed communication link from \( i \) to \( k \).

Theorem: The enclosure graph is strongly connected.

Design Issue: Power Management

Phase 1: Computation of the enclosure

\( F = \emptyset \) // Area searched so far
\( A = \emptyset \) // Area used so far
\( N = \emptyset \) // Neighbor set for node \( i \)

While (\( |F| < |N(i)| \))

\( r = \text{NextNode} \) \// Increase the radius
\( F = \text{Disk}(r, i) \) \// Expand the search disk
\( M = (\{(x, y) \mid (x, y) \in F \text{ and } d(x, i) = 1\text{ and } k \in N(i)\}) \) // New nodes found

\( A = A \cup M \)
\( N = \text{GetNodesFrom}(i, M) \) \// Provide new neighbors ordered in growing distance from \( i \)
\( \text{MarkUniq}(x_i) \)
\( \text{MarkNode}(x_i) \)

\( \eta = \bigcap_{i \in \text{Nodes}} R_i \cap D_i \) \// intersection with deployment region \( D_i \)

\( \gamma = F \cup \eta \) \// MarkUniq break

\( N(i) = \text{UniqNodes} \)

Phase 2: Computation of the optimal cost

Principle: use distributed Bellman-Ford

- Cost\((i)\) : Cost of node \( i \): minimum power necessary for \( i \) to establish a path to the sink

Detail:
Each node \( i \) computes the minimum cost \( C_i \) it can attain given the costs of its neighbors. Let \( n \in N(i) \). When \( i \) receives \( \text{Cost}(n) \), it computes:

\[
C_i = \text{Cost}(n) + P_{\text{com}}(i, n) + P_{\text{trans}}(n)
\]

Then, \( i \) computes:

\[
\text{Cost}(i) = \min_{n \in N(i)} C_n
\]

Use Mobility for Load-balancing

- Move the base station to distribute the role of “hot spots” (i.e., nodes around the base station) over time
- The data collection continues through multi-hop routing wherever the base station is, so the solution does not sacrifice latency