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Wireless Networks and Applications
Lecture 21: Sensor Networks

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http://www.cs.cmu.edu/~prs/wirelessS17/

Outline

- Example applications?
- Characteristics and design issues:
  - » 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

Wireless Sensors

Low-power microscopic sensors with wireless communication capability

- Miniaturization of computer hardware → Intelligence
- Micro Electro-Mechanical Structures (MEMS) → Sensing
- Low-cost CMOS-based RF Radios →Wireless Communication

Wireless Sensor Networks(WSN)

- Even though wireless sensors has limited resources in memory, computation power, bandwidth, and energy.
- With small physical size→Can be embedded in the physical environment.
- Support powerful service in aggregated form (interacting/collaborating among nodes)
- *Self-organizing multi-hop ad-doc networks*
- Pervasive computing/sensoring

WSN Applications

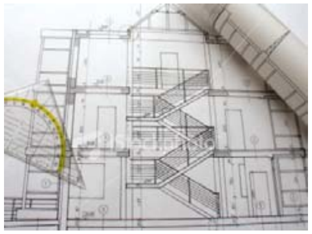
- Commercial Applications
  - » Light/temperature control
  - » Precision agriculture (optimize watering schedule)
  - » Asset management (tracking freight movement/storage)
- Wide area monitoring tools supporting Scientific Research
  - » Wild life Habitat monitoring projects Great Duck Island (UCB), James Reserve (UCLA), ZebraNet (Princeton.
  - » Building/Infrastructure 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 photo-synthesis):
  - » 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

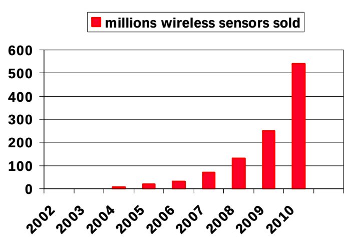
- Goal: Help define and implement farming strategies for farmers in a situation of water scarcity.
  - » Crop assessment
  - » Water conservation measures
  - » Time of farming operations
  - » Real-time monitoring of the field conditions
- Desired Outcome: farming decision support system based on environmental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

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
  - » Hybrid network infrastructure
  - » Security

Wireless helps but may not be required!

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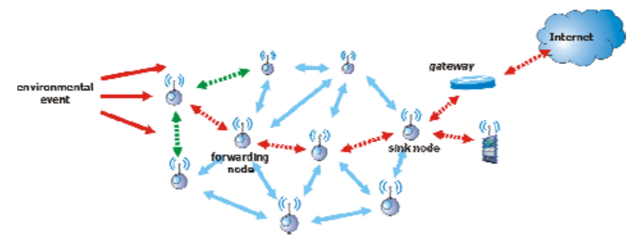
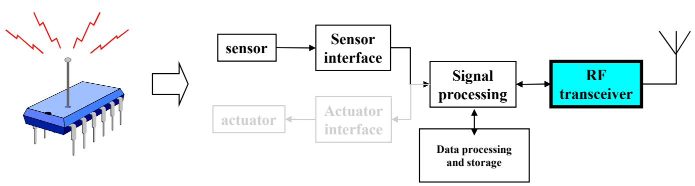
Wireless Sensor Network architecture

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



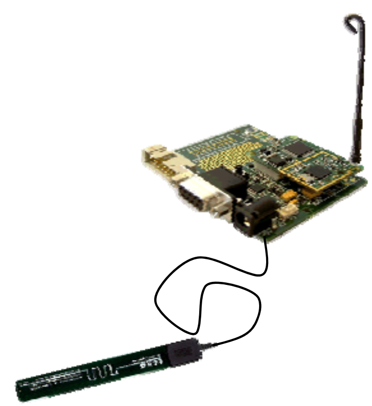
Sensor Node architecture



- 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

(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

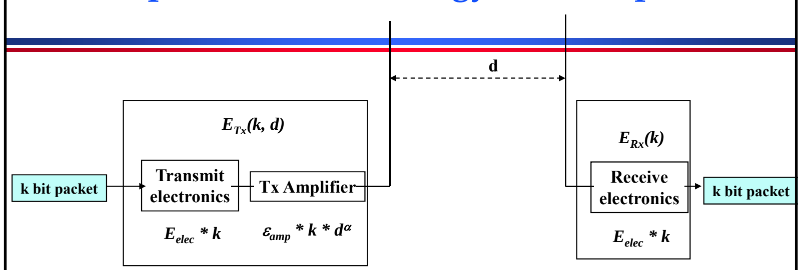
Design Issue: Low-cost

- **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

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

Simple Model for Energy Consumption



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

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

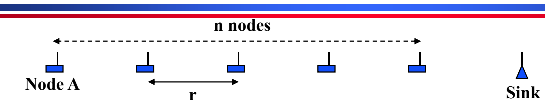
Typical values:

