18-759: Wireless Networks

Lecture 28: Sensor Networks

Peter Steenkiste

CS and ECE, Carnegie Mellon University

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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

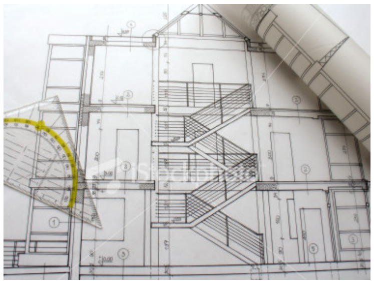
- Based on slides by Prof JP Hubaux, EPFL, and Dr. Lama Nachman, Intel

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
- 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.

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.

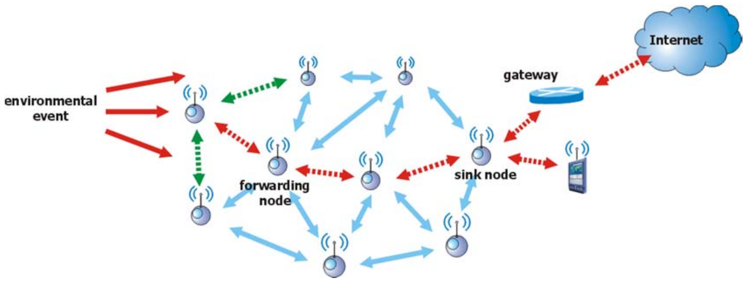
WSN Characteristics and Design Issues

- **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

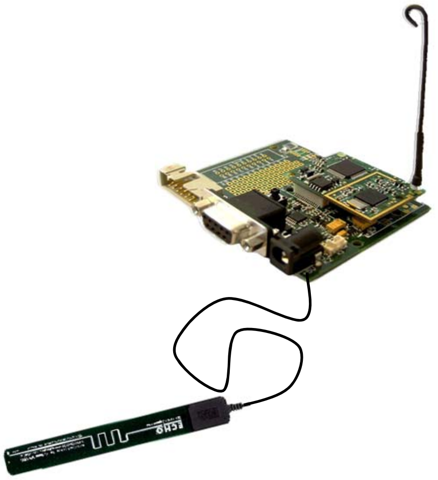
Wireless helps but may not be required!

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

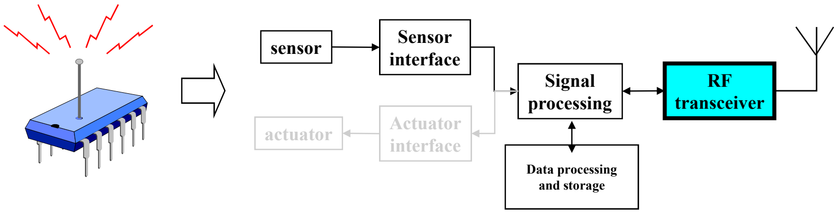


Example of a Low Power Transceiver: Tinynode^{TM}



- 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

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)

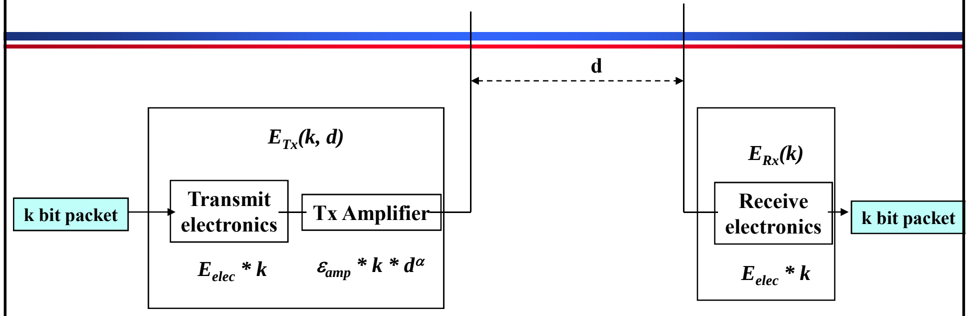
Design Issue: Low-cost

- **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



$E_{Tx}(k, d) = E_{elec} * k + \varepsilon_{amp} * k * d^{\alpha}$

$E_{Rx}(k) = E_{elec} * k$

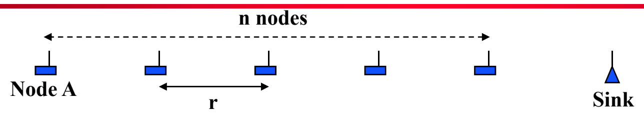
Typical values:

