Announcements

- P2 checkpoint 1 is due today.
  » E-mail it to me
  » There is a sign up sheet for meetings posted on Canvas
  » Includes zoom link
- Survey talk drafts are due next week, Monday or Wednesday
  » Schedule is now on the web page
  » The Monday lecture will run long so we complete the surveys in 2 lecture slots

Some Thoughts about Surveys

- Many students use the google templates, which as generally a disaster (24pt)
  » No slide numbers
  » Tiny font sizes (12pt) – I want to be bigger! (18pt)
  » 50%-80% of the slide is empty
  » Use the space wisely!
- Outline generally looks like:
  » Background: why useful, challenges, design options, etc.
  » Discussion on the three papers:
    – What is the key idea – this should be clear (figure!)
    – Some sample results illustrating benefits
    – Do not use terminology specific to the paper
  » Personal opinion on pros or cons (global or per paper)

Outline

- Example applications
- Early sensor networks
  » Power management
  » Routing
  » Efficient data collection
- Today’s sensor networks

Based on slides by Prof JP Hubaux (EPFL), Lama Nachman (Intel), Revathy Narayanan (CMU)
Wireless Sensor Networks (WSN)

- Wireless sensors have limited compute, energy, memory, and bandwidth resources, but:
- Sensing capabilities → Can observe properties the physical world
- CPU and actuators → Can control some aspects of the physical world
- Small physical size → Can be embedded throughout the physical environment
- Basis for “Cyber physical” systems, “Internet of Things”

Architecture for Wireless Sensor Networks

- There is no such thing!
- Early systems: highly specialized, relatively small-scale deployments
  » Home security systems, HVAC systems, security, …
- Later systems: focus on scaling, conserve battery, collaboration between sensors
  » A lot of research on multi-hop ad hoc networks that reduce energy consumption
- Today: trend towards more general, highly scalable, very low energy systems
  » Must be easy to deploy and maintain

WSN Applications

- Commercial Applications
  » Light/temperature control
  » Precision agriculture (optimize watering schedule)
  » Asset management (tracking freight movement/storage)
- Monitoring tools supporting Scientific Research
  » Wild life Habitat monitoring projects Great Duck Island (UCB), James Reserve (UCLA), ZebraNet (Princeton.
  » Building/Infrastrcutre structure (Earthquake impact)
- Military Applications
  » Shooter Localization
  » Perimeter Defense (Oil pipeline protection)
  » Insurgent Activity Monitoring (MicroRadar)

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

- 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 (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.

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

- Other areas:
  - Performance monitoring in sports
  - Patient monitoring in health/medicine
  - Wireless sensor in vehicular networks

Recent forecast: 7 Billion $ by 2026
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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
- Design issues
  - Low-cost (hardware and communication)
  - Extended life-time – long battery life
  - Reliable communication
  - Efficient integrated data processing
  - Hybrid network infrastructure
  - Security

Wireless helps but may not be required!

Second Generation Wireless Sensor Network

- Numerous sensor devices
  - Modest wireless communication, processing, memory capabilities
  - Form Ad Hoc Network (self-organized)
    - Uses short-range wireless technologies
  - 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

(courtesy of Swiss Center for Electronics and Microelectronics, Neuchâtel)
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

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

- Traditional metrics for network optimization: bandwidth, latency, economics ($$$), ...
- Wireless sensor networks: power efficiency
  - Energy-efficient routing
  - Load balancing to distribute power consumption
  - In network aggregation to reduce traffic load
  - Minimize up-time of sensors
- Requires new network technologies
  - Different routing algorithms
  - New MAC protocols

Simple Model for Energy Consumption

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

Typical values:
\[ \alpha = 2...6 \]
\[ E_{elec} = 50 \text{ nJ/bit} \]
\[ E_{amp} = 100 \text{ pJ/bit/m} \]
Energy-efficient Routing: Example

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

Direct transmission: \[ E_{\text{direct}} = E_{\text{Tx}}(k, d = n^*r) = E_{\text{elec}}k + E_{\text{amp}}k(n^*r) \]

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

MultiHop routing requires less energy than direct communication if:

\[ \frac{E_{\text{elec}}}{E_{\text{amp}} < \frac{r^a(n^*r - 1)}{2}} \]

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

Minimum Energy in a More General Wireless Network

- Problem: for an arbitrary set 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 exact location (e.g., using GPS)
  - The power decreases with distance according to a power law with a known and path loss exponent \( a \)
  - Each node can communicate with another node located at an arbitrary distance
  - Nodes do not move
  - Slightly different power model
- Example:

\[ \text{Power to send from A to C via B:} \]
\[ td_{AB}^a + td_{BC}^a + c \]

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.

