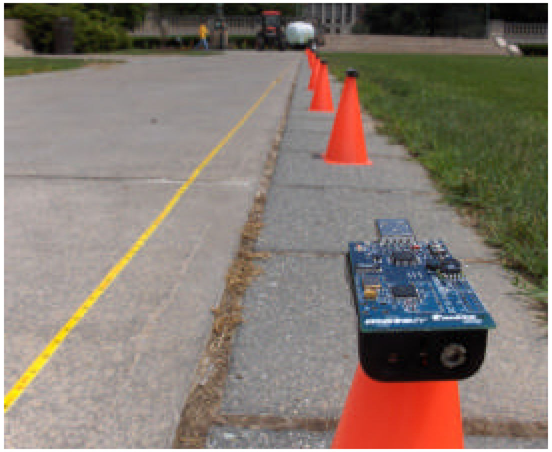
# Wireless Sensor Networks

Reading:

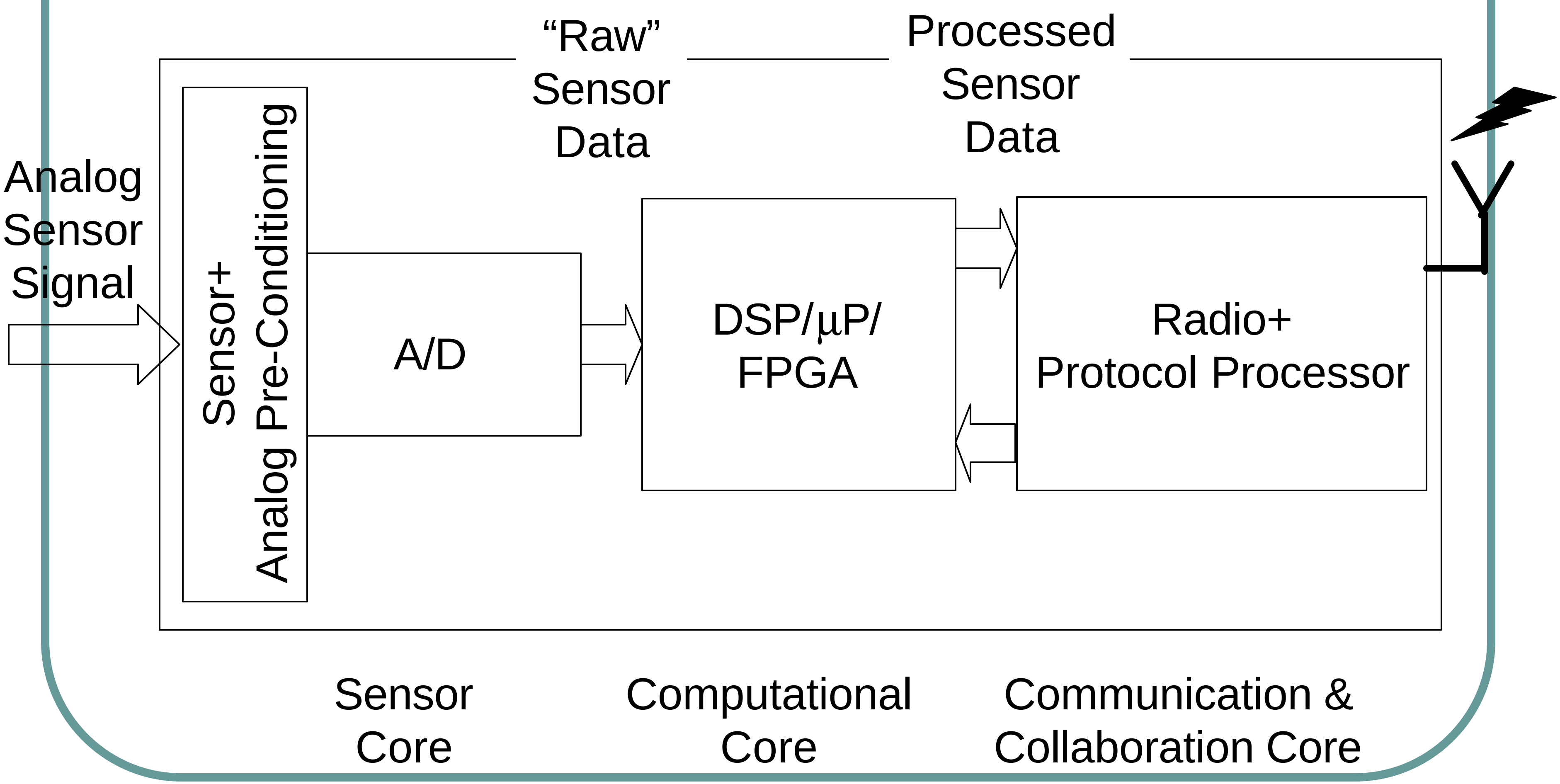
I. Akyildiz, W. Su, Y. Sankarasubramaniam and E. Cayirci, "A Survey on Sensor Networks," *IEEE Communications Magazine*, August 2002.

# Wireless Sensor Nodes

- Sensors monitor environment
  - Cameras, microphones, physiological, pressure, biological sensors, etc.
  - Sensor data limited in range and accuracy
- Micro-sensors
  - Sensor module (e.g., acoustic, seismic, image)
  - Digital processor for signal processing and network protocol functions
  - Radio for communication
  - Battery-operated



# Wireless Sensor Nodes



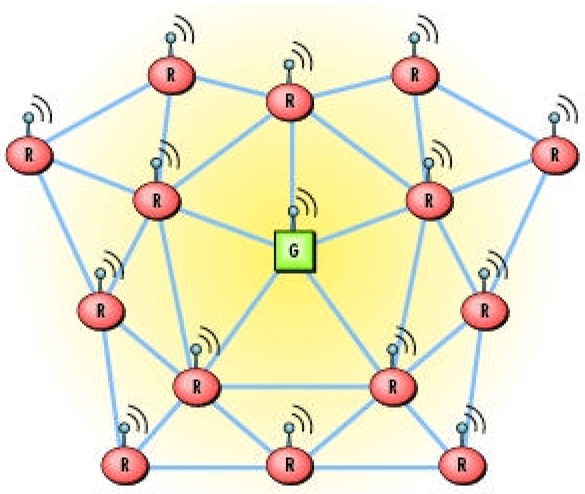



[http://mtlweb.mit.edu/researchgroups/icsystems/uamps/pubs/files/darpa_oct_01.ppt]

# Wireless Sensor Networks (WSNs)

Networks of distributed data sources that provide information about environmental phenomena to an end user or multiple end users

- Tens to thousands of nodes scattered throughout an environment
- Data routed via other sensors to
  - One or more sinks or base stations
  - Other sensors
- Unique characteristics
  - Ad hoc network
  - No end-to-end communication
  - Co-operative operation
  - Redundancy in information



# WSN Advantages

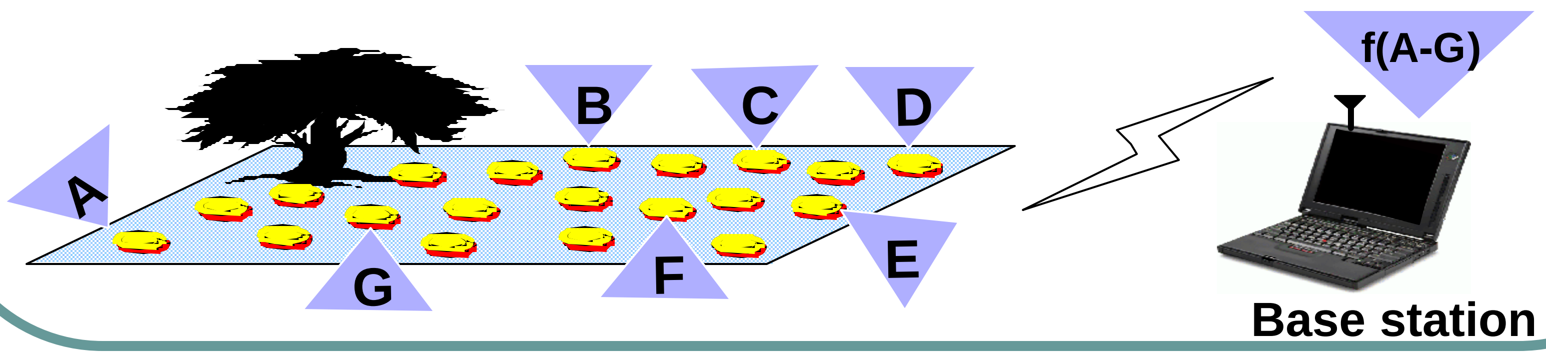
- Networking sensors enables
  - Extended range of sensing → improved quality
  - Fault tolerance due to redundancy in data from different sensors
  - Distributed processing of large amounts of data
  - Duty-cycling individual nodes
  - Scalability: quality can be traded for system lifetime
  - “Team-work”: nodes can help each perform a larger sensing task

# WSN Networking

- New wireless networking paradigm
  - Requires autonomous operation
  - Highly dynamic environments
    - Sensor nodes added/fail
    - Events in the environment
  - Distributed computation and communication protocols required

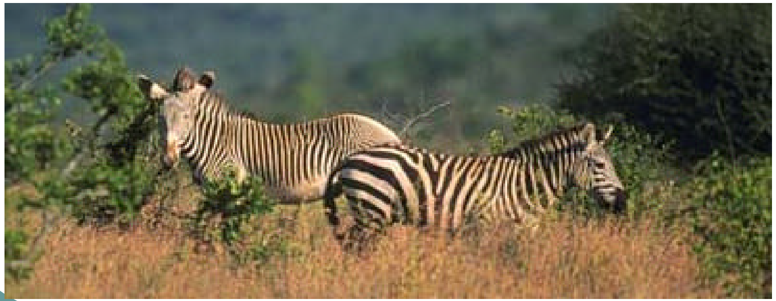
# Sample Applications

- Remote surveillance
- Research (e.g., tracking animals)
- Chemical/biological agent detection
- Medical/machine monitoring
- US military Sense and Respond Logistics
- Agriculture monitoring
- Psychological and behavioral studies



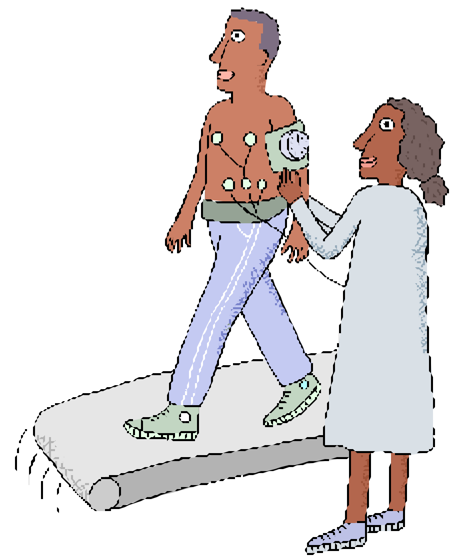
# Example Application: Environmental Monitoring

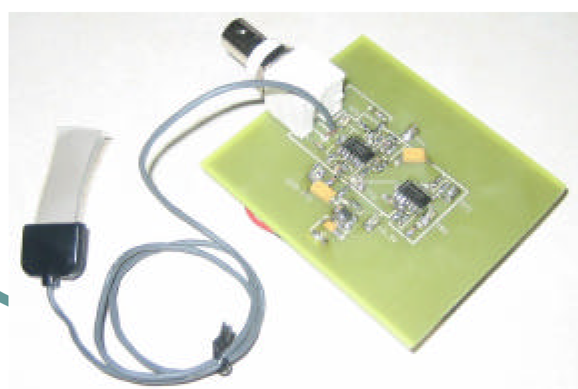
- Raw sensor data or high level descriptions about environmental phenomena
- Example projects
  - ZebraNet
  - Ecology of rare plants in Hawaii

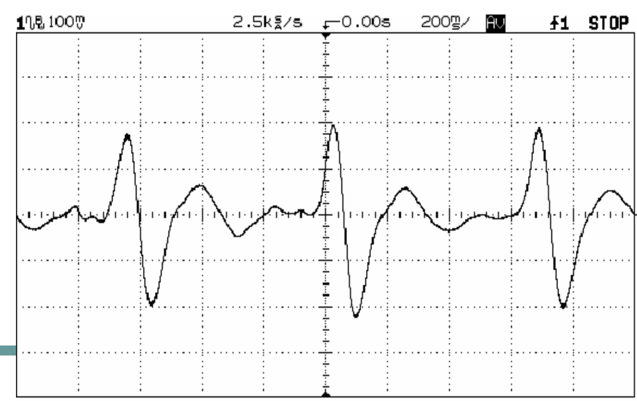


# Example Application: Health Monitoring

- Sensors monitor vital signs
  - Blood pressure, heart rate, EKG, blood O2
- Sense, process, understand, control
- Requires protocols that are
  - Reliable, flexible, scalable, secure