$\alpha = 2 \ldots 6$

$E_{elec} = 50$ nJ/bit

$\varepsilon_{amp} = 100$ pJ/bit/m^{α}

Energy-efficient Routing : Example



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

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

Multi-Hop Transmission: $E_{multi\text{-}hop} = n*E_{Tx}(k, d = r) + (n-1)*E_{Rx}(k)$

$$= n(E_{elec} * k + \varepsilon_{amp} * k * r^{\alpha}) + (n-1)* E_{elec} * k = k((2n-1)E_{elec} + \varepsilon_{amp} n r^{\alpha})$$

MultiHop routing requires *less* energy than direct communication if: $\boxed{\frac{E_{elec}}{\varepsilon_{amp}} < \frac{r^{\alpha}(n^{\alpha-1}-1)}{2}}$

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

Minimum Energy in a 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 uniform exponent α**
  - **Each node can communicate with another node located at an arbitrary distance**
  - **Nodes do not move**
  - **Slightly different power model**

sending: td^{α}
receiving: c

- **Example:**

Power to send from A to C via B:

$$td_{AB}^{\alpha} + td_{BC}^{\alpha} + c$$

Relay region

Relay region:

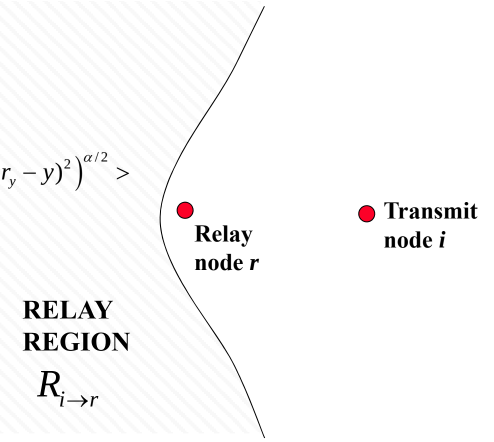
$$\boxed{R_{i\to r} \equiv \{(x,y) \mid P_{i\to r\to(x,y)} < P_{i\to(x,y)}\}}$$

We can expand this to:

$$td_{i,r}^{\alpha} + td_{r,(x,y)}^{\alpha} + c < td_{i,(x,y)}^{\alpha}$$

$$t\left((i_x-x)^2+(i_y-y)^2\right)^{\alpha/2} - t\left((r_x-x)^2+(r_y-y)^2\right)^{\alpha/2} >$$

$$t\left((i_x-r_x)^2+(i_y-r_y)^2\right)^{\alpha/2} + c$$

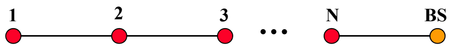


Load-balancing

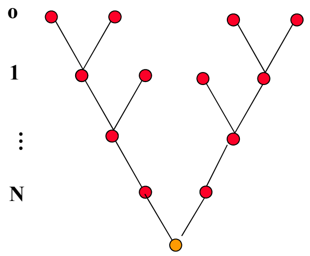
- **Assumption: in a multi-hop many-to-one sensor network, the data collection follows a spanning tree.**
- **Power consumption due to transmission/reception grows exponentially from the leaves to the root of the tree**
- **Consequence: the power sources of the nodes close to the sink deplete faster.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