$\alpha = 2 \ldots 6$

$E_{elec} = 50$ nJ/bit

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

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: $\frac{E_{elec}}{\varepsilon_{amp}} < \frac{r^{\alpha}(n^{\alpha-1} - 1)}{2}$

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

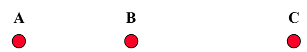
Minimum Energy in a Wireless Network

- 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:

$td^{\alpha}_{AB} + td^{\alpha}_{BC} + c$

Relay region

Relay region:

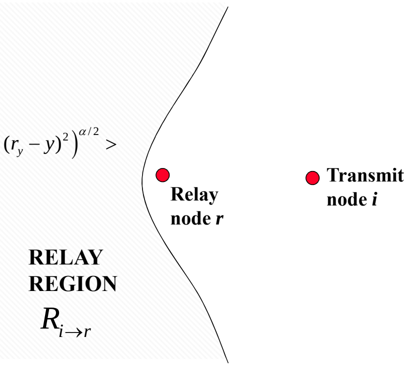
$$R_{i\to r} \equiv \{(x,y) \mid P_{i\to r\to(x,y)} < P_{i\to(x,y)}\}$$

We can expand this to:

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

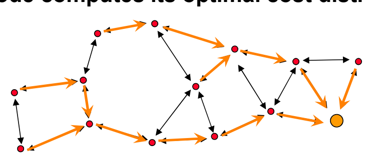
$$t\left((i_x - x)^2 + (i_y - y)^2\right)^{\alpha/2} - t\left((r_x - x)^2 + (r_y - y)^2\right)^{\alpha/2} >$$

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



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

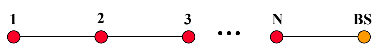


Load-balancing

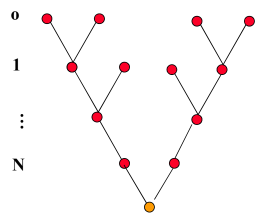
- Assumption: in a multi-hop many-to-one sensor network, the data collection follows a spanning tree.
- Power consumption due to transmission/reception grows exponentially from the leaves to the root of the tree
- Consequence: the power sources of the nodes close to the sink deplete faster. Since they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

Load-balancing

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

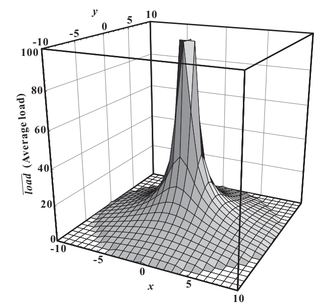
$F(d) \geq 2^d$

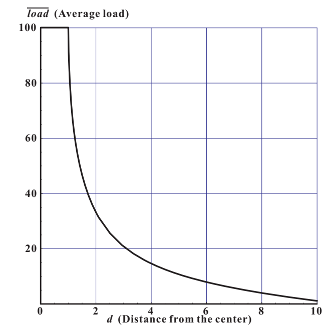
$P(d) \geq P_{tx} + 2^d (P_{tx} + P_{rx})$

P grows exponentially with distance from leaf node

Load balancing

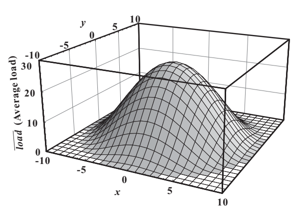
- Power consumption increases at least linearly when nodes are closer to the sink
- Typical case is much worse