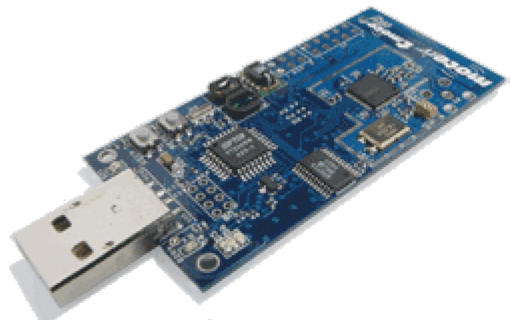


# Sensor Platforms

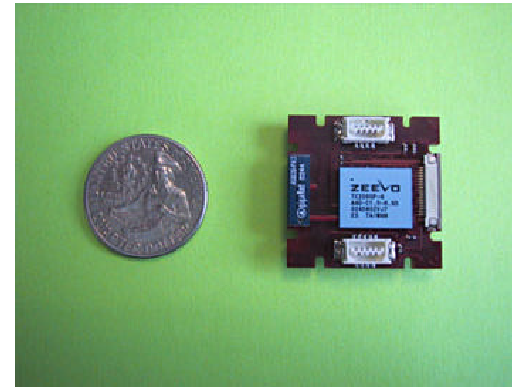
- Example platforms
  - MicaZ (Crossbow)
    - http://www.xbow.com/Products/Wireless_Sensor_Networks.htm
  - Tmote Sky (MoteIV)
    - http://www.moteiv.com/products-tmotesky.php
  - Intel Motes (Intel)
    - http://www.intel.com/research/exploratory/motes.htm
  - iBadge (UCLA)
    - http://nesl.ee.ucla.edu/projects/ibadge/default.htm
  - BTNode (ETH Zurich)
    - http://www.btnode.ethz.ch/
  - mAMPS (MIT)
    - http://mtlweb.mit.edu/researchgroups/icsystems/uamps/

# Sensor Platforms

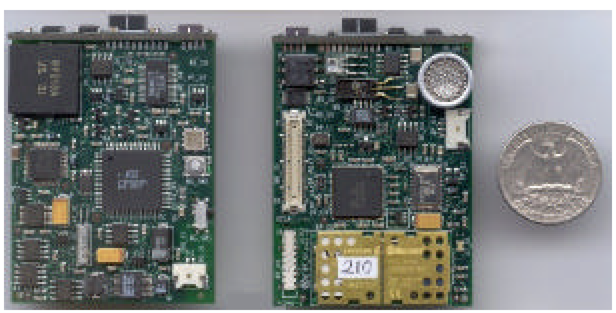

Crossbow MicaZ mote



MoteIV Tmote Sky

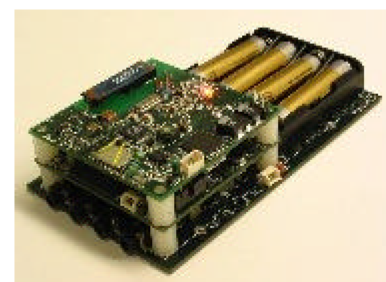


Intel mote



UCLA iBadge

ETH BTNode



MIT µAMPS-I

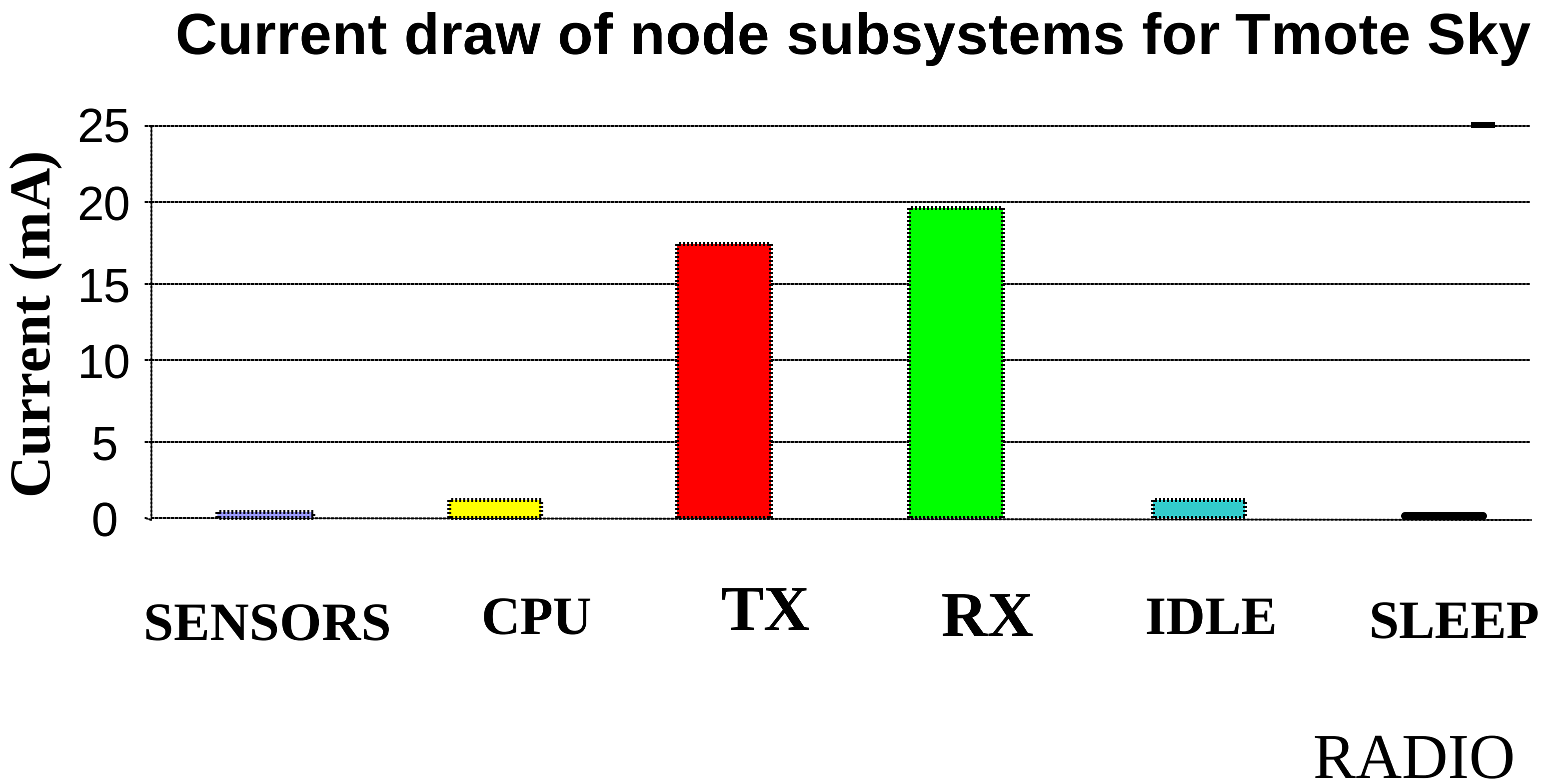
# WSN Limitations

- Communication
  - Bandwidth is limited and must be shared among all the nodes in the sensor network
  - Spatial reuse essential
  - Efficient local use of bandwidth needed

# WSN Limitations (cont.)

- Sensor energy
  - Each sensor node has limited energy supply
    - Nodes may not be rechargeable
    - Eventually nodes may be self-powered
  - Energy consumption in sensing, data processing, and communication
    - Communication often the most energy-intensive
    - For some sensors (e.g., imagers), sensing may also be energy-intensive
    - Must use energy-conserving protocols

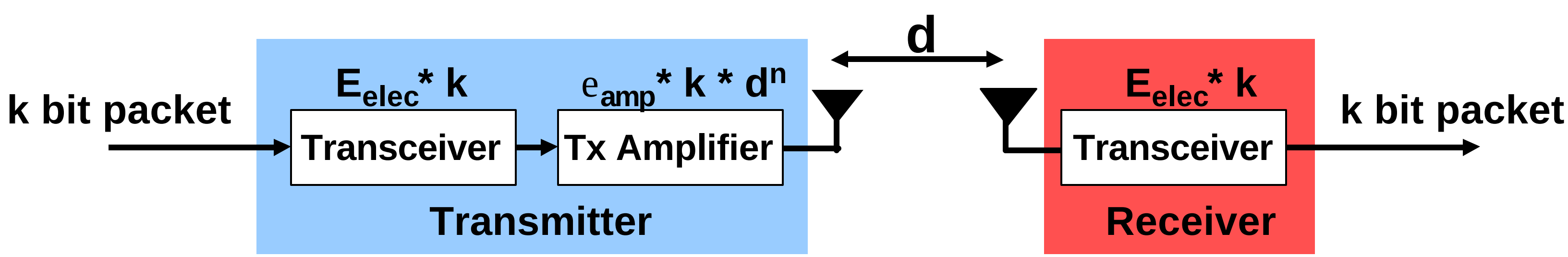
# Sensor Node Current Draw




- Operating voltage: 2.1 – 3.6 V

# Communication Module Energy Dissipation Model

- Transmitter dissipates energy for
  - Transceiver electronics (e.g., baseband processing)
  - Transmit amplifier
    - Fixed or variable transmit power
- Receiver dissipates energy for
  - Transceiver electronics



| General Ad Hoc Networks | Sensor Networks |
|---|---|
| Unreliable communication | Unreliable communication |
| Require self-configuration | Require self-configuration |
| Constrained energy and bandwidth | Very constrained energy and bandwidth |
| Small-scale | Large-scale |
| Typically mobile | Typically immobile |
| Competitive | Cooperative |
| One-to-one traffic pattern | Many-to-one traffic pattern |
| Address-centric | Data-centric |
| QoS: delay, packet drop threshold, etc | Application-specific QoS |

# Design Factors

- What are the important features of WSNs?
- Fault tolerance/reliability
  - Network should be robust to individual node failures
  - Failures due to running out of energy, hardware failures, malicious intercept of sensor, etc.
- Cost
  - Must have cheap sensors

# Design Factors (cont.)

- Scalability
  - Protocols must scale to thousands or millions of sensor nodes
  - Requires intelligent management of high densities of nodes
- Energy consumption
  - Sensor functions: sensing, communication, data processing
  - All require energy
  - Lifetime a function of sensors’ remaining energy

# Design Factors (cont.)

- Topology
  - Deployment
    - Random or deliberate placement of nodes
    - Fixed locations or can place optimally
  - Changes in topology during network operation
    - New nodes added to the system
    - Nodes failing
    - Environmental changes

# Evaluating WSNs

- What are the performance metrics for WSNs?
- System lifetime
  - E.g., time until network partition
  - E.g., time until probability of missed detection exceeds a threshold
- Quality of result of sensor network
  - Application-specific measure
  - Latency of data transfer
  - SNR of aggregate data signal
  - Probability of missed detection or false alarm
  - Coverage probability

# Evaluating WSNs (cont.)

- Tradeoffs can be made among network parameters
  - E.g., can reduce quality of result of sensor network to increase system lifetime

# Taxonomy of WSN Architectures

- In what ways do sensor networks for various applications differ?
- Data sink(s)
  - Embedded within network
  - Located on network edge or outside network
  - Mobile access point
  - One or several sinks

# Taxonomy (cont.)

- Sensor mobility
  - Often assume stationary sensors
  - Some projects use mobile sensors
    - ZebraNet
    - Military operations
    - Self-propelled sensors
    - Robots
    - Medical monitoring

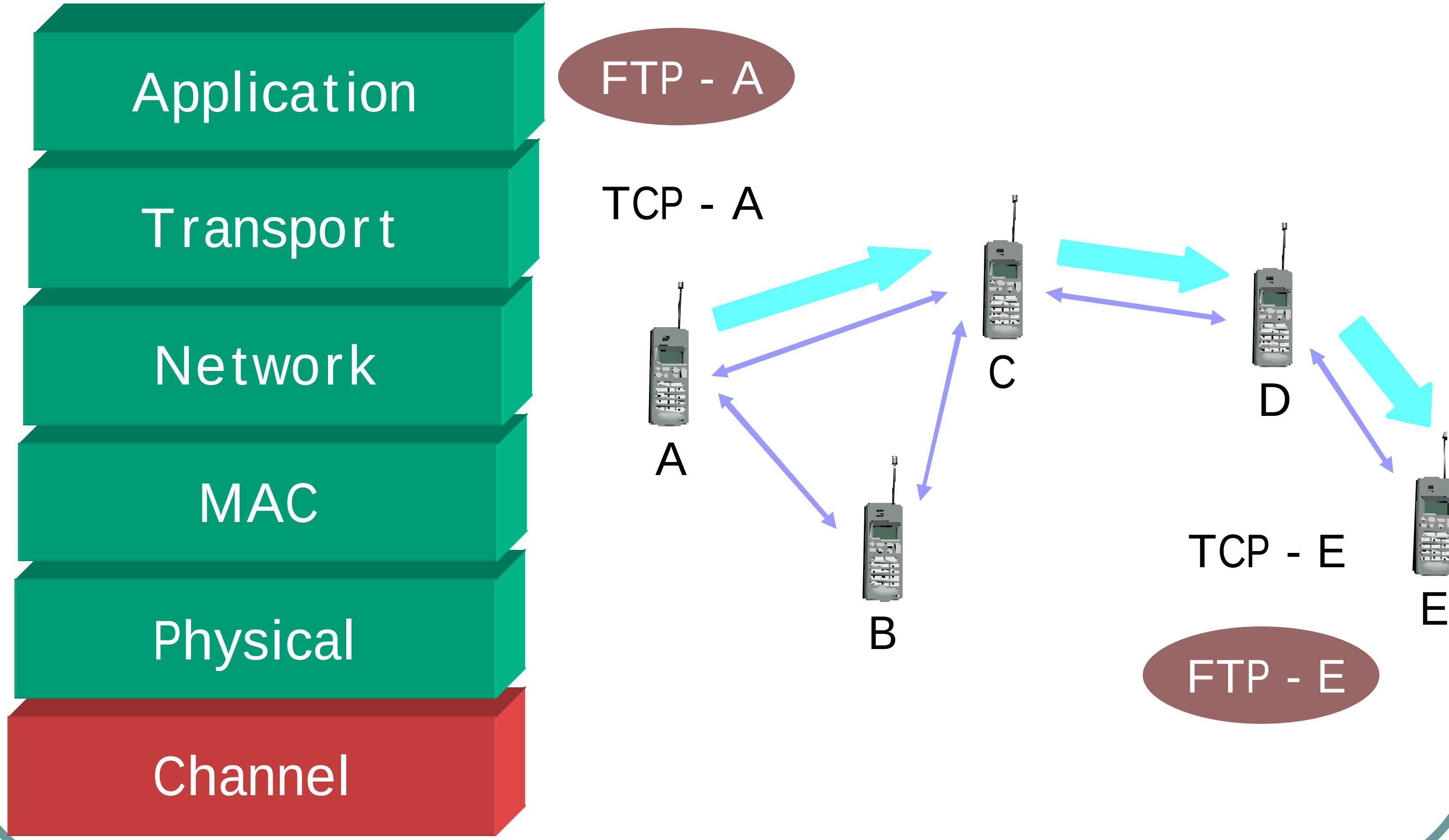
# Taxonomy (cont.)