Load balancing

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

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.
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 is awake so it can receive packet.
- 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

Synchronous MACs

- TDMA (similar to cellular networks)

  ![Frame 1](1 2 3 ... N)
  ![Frame 2](1 2 3 ... N)

- 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
- Refinements: sender and receiver synchronize clocks
  - Many variants, e.g., coordinate cycle of the receivers

<table>
<thead>
<tr>
<th>Receiver</th>
<th>Off</th>
<th>On</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sender</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

  | off period | ≈ | preamble |
Design Issue: Efficient Data Collection

- Many-to-one communication paradigm
- Multi-hop communication based on tree topology
  » Nodes select one parent to send their data packets
  » Traffic volume increases near the root: impacts battery life time and possibly network performance
- Aggregate packets before sending them
  » Reduces the number of packets near the root
  » In low duty cycle network, gain may be substantial
- Aggregate information using simple operations
  » Max, min, average, …
- Price to pay: loss of real-time

Delay Tolerant Network with Data Mules

- Clusters are not directly connected by a network 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

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Today’s Sensor Networks

- Push toward diverse set of low-power wireless technologies
  » Differ in MAC, licensed/unlicensed, range, power, target bit rates, …
- New types of MAC technologies
  » IEEE WiFi and PAN technologies: both WiFi and PAN
    – Zigbee, Bluetooth Low Energy, 802.11ah
  » Cellular: LTE-M, NB-IoT
  » Industry-driven technologies using diverse PHY and MAC protocols
    – LoRa, Sigfox, Z-Wave, …
    – Protocols can be as simple as Aloha
- RFID, e.g., DASH7
WiFi HaLow – 802.11ah

- Low power version of WiFi operating in the unlicensed 900 MHz band (2017)
  » Increased range (1km), lower transmit power
- Based on 802.11a/g but uses 1 MHz channels
  » 26 channels; can do channel bonding up to 16 MHz
  » Transmit rates in range of 0.3 to 347 Mbps
- Support for relaying, limiting contention, and power save mode
  » Relays: increase AP coverage; increase bit rates thus reducing paper
  » Contention-free periods for AP-stations, timed access
  » Sectorization: groups of nodes can only send in certain time windows, e.g., to reduce hidden terminal effects

IEEE PAN - ZigBee

- 802.15.4 PHY layer is used by Zigbee (2003) and some non-IEEE protocols
  » Defined for the 900 MHz and 2.4 GHz unlicensed bands
- Uses Direct Sequence Spread Spectrum
- MAC uses CSMA-CA
- Can create star and point-to-point topologies
  » See PAN lecture
- Targets low-bandwidth, relatively short range applications
  » Up to 250 Kbps, range 10-100 m
  » 127 byte packets

Bluetooth Low Energy

- Lower power consumption and cost than Bluetooth but similar transmissions range
- Not backwards compatible with Bluetooth
  » Uses the same 2.4 GHz frequencies to radio can be shared
- Uses frequency hopping on 40 2-MHz channels
  » Compared to 79 1-MHz channels for Bluetooth classic
  » Also some differences in the frequency hopping
  » Similar modulation (Gaussian frequency shift keying)
- Targets applications with low bit rates
  » PHY rates up to 1 Mbps (2 Mbps for Bluetooth 5)
  » Data rates much lower: up to 0.5 Mbps for Bluetooth 5

Low Power Cellular

- Narrowband – IoT (NB-IoT) – 2016
  » Focus on indoor coverage, low bitrates, dense deployments
  » Two categories with different performance
  » Uplink typically faster: 16-159 kbps vs 26-127 kbps
- LTE-M machine type communication - 2016
  » High bandwidth including voice, mobility
  » Lower latency but higher cost compared with NB-IoT
  » Uplink 1-7 Mbps – Downlink 1-4 Mbps
- Both standards are defined by 3GPP
- Simple node design: single antenna, SISO
  » Half duplex: always for NB-IoT, optional for LTE-M
Low-Power Wide-Area Networks (LPWAN)

- Longer range to simplify deployment
  » “Metropolitan” area – cite-wide sensor network
  » Star topology, up to 10 km of range
- Based on spread spectrum across 125+ KHz band
  » Chirp spread spectrum
- Sub-GHz bands
  » 900 MHz in US
- Low throughput
  » 0.25-27 Kbps
  » Payload up to 243B
- Aloha protocol
  » What about capacity?

SigFox

- Ultra-narrowband technology:
  » Transmits in 200 Hz in 200 KHz of sub-GHz spectrum
  » Low data rate 100s of bits/sec
  » Uses differential BPSK – phase modulation
- Based on Aloha protocol: transmitter picks a carrier frequency; received decodes full band
- Very basic protocol: small packets, no encryption, single bit rate
  » Payload is 12 bytes uplink, 8 bytes downlink
- Also uses star topology
- Radios are cheaper than LoRaWAN
  » With roughly double the range

Comparison

Throughput versus Range

Power Efficiency

"Challenge: Unlicensed LPWANs Are not Yes the Path to Ubiquitous Connectivity", Branden Ghena et al., ACM Mobicom’19

https://dl.acm.org/doi/10.1145/3300061.3345444

Max range
Good Signal