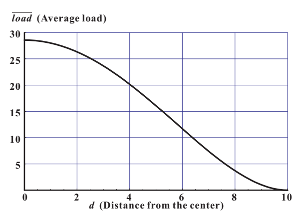




Use Mobility for Load-balancing

- 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





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

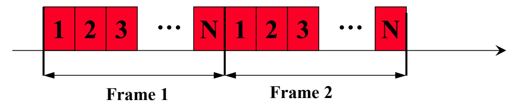
- MAC attributes:
  - » Collision avoidance
  - » Energy efficiency
  - » Scalability and adaptivity
- Nodes transmit very intermittently, but once a transmission is taking place, we must ensure that the intended receiver gets it.
- Current-consumption in receive state or in radio-on idle state are comparable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

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

Synchronous MACs

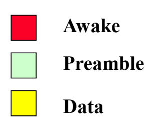
- TDMA (similar to cellular networks)

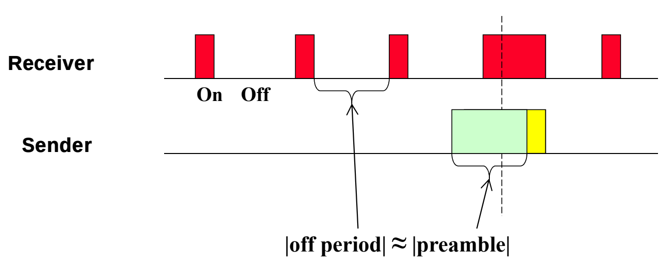


- Shortcomings
  - » Necessity to organize nodes in clusters and cluster hierarchies
  - » High control traffic cost
- Possible solution
  - » Each node maintains two schedules
    - – Its parent schedule
    - – The schedule it sets for its children
  - » Beacons are used to compensate for clock drifts

Asynchronous: B-MAC

- Asynchronous
- Low Power listening





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)

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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

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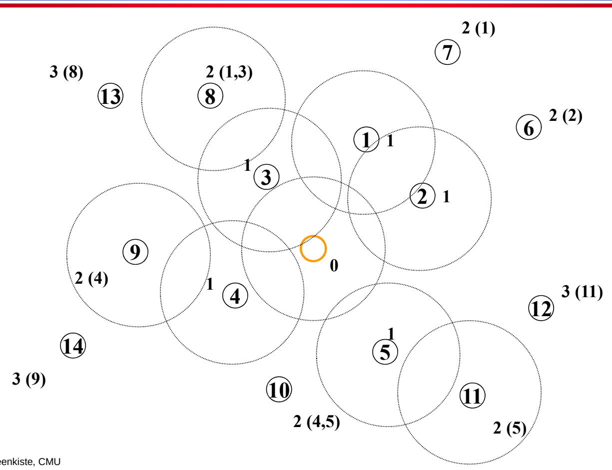
MintRoute : Root Beaconing



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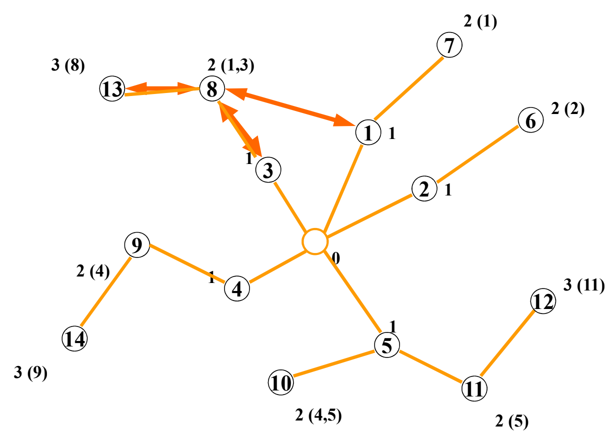
MintRoute : Link Estimation



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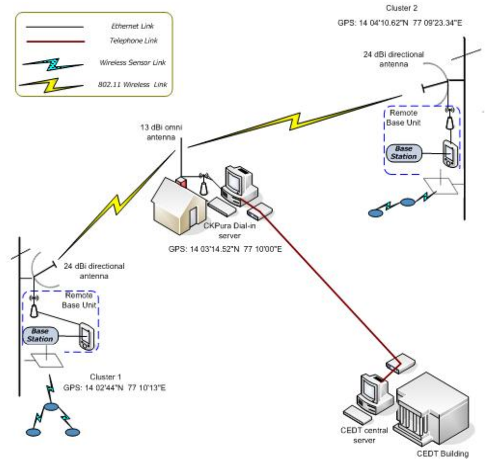
How Large can Sensor Networks Feasibly Grow?

- 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

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

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