- Sensor resources
  - Memory
  - Processing
  - Transmit power (fixed vs. variable)
  - Location/density
- Traffic patterns
  - Event-driven applications
  - Continuous data generation
  - Query-driven applications

# WSN Architectures

- Several different architectures proposed for WSNs
- Traditional layered architecture
  - Benefits from modularity and existing protocols
- Cross-layer architectures
  - Provides greater QoS and longer lifetime
- Sensor network architecture (SNA)
  - Provides link layer and hardware platform abstractions
- Information-sharing architecture
  - Provides layered protocols with ability to share information for cross-layer optimizations

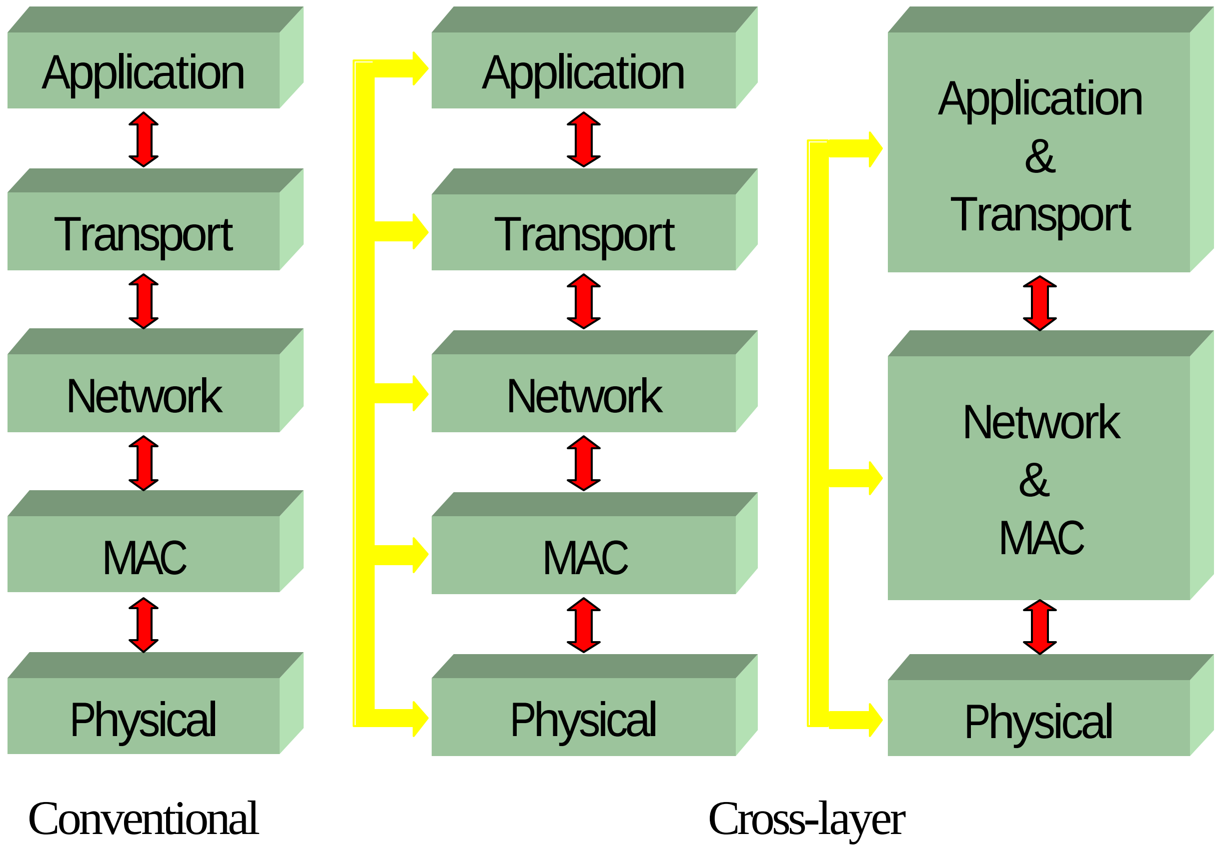
# Traditional Layered Architecture



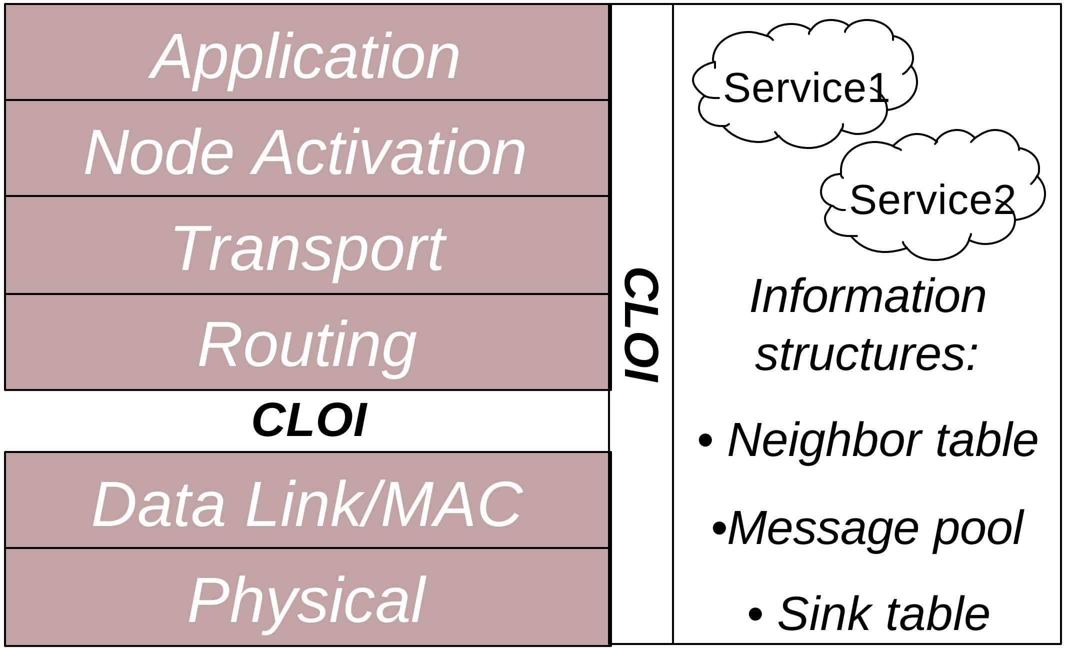
# Cross-layer Definitions

- Two or more layers cooperate to improve network's response
- Layer fusion: operations from two or more layers performed jointly
- Information sharing: several layers share information
- Former shows surprisingly little improvement in face of other design optimizations

# Cross-layer Architectures



# X-lisa: X-layer Information Sharing Architecture




- Maintain layered stack but enable *information sharing*
- Cross-layer optimization interface (CLOI)
  - Repository for information that can be used for optimizations
  - Provides services

# Design Issues

- New protocols needed
- MAC
  - Cooperative nature of sensor networks
    - Fairness not an issue
    - Sensors should not compete for limited bandwidth
  - Exploit traffic patterns
  - Energy efficiency extremely important
    - Reduce idle listening
    - Reduce unnecessary reception

# Design Issues (cont.)

- Routing
  - Different traffic models
  - Data dissemination rather than point-to-point routing
  - Data-centric rather than address-centric
  - Location-aware sensors
  - Resource-aware routing needed
  - Exploit local aggregation
  - Time-varying channels leads to necessity for dynamic routing approaches

# Design Issues (cont.)

- Topology control
  - Reduce idle power consumption → nodes sleep
  - Create fully-connected dominating set from active routers
- Transmission power control
  - How to avoid "hot spot" problem?
  - Provide connected network

# Design Issues (cont.)

- QoS Management
  - QoS determined by content of data rather than amount
  - Transport layer
    - Intelligent congestion management
    - Throttle back irrelevant data rather than each node's sending rate
  - Coverage
    - Ensure the correct sensors provide data
    - K-coverage: each location monitored by at least K sensors

# Design Issues (cont.)

- Time synchronization
  - Very important in sensor networks
  - Needed to determine if event sensed by two sensors is in fact the same event
  - Needed to determine object speed
  - Approaches
    - GPS – expensive, not energy-efficient
    - NTP (used in computer networks) – not enough precision
    - Post-facto synchronization– using stimulus arrival time to synchronize nodes
    - Multi-hop time synchronization
    - Several other approaches being researched

# Design Issues (cont.)

- Localization
  - Important for same reasons as time synchronization
  - Often times, only relative position is necessary
    - GPS is unattractive for energy reasons
    - RSSI often used to infer distances
    - Time of Arrival (ToA)
    - Time Difference of Arrival (TDoA)
    - Angle of Arrival (AoA)

# Design Issues (cont.)

- Localization (cont.)
  - Sensor can find its own location using received beacons
  - Sensor can have other nodes measure its location
    - Sensor sends beacon message and neighbors use trilateration based on signal strength measurements
  - Problem – small scale fading

# Routing Protocols

# Sensor Network Routing

- Energy-efficiency even more important than in MANETs
- “Resource”-aware, data-centric routing needed
  - Reduce power consumption
  - Distribute energy load (maximize network lifetime)
  - Take into account sensors’ importance to application
- May be tightly coupled with protocols from different layers
  - Take advantage of data fusion opportunities
  - Cross-layer architectures

# Taxonomy of Routing Protocols

- Traffic patterns
  - One-to-one: data to sink
  - Many-to-one: all sensors' data to sink
  - One-to-many: sink commands to sensors
  - Many-to-many: data dissemination, flooding, gossiping
- Resource-aware routing
  - Energy-aware routing
  - Fidelity-aware routing
- Data-centric routing
  - SPIN
  - Directed diffusion
  - Rumor routing

# Taxonomy (cont.)

- Geographic routing
  - GFG
  - GPSR
  - TBF
  - RBF
- Clustering
  - LEACH
  - HEED
- Querying a distributed database
  - TAG
  - TinyDB
  - GHT

# Resource-aware Routing

- Consider each sensor's resources for routing decisions
  - Energy resources
  - Sensing resources
  - Others?
- Energy-aware routing
  - Balance power consumption so nodes fail uniformly
  - Node costs and link costs considered
- Fidelity-aware routing
  - Consider importance of node to sensing application
  - Route around "important" sensors
  - Requires local communication to learn importance

# Energy-aware Routing

- Consider energy resources of each sensor
- Balance energy consumption
- Energy-aware routing metric
  - For packet j sent from n1 to nk, minimize

$$c_j = \sum_{i=1}^{k-1} \frac{1}{1 - g(z_i)}$$

  - g(zi) = normalized remaining lifetime corresponding to node ni's battery zi

# Energy-aware Routing (cont.)

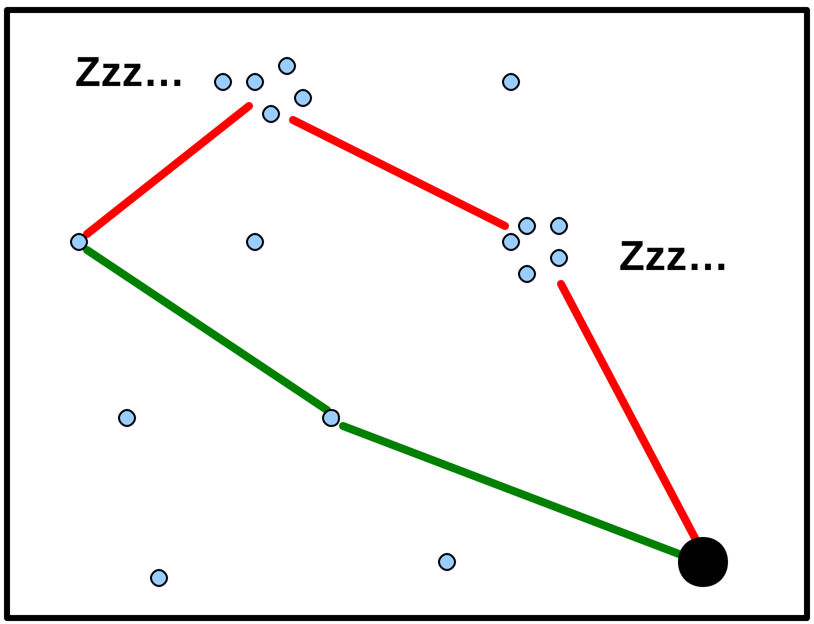
- Can also use routing cost that is sum of individual link costs

$$c_{ij} = e_{ij}\,\underline{E}_{i}^{-x_2} E_i^{x_3}$$

- $e_{ij}$ = energy to transmit from node i to node j
- Ei = residual energy of node i
- Ei = initial energy of node i

