18-759: Wireless Networks
Lecture 14: Sensor Networks

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Spring Semester 2016
http://www.cs.cmu.edu/~prs/wirelessS16/

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
  - Security cameras, controlling access, …
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
  - Pest treatment
- To be optimal, these actions should be highly localized (homogeneous 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 5-10km/s
- If the epicenter of an earthquake is in an unpopulated area 200km 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.

Economic Forecast

- Industrial Monitoring (35% – 45%)
  - Monitor and control production chain
  - Storage management
  - Monitor and control distribution
- Building Monitoring and Control (20 – 30%)
  - Alarms (fire, intrusion etc.)
  - Access control
- Home Automation (15 – 25%)
  - Energy management (light, heating, AC etc.)
  - Remote control of appliances
- Automated Meter Reading (10-20%)
  - Water meter, electricity meter, etc.
- Environmental Monitoring (5%)
  - Agriculture
  - Wildlife monitoring
- One recent forecast: 1.8 Billion $ by 2024

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
  - Security

**Wireless helps but may not be required in all cases!**

**Numerous sensor devices**
- Modest wireless communication, processing, memory capabilities
- Form Ad Hoc Network (self-organized)
- Report the measured data to the user

**Example of a Low Power Transceiver: Tinynode™**

- 868 MHz multi-channel transceiver
- 8 MHz μ-Controller
- 10KB RAM
- 48 kB Program space
- 512 External Flash
- 115 kbps data rate
- 3 V supply voltage
- Current consumption
  - Transmit 33 mA
  - Receive 14 mA
  - Sleep < μA
- -121 dBm sensitivity
- Radio range 200m (outdoor)
- 39 MHz quartz reference

**Wireless Sensor Network architecture**

- **Numerous sensor devices**
  - Modest wireless communication, processing, memory capabilities
  - Form Ad Hoc Network (self-organized)
  - Report the measured data to the user

**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
Design Issue: Low-cost

- Hardware
  - Low-cost radio
  - Low cost internal clock
  - Limited storage and processing capabilities
  - Not tamper-proof
  - May have to withstand tough environmental conditions

- Communication
  - Cannot rely on existing pay-per-use cellular infrastructure
  - Use unlicensed spectrum to reach a “gateway”, which has internet connectivity
    - Wired, WiFi, drive-by, cellular,...

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

\[ E_{Tx}(k, d) = E_{elec} \cdot k + \varepsilon_{amp} \cdot k \cdot d^\alpha \]

\[ E_{Rx}(k) = E_{elec} \cdot k \]

Typical values:
\( \alpha = 2...6 \)
\( E_{elec} = 50 \text{ nJ/bit} \)
\( \varepsilon_{amp} = 100 \text{ pJ/bit/m} \)

Energy-efficient Routing: Example

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

Direct transmission:
\[ E_{direct} = E_{Tx}(k, d = nr) = E_{elec} \cdot k + \varepsilon_{amp} \cdot k \cdot (nr)^\alpha = k(E_{elec} + \varepsilon_{amp} n^\alpha \cdot r^\alpha) \]

Multi-Hop Transmission:
\[ E_{multi-hop} = n E_{Tx}(k, d = r) + (n-1) E_{Rx}(k) = n(E_{elec} \cdot k + \varepsilon_{amp} \cdot k \cdot r^\alpha) + (n-1) E_{elec} \cdot k = k((2n-1)E_{elec} + \varepsilon_{amp} \cdot n^\alpha \cdot r^\alpha) \]

MultiHop routing requires less energy than direct communication if:
\[ \frac{E_{direct}}{E_{multi-hop}} < \frac{1}{(n^\alpha \cdot r^\alpha) - 1} \]

Assuming \( \alpha = 3, r = 10\text{m} \), we get \( E_{multi-hop} < E_{direct} \) as soon as \( n \geq 2 \)

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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 precisely its own location (e.g., using GPS)
  - The power decreases with distance according to a power law with a known and uniform exponent $\alpha$
  - Each node can communicate with another node located at an arbitrary distance
  - Nodes do not move
  - Slightly different power model
- Example:

\[
\text{Power to send from A to C via B:}
\]

\[
td_{AB}^s + td_{BC}^r + c
\]

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.
Power consumption increases at least linearly when nodes are closer to the sink.

Typical case is much worse.
Synchronous MACs

- TDMA (similar to cellular networks)

\[
\begin{array}{cccc|cccc|c}
1 & 2 & 3 & \cdots & N & 1 & 2 & 3 & \cdots & N \\
\end{array}
\]

Frame 1 Frame 2

- 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

Asynchronous: B-MAC

- Asynchronous
- Low Power listening

![Beacon and Off Period Diagram]

\[|\text{off period}| \approx |\text{preamble}|\]

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

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
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
How Large is Too Large?

- Largest Scale demonstration
  - ExScal: Ohio State University, DARPA-NEST project
    - Intrusion detection application (perimeter, pipeline, border, etc)
    - Demonstrated 3 tier WSN consisting of 1000 XSM motes, 200 stargate nodes, Dec 2004
    - 3rd tier controls stargates, each stargate controls 20-50 motes
    - 1.3 km x 300 m, 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 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

Based on Lama Nachman’s SECON 2006 panel talk
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/

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, plane, etc.
- When a cluster-head detects a mule, it uploads to it the data it had in store

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 middle-ware and provide data processing
  - They will often rely on a hybrid network infrastructure
Unused Slides

Properties

Notation: For a particular transmit node $i$, we will denote $(x_i, y_j)$ by $R_{ij}$.

Distance properties of relay nodes:
Let $i$ be the transmit node, $r$ the relay node, and $j$ the receive node. If $j \in R(r)$, then:
- $d_r < d_j$
- $d_r > d_j$

Enclosure

The enclosure of a transmit node $i$ is defined as the nonempty solution $\epsilon_i$ to the set of equations:

$$\epsilon_i = \bigcap_{k \in N(i)} R_{ik} \cap D_x$$

$$N(i) = \{ n \in N | (x_i, y_n) \in \epsilon_i, n \neq i \}$$

Design Issue: Power Management

Phase 1: computation of the enclosure

```
F = \emptyset; // Area searched so far
L = \emptyset; // All nodes found by i so far
AliveNodes = \emptyset; // Potential neighbors
DeadNodes = \emptyset; // Discarded nodes
While(TRUE)
    r = NewRadius; // Increase the radius
    F = Disk((r), F); // Expand the search disk
    M = \{ n | (x_i, y_n) \in F, n \notin A, n \neq i \}; // new nodes found
    A = A \cup M;
    m = GetOrderedFrom(i, M) // Provides new neighbors ordered in growing distance from i
    MarkAlive(m);
    foreach(m \in M)
        MarkDead(m);
    if (m \notin R(i)) MarkDead(m);

\eta = \bigcap_{k \in \text{neighbors}} R_{ik} \cap D_x; // intersection with deployment region $D_x$
if (\eta \subseteq F \cup r = \text{MaxRadius}) break;
N(i) = AliveNodes;
```
**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 it can attain given the costs of its neighbors. Let n ∈ N(i). When i receives Cost(n), it computes:

  \[ C_{i,n} = \text{Cost}(n) + P_{\text{transmit}}(i,n) + P_{\text{receiver}}(n) \]

  Then, i computes

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

  and picks the link corresponding to the minimum cost neighbor.

**Theorem:** This protocol finds the minimum power topology