Load-balancing

Line topology



Tree topology

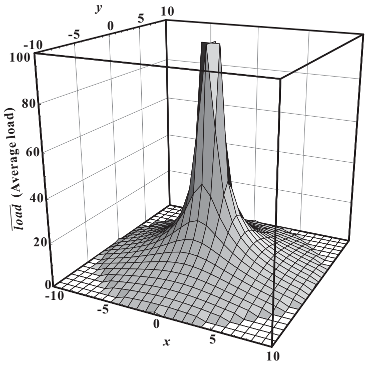


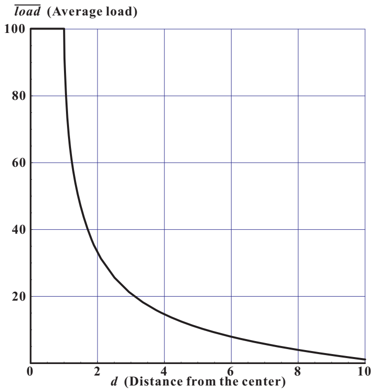
P_{tx} : Average transmission power consumption
P_{rx} : Average reception power consumption
P_{pr} : Average processing power consumption
$P_T(k)$: Total power consumption of node k
$P = P_{pr} + P_{tx} + (k-1)(P_{tx} + P_{rx})$
P grows linearly with the distance from the leaf node

d : distance from leaf
F : number of messages forwarded
P : Power consumption
Assumptions:
1) all nodes have either 0 or $n_k > 2$ children
2) all leaves are at the same distance from the sink
$F(d) \geq 2^d$
$P(d) \geq P_{tx} + 2^d (P_{tx} + P_{rx})$
P grows exponentially with distance from leaf node

Load balancing

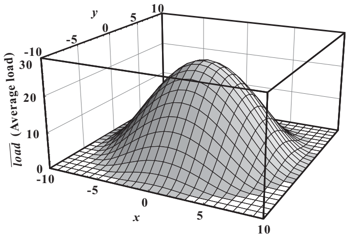
- **Power consumption increases at least linearly when nodes are closer to the sink**
- **Typical case is much worse**

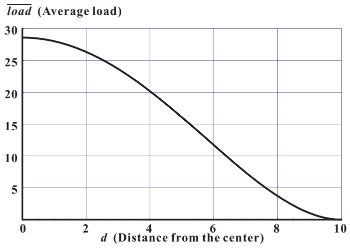




Use Mobility for Load-balancing

- 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





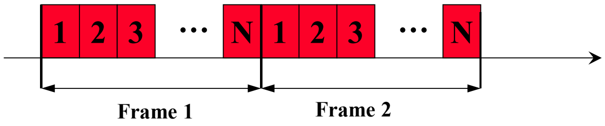
Medium-Access Control

- 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 http://research.cens.ucla.edu/people/estrin/resources/conferences/2002jun-Ye-Estrin-Energy.pdf

Synchronous MACs

- TDMA (similar to cellular networks)

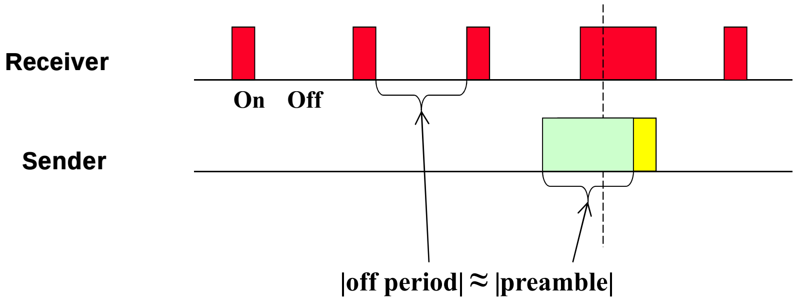


- Shortcomings
  - » Necessity to organize nodes in clusters and cluster hierarchies
  - » High control traffic cost
- Possible solution
  - » Each node maintains two schedules
    - – Its parent schedule
    - – The schedule it sets for its children
  - » Beacons are used to compensate for clock drifts

Asynchronous: B-MAC

- Asynchronous
- Low Power listening

🟥 Awake
🟩 Preamble
🟨 Data



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

Conclusion

- 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