# Fidelity-aware Routing

- Rather than ensuring uniform energy usage, consider importance of sensor to application
  - Sensors must determine “application cost”
  - E.g., “Redundant” sensors less important




Possible routes:

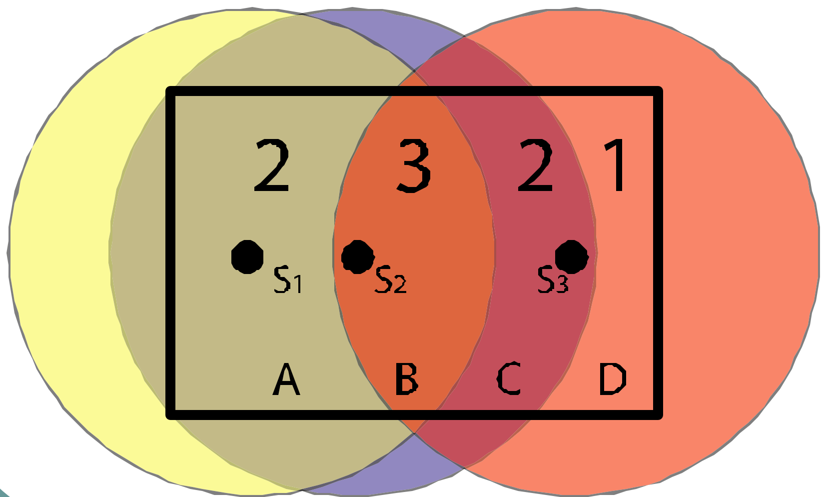
Shortest path

Path of most sensing redundancy

# Application Cost: Coverage

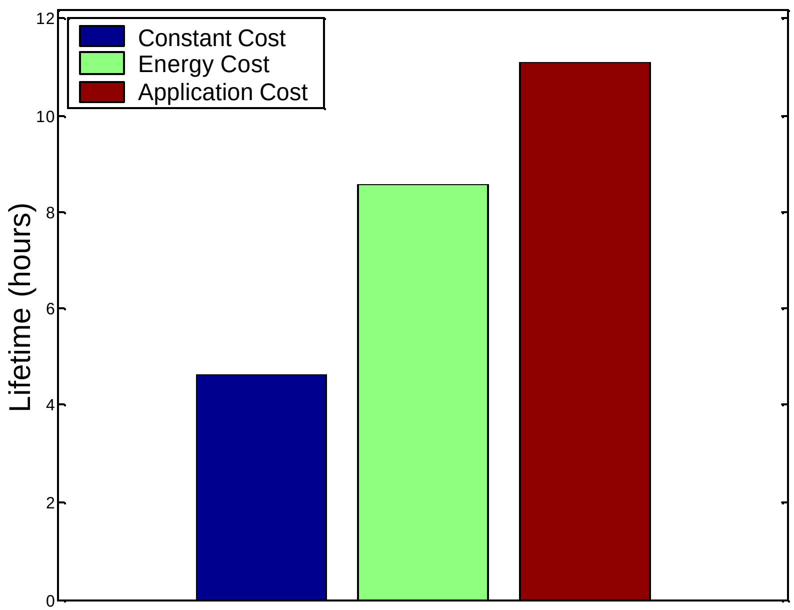
- Each subregion characterized by unique sensor set
  - Important factor: energy of sensors in set
- Intuitively, sensors equivalent if they cover equivalent regions

$$C_{\text{app\_cost}}(S_i) = \int_{R(S_i)} \frac{dx}{e(x)} = \int_{R(S_i)} \frac{dx}{\sum_{S_j : x \in R(S_j)} e_{res}(S_j)}$$



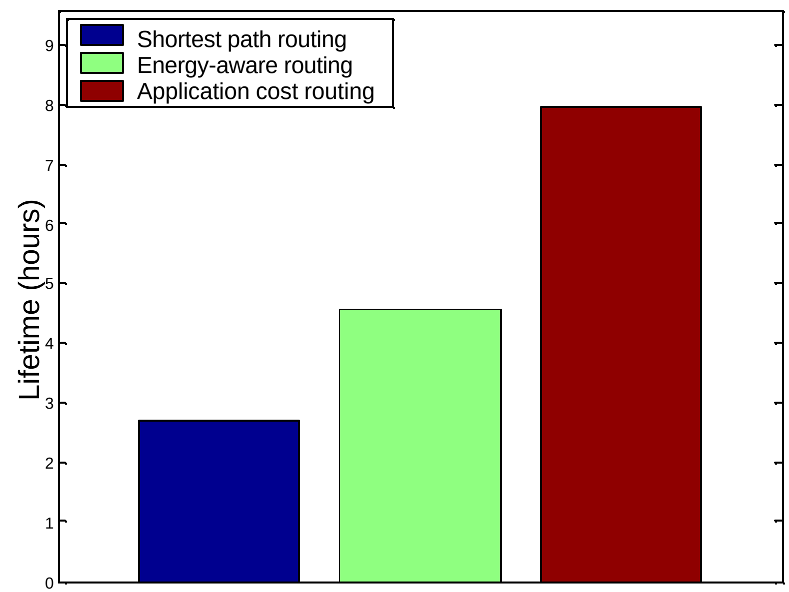
# Comparison of Fidelity-aware and Energy-aware

## Balanced Energy




Application cost: 56% improvement over energy cost

## Unbalanced Energy



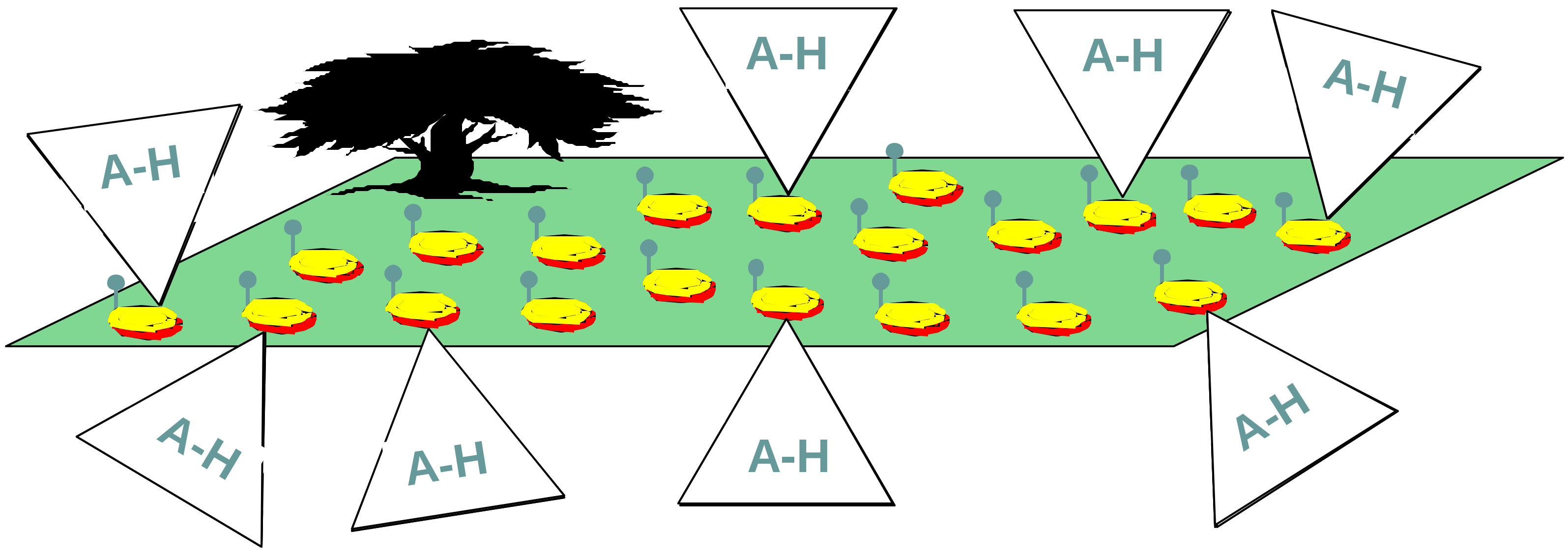

Application cost: 75% improvement over energy cost

# Data-Centric Routing

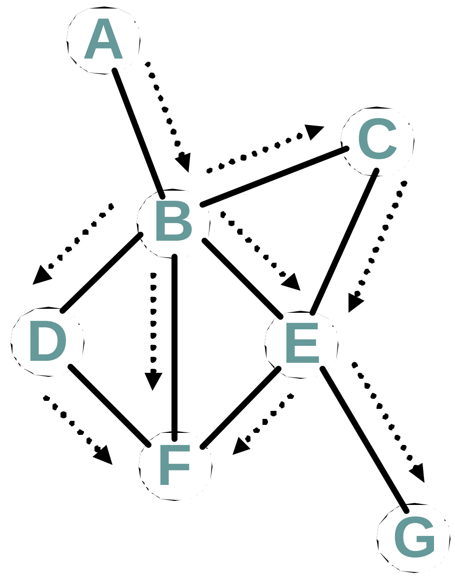
- Aggregate data or information from data important
  - Individual data items not important
- Sensor nodes themselves less important than data
- Queries posed for specific data rather than data from a particular sensor
- Routing exploits the requirement for aggregate data rather than individual data
- Example protocols
  - SPIN
  - Directed Diffusion
  - Rumor Routing

# Network-wide Data Dissemination

- Problem: information dissemination



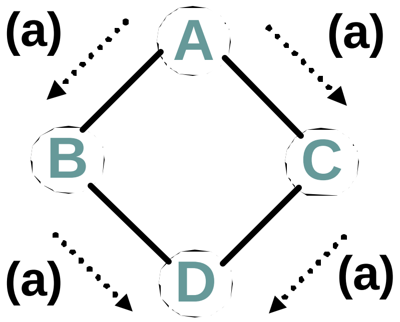
# Flooding



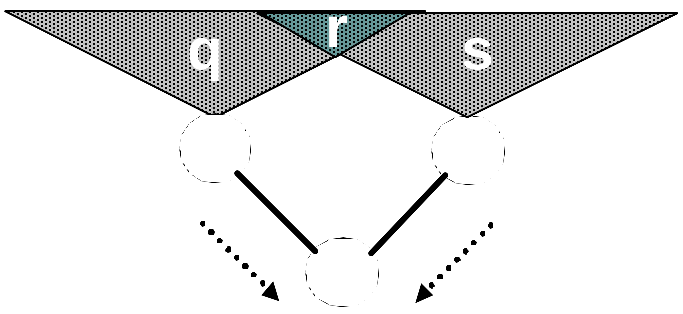

- Flooding
  - Send to all neighbors
  - E.g., routing table updates

# Resource Inefficiencies

- Implosion




- Data overlap

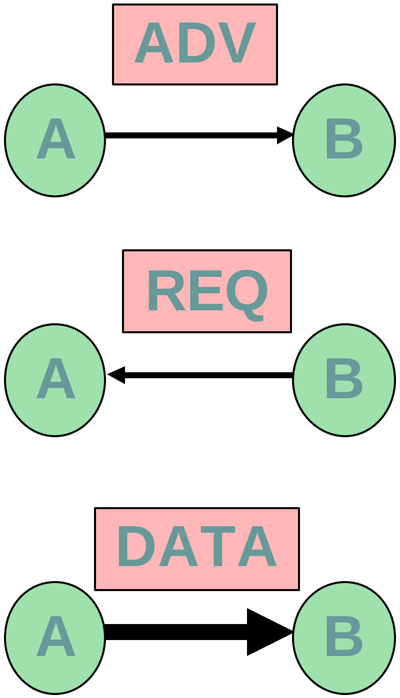



- Resource blindness

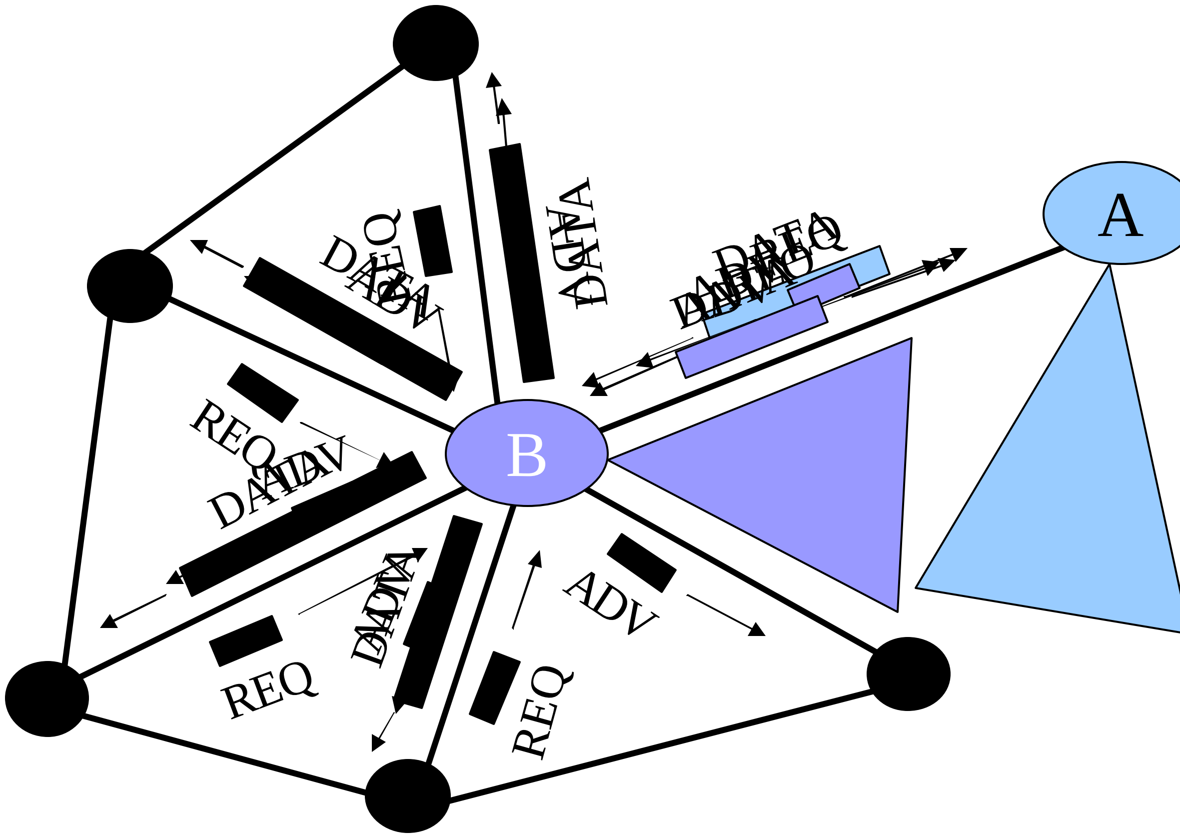
# SPIN Family

**Sensor Protocol for Information via Negotiation**

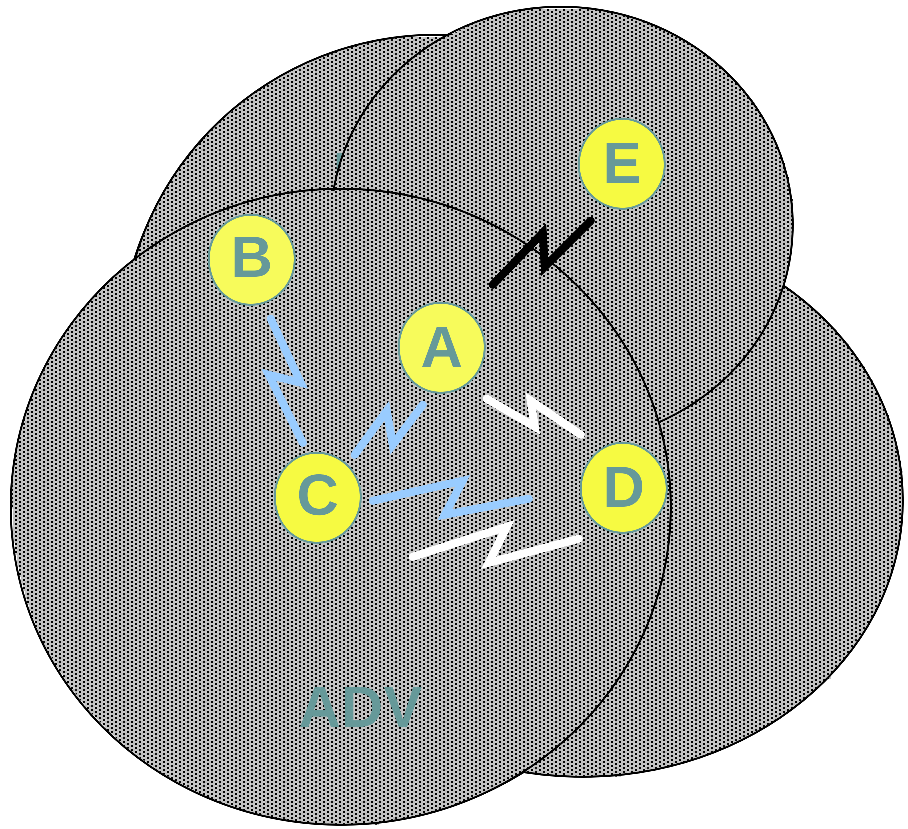
- Data negotiation
  - Meta-data (data naming)
  - Application-level control
  - Model “ideal” data paths
- SPIN messages
  - ADV- advertise data
  - REQ- request specific data
  - DATA- requested data
- Resource management



# SPIN Example



# SPIN Example 2

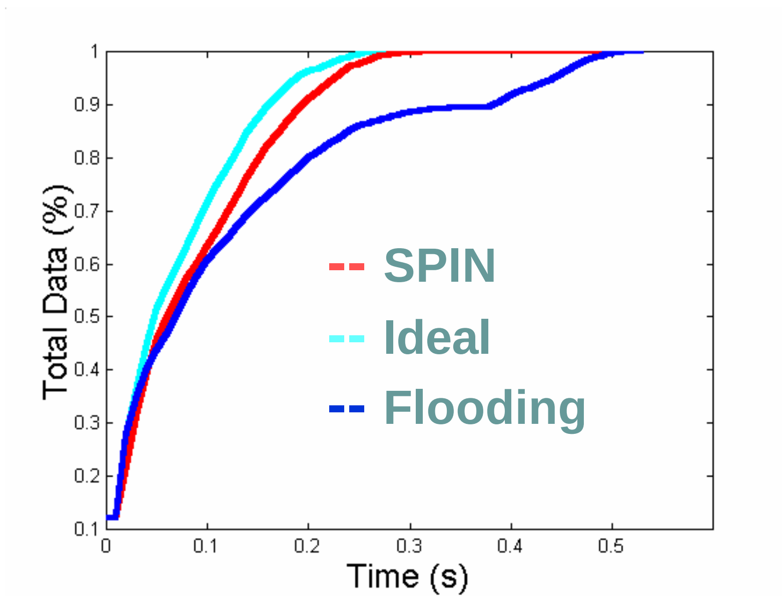


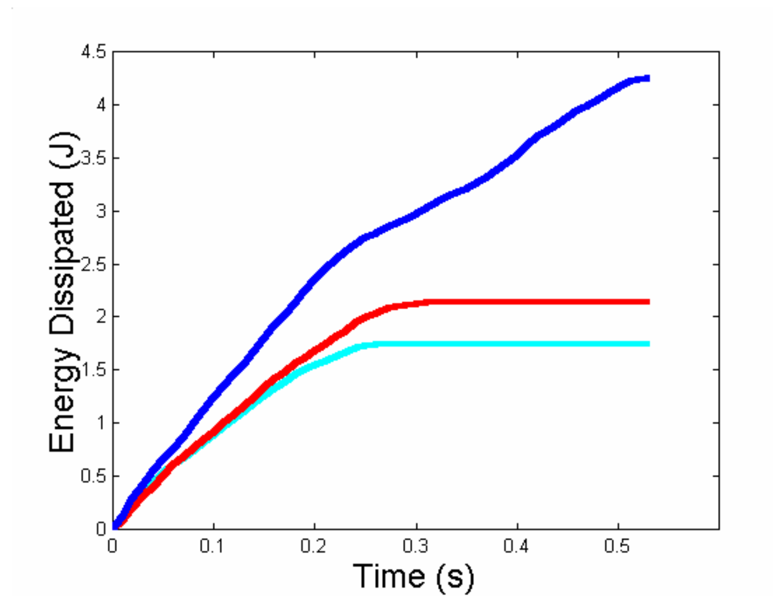

A **Nodes with data**

A **Nodes without data**

A **Nodes waiting to transmit REQ**

# SPIN Performance




- SPIN
  - Converges quicker than flooding
  - Reduces energy by 50% compared with flooding
  - Meta-data negotiation successful in broadcast

# Directed Diffusion

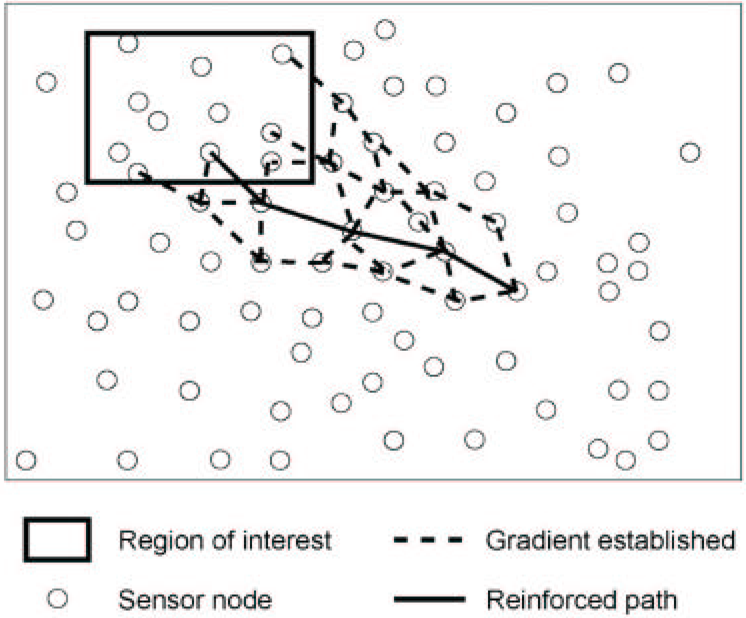
- Abstraction that tries to describe communication patterns underlying many localized algorithms
- Data named with attribute-value pairs
- Nodes that want data express interests based on the predefined attributes
- Interests disseminated throughout network
- Interests diffuse to correct area
  - Intermediate nodes propagate interests based on the contents of the interest
  - E.g., interest for data from location (x,y)
  - Interests may be propagated to multiple neighbors for robustness

# Directed Diffusion (cont.)

- Gradients set up that draw events of interest back to originating node
  - Strength of gradient depends on quality of routing path
  - Application-specific meaning to a gradient
- Interests/data propagated along routes with strong gradients
  - Good routes inherently reinforced
  - Creates low-energy routing of data
- Data aggregation and caching performed in network
  - Further reduces node energy dissipation

# Example: Animal Monitoring

- Interested in receiving data about all 4-legged creatures in area
- Specify desired data rate
- Query/interest
  - Type=four-legged animal
  - Interval=20ms (event data rate)
  - Duration=10 seconds (t to cache)
  - Rect=[-100, 100, 200, 400]
- Reply
  - Type=four-legged animal
  - Instance = elephant
  - Location = [125, 220]
  - Intensity = 0.6
  - Confidence = 0.85
  - Timestamp = 01:20:40
- Attribute-Value pairs → no advanced naming scheme



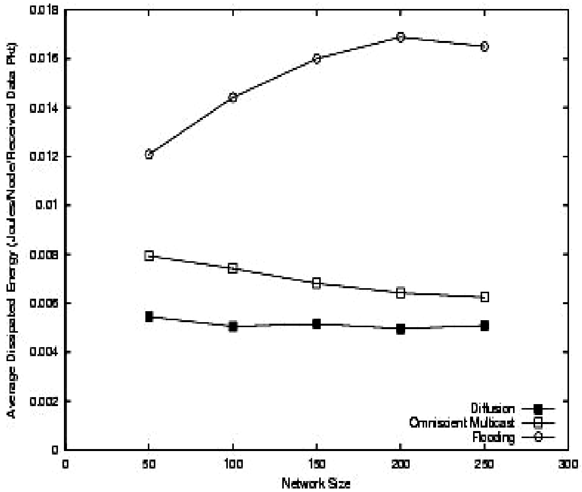
# Design Considerations

| Diffusion element | Design Choices |
|---|---|
| Interest Propagation | • Flooding<br>• Constrained or directional flooding based on location<br>• Directional propagation based on previously cached data |
| Data Propagation | • Reinforcement to single path delivery<br>• Multipath delivery with selective quality along different paths<br>• Multipath delivery with probabilistic forwarding |
| Data caching and aggregation | • For robust data delivery in the face of node failure<br>• For coordinated sensing and data reduction<br>• For directing interests |
| Reinforcement | • Rules for deciding when to reinforce<br>• Rules for how many neighbors to reinforce<br>• Negative reinforcement mechanisms and rules |

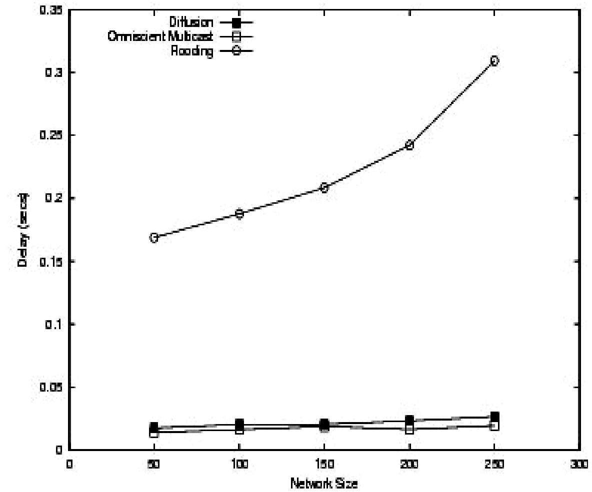
**Figure 3: Design Space for Diffusion**

[http://www.isi.edu/scadds/projects/diffusion.html]

# DD Performance




(a) Average dissipated energy




(b) Average delay

[http://www.isi.edu/scadds/projects/diffusion.html]

# Rumor Routing

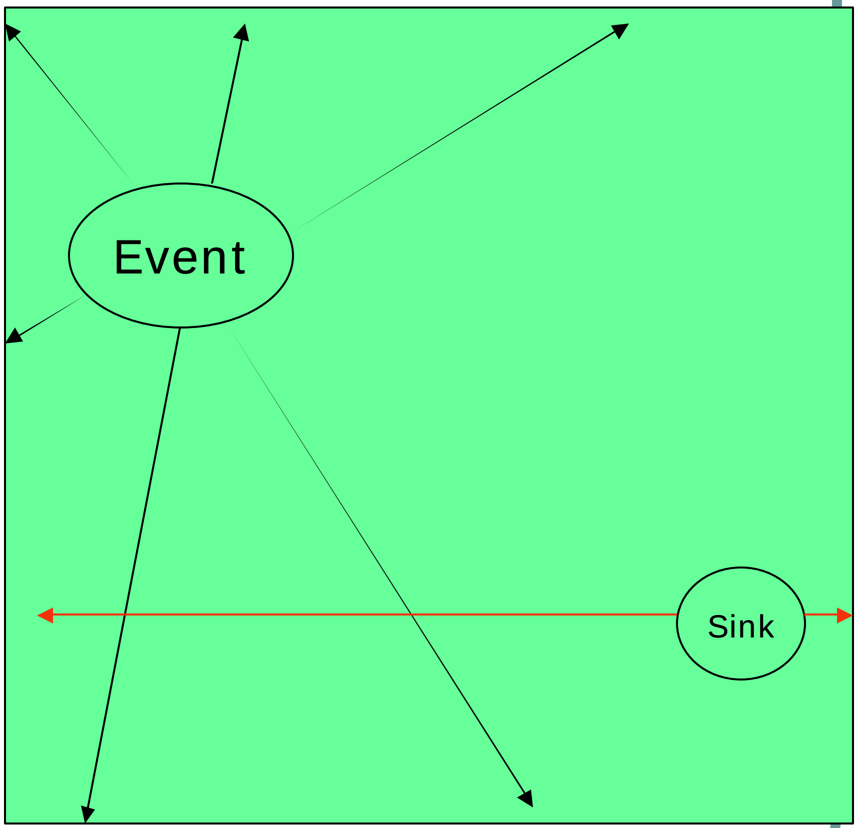
- In query-based networks, different techniques for routing data and queries
  - Query flooding
    - Expensive for large query/event ratio
    - Allows for optimal reverse path setup
    - Gossiping scheme can be use to reduce overhead
  - Event Flooding
    - Expensive for low query/event ratio
  - Note
    - Both of them provide shortest delay paths

# Rumor Routing (cont.)

- Alternative: Rumor Routing
  - Designed for query/event ratios between query and event flooding
  - Motivation: sometimes non-optimal route is fine
  - Advantages
    - Tunable best effort delivery
    - Tunable for a range of query/event ratios
  - Disadvantages
    - Optimal parameters depend heavily on topology (but can be adaptively tuned)
    - Does not guarantee delivery

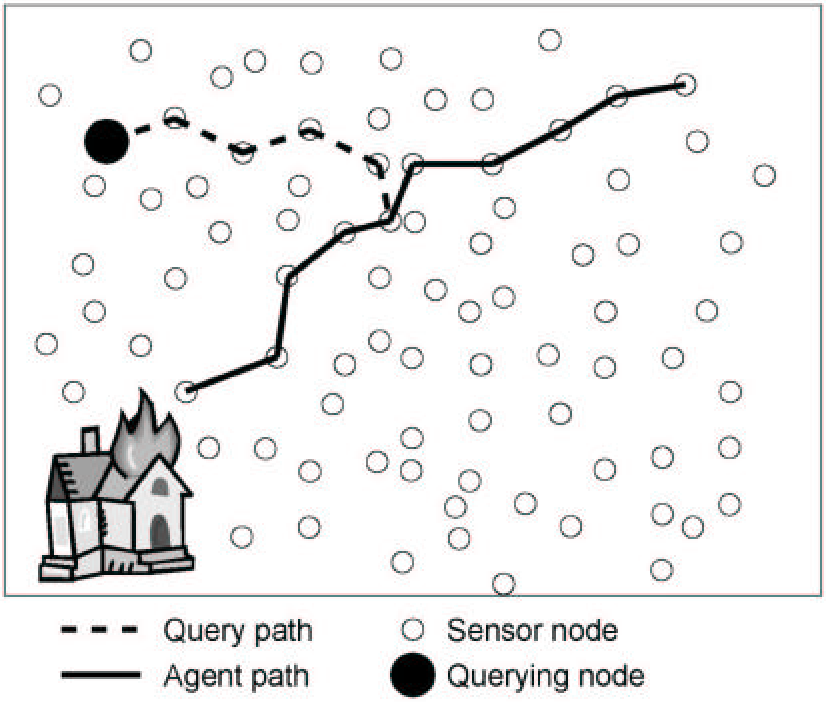
# Basis for Algorithm

- Observation
  - Two lines in a bounded rectangle have a 69% chance of intersecting
- Idea
  - Create set of straight line gradients from event
  - Send query along a random straight line from sink
- What if this line is not really straight?

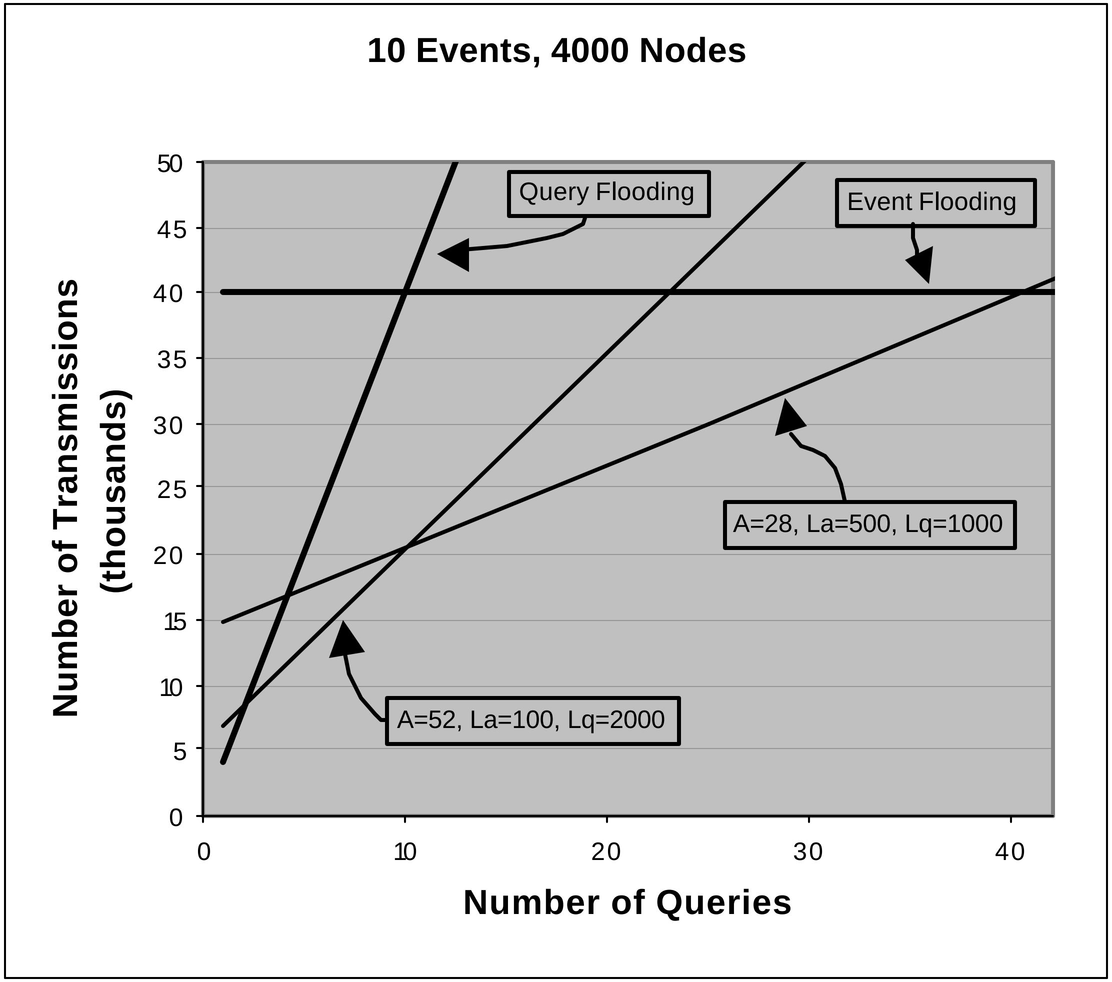


# Creating Paths

- Nodes with data send agents
  - Agents leave routing info t event as state in intermediate nodes
- Agents attempt to travel in a straight line
- If an agent crosses a pat to another event, it begir to build the path to both
- Agents also optimize paths if they find shorter ones



# Rumor Routing Performance




[http://www.cse.nd.edu/~surendar/conferences/wsna02/papers/p22-braginsky.pdf]

# Observations

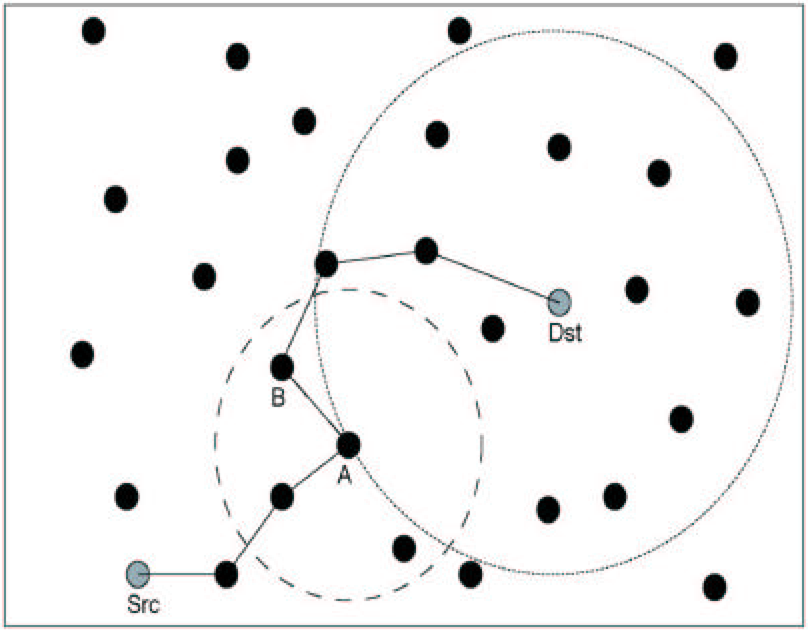
- Wide range of parameters allow for energy savings over simple alternatives
- Optimal parameters depend on
  - Network topology
  - Query/event distribution and frequency
- Algorithm very sensitive to event distribution
- Fault tolerance
  - After agents propagated paths to events, some nodes were disabled
  - Delivery probability degraded linearly up to 20% node failure, then dropped sharply

# Geographic Routing

- Sensors often know location
- Use location information to get data/queries to particular part of network
- Geographic forwarding reduces
  - Routing overhead
  - Memory utilization
- Example protocols
  - GFG
  - GPSR
  - TBF
  - RBF

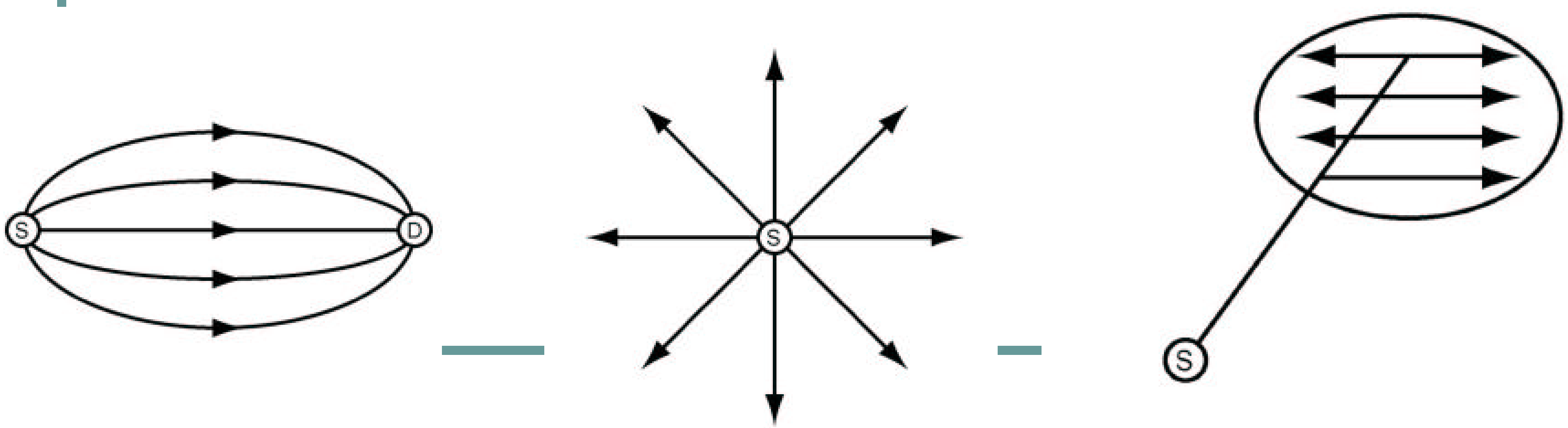
# Greedy-FACE-Greedy (GFG) and Greedy Perimeter Stateless Routing (GPSR)

- Greedy geographic forwarding algorithm
  - Forward data to node's neighbor that makes most progress towards destination
  - Must keep track of neighbors' locations
- Obstacles can cause problems
  - Use "right hand rule" routing around holes



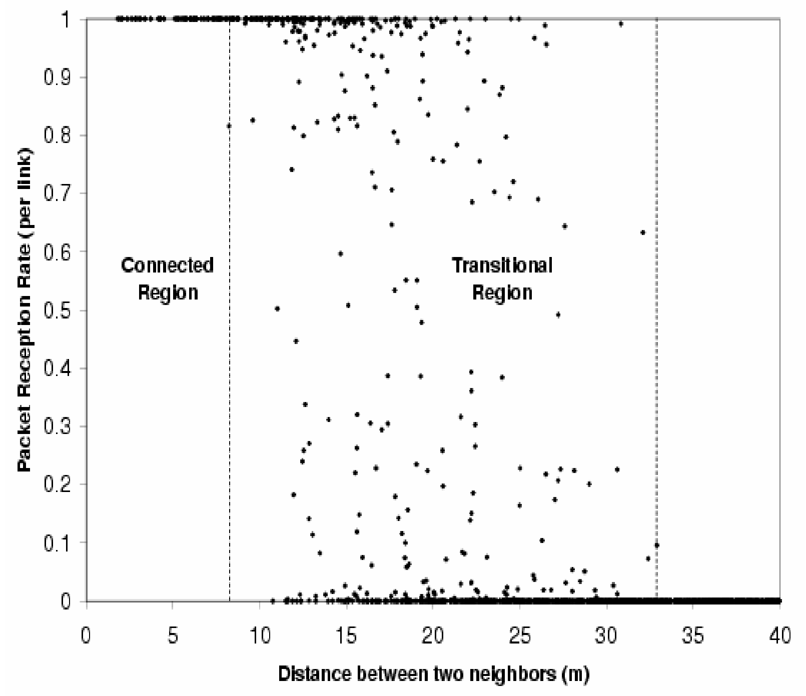
# Trajectory Based Forwarding (TBF)

- Similar to GFG/GPSR but allow source-specified trajectories for routes
- Enables
  - Multipath routing for added resilience
  - Spoke broadcasting
  - Broadcast to remote subregion



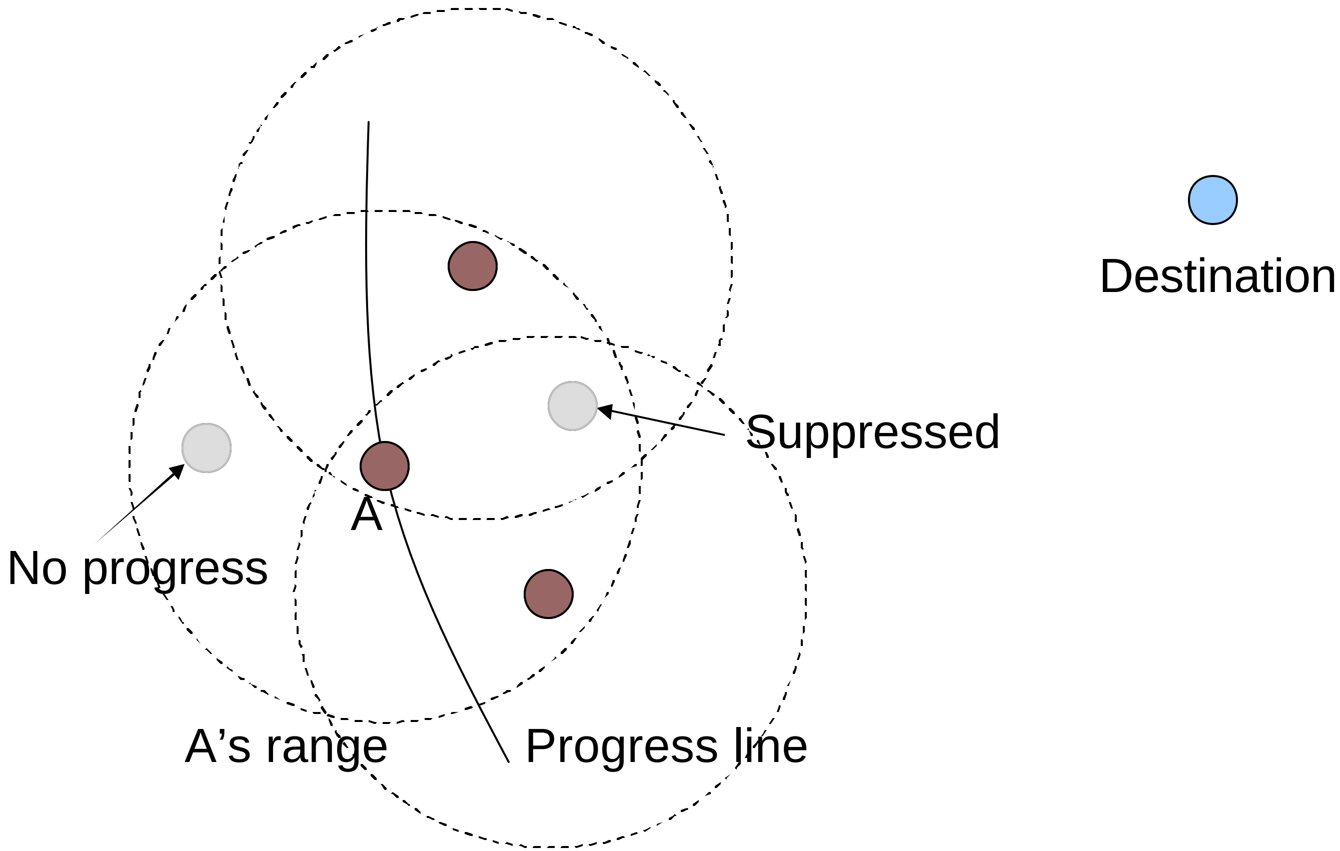
# Receiver-based Forwarding (RBF)

- Receivers determine whether or not to forward
  - Ensures good links selected for forwarding data
- RBF protocol
  - Sender broadcasts
  - Receiver determines if elligible (progress)
  - Receiver sets a timer for retransmission
  - If another retransmission is heard, cancel timer
  - Keep messages heard in a cache



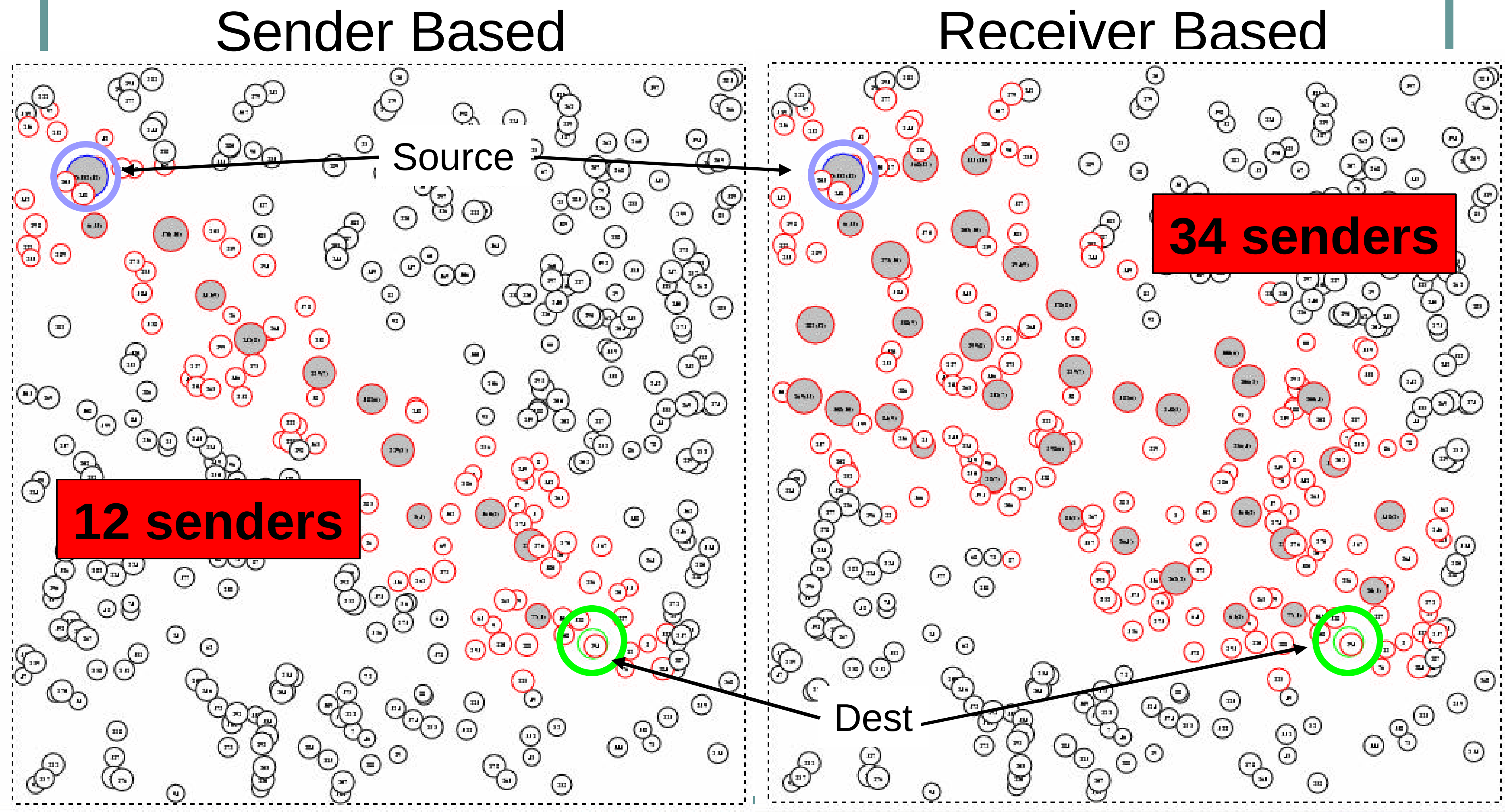

[http://oasis.cs.berkeley.edu/retreats/jan2005/talks/fonseca.ppt]

# RBF Protocol




[http://oasis.cs.berkeley.edu/retreats/jan2005/talks/fonseca.ppt]

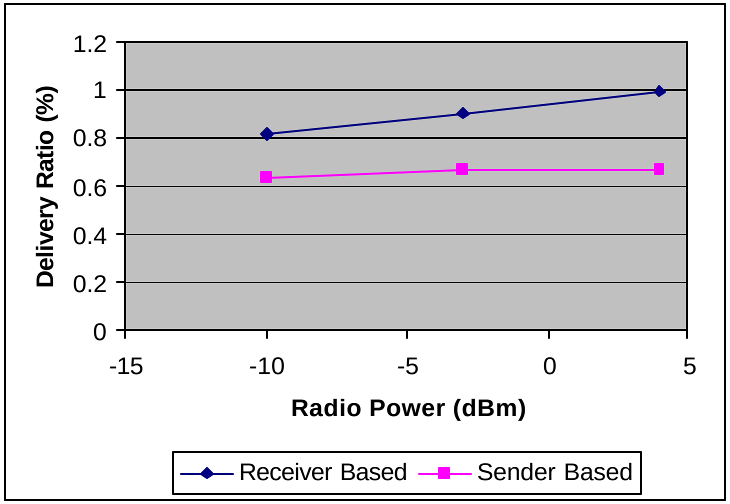
# Sample Routes



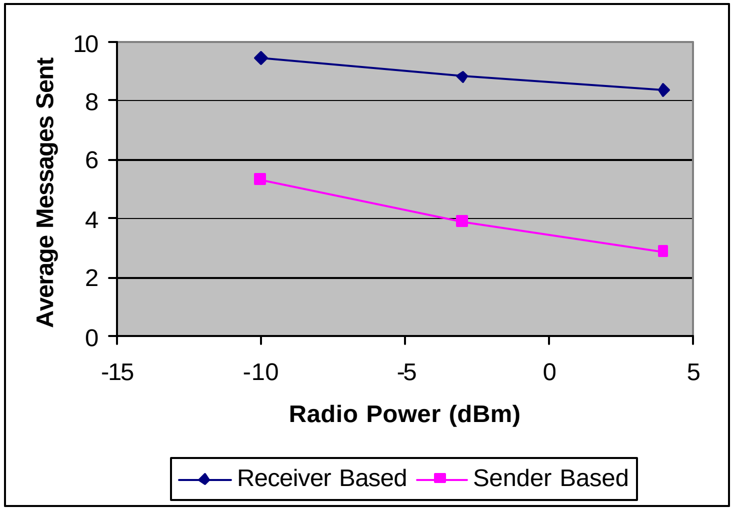

[http://oasis.cs.berkeley.edu/retreats/jan2005/talks/fonseca.ppt]

# RBF Performance

Packet delivery ratio




Energy dissipation




**RBF 20 to 30% better**

**2 ~ 3 times more , better in less dense networks**

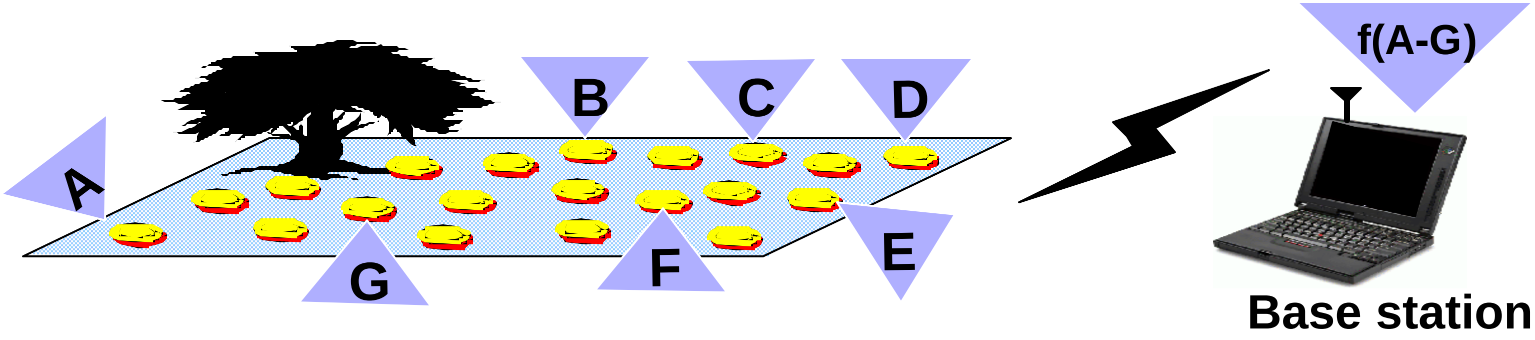
[http://oasis.cs.berkeley.edu/retreats/jan2005/talks/fonseca.ppt]

# Clustering

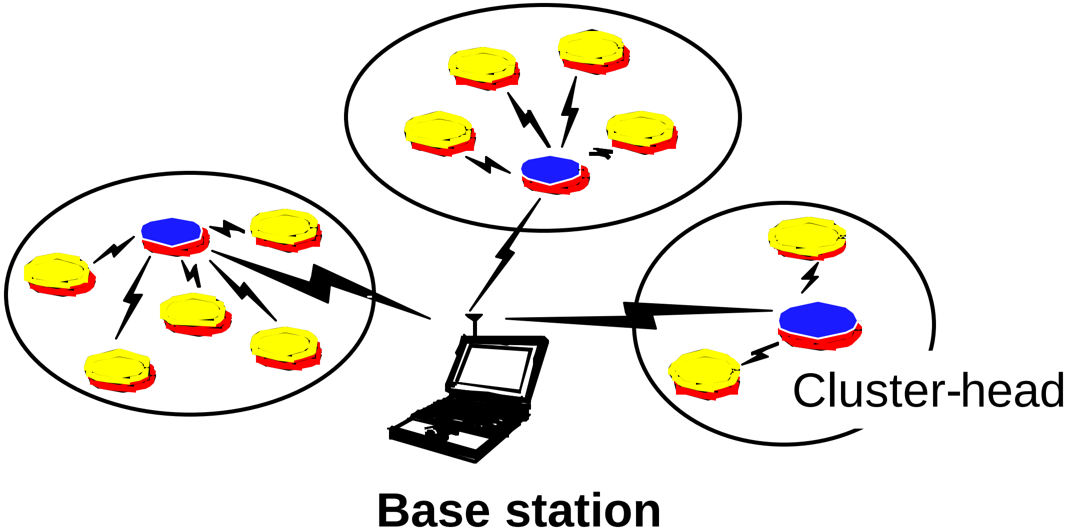
- To scale, hierarchical approach beneficial
- Form local clusters managed by cluster head
  - Fixed or adaptive cluster maintenance
- Clustering provides
  - Framework for resource management
  - Support for intra-cluster channel access and power control
  - Support for inter-cluster routing and channel separation
  - Distributes management responsibility from sink to cluster heads
  - Provides framework for data fusion, local decision making, local control and energy savings

# LEACH Framework

- Assumptions:
  - Base station away from nodes
  - All nodes energy-constrained
  - Locally, data correlated

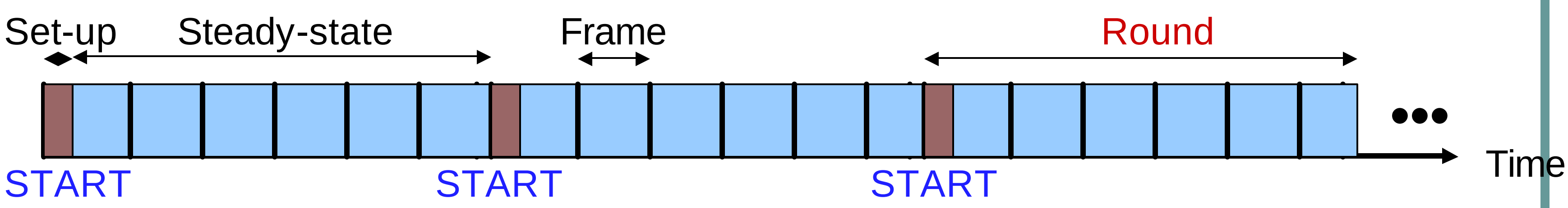


# LEACH Protocol Architecture

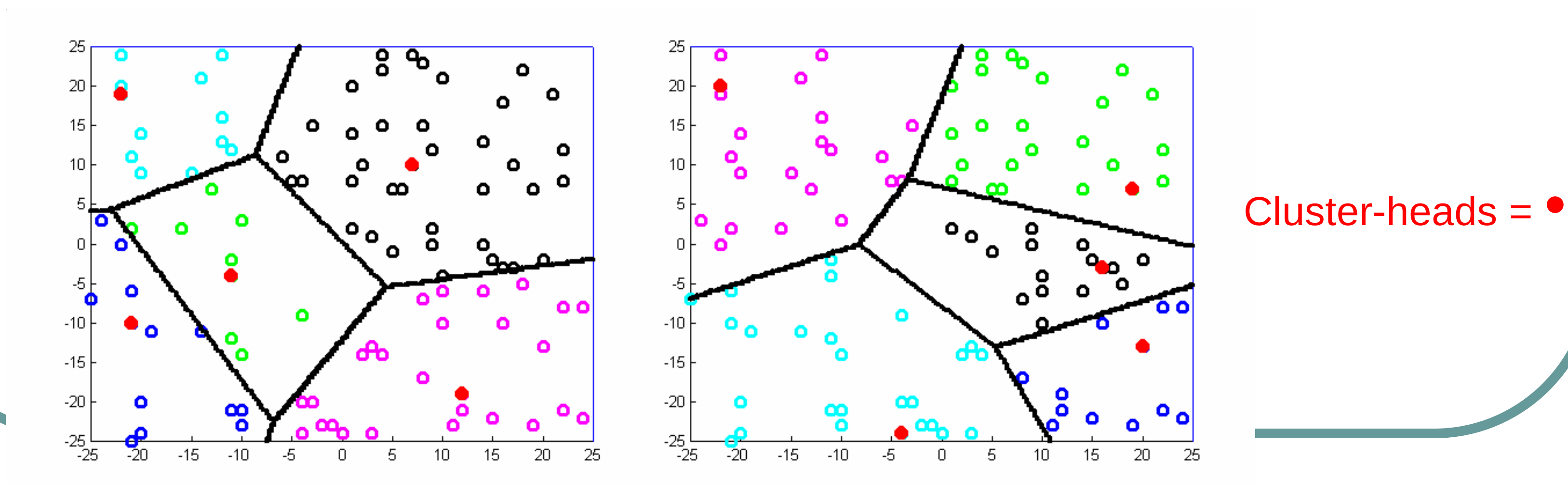



- Low-Energy Adaptive Clustering Hierarchy
  - Adaptive, self-configuring cluster formation
  - Localized control for data transfers
  - Low-energy medium access
  - Application-specific data aggregation

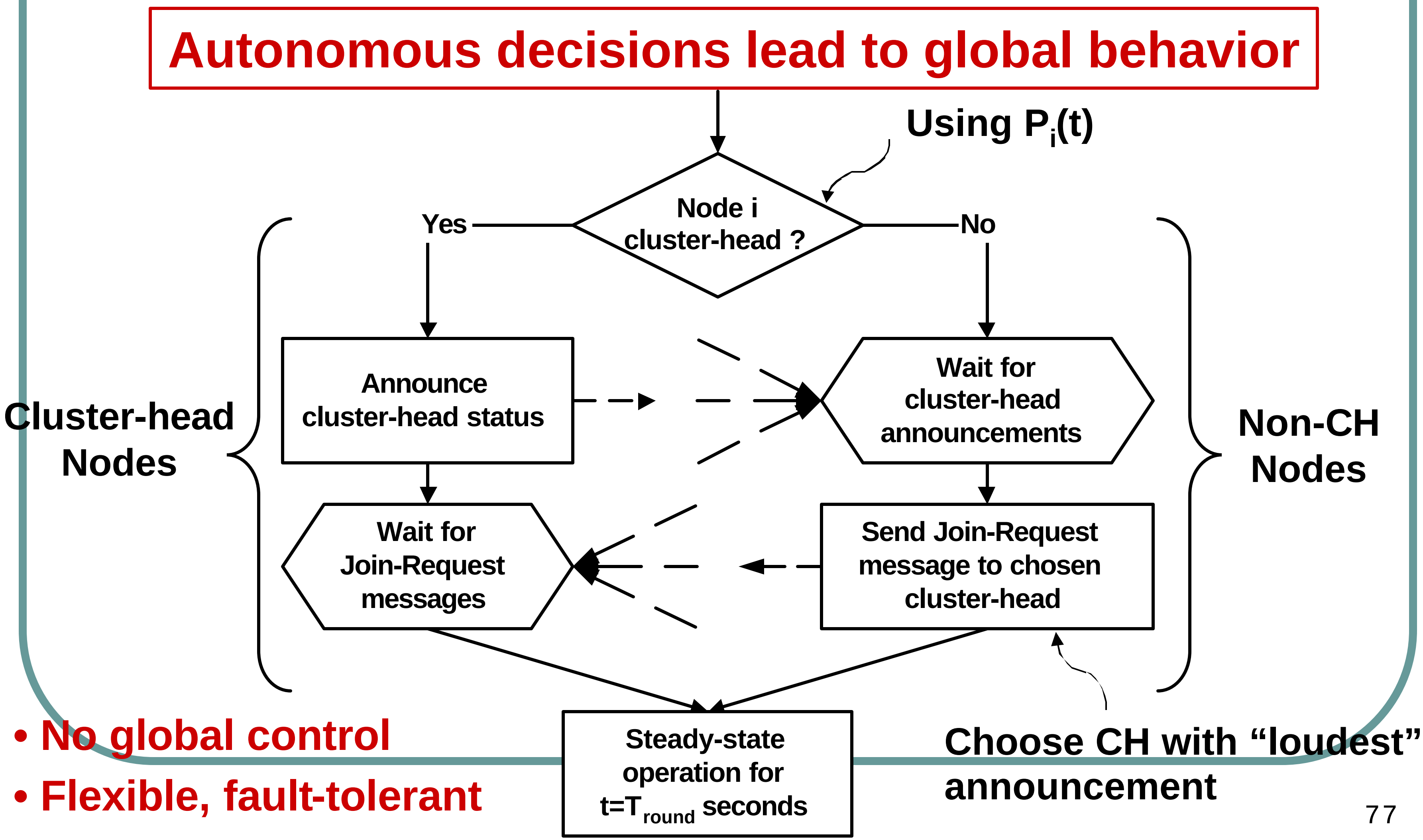
# Dynamic Clusters




- Cluster-head rotation to evenly distribute energy load
- Adaptive clusters
  - Clusters formed during set-up
  - Scheduled data transfers during steady-state



# Distributed Cluster Formation




- No global control
- Flexible, fault-tolerant

# Distributed Cluster Formation

- Assume nodes begin with equal energy
- Design for *k* clusters per round
- Want to evenly distribute energy load
- ⇨ Each node CH once in N/k rounds

*k* = system param.
(analytical optimum)

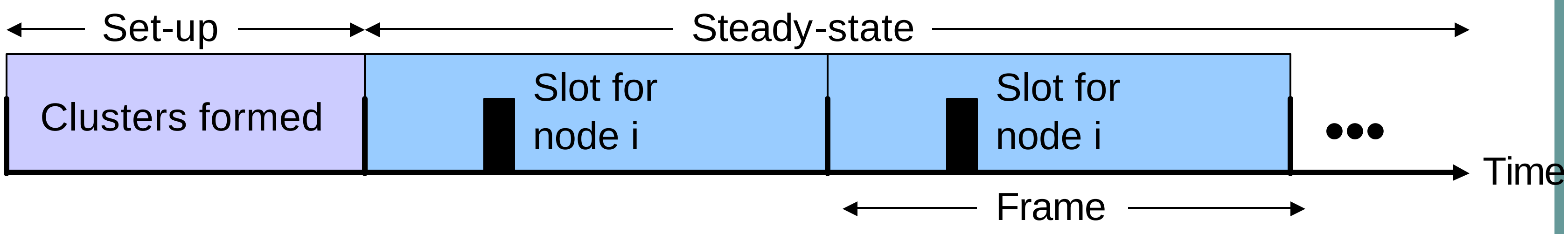
$$E[\#CH] = \sum_{i=1}^{N} P_i(t) * 1 = k$$

$$P_i(t) = \begin{cases} \dfrac{k}{N - k * r \bmod (N/k)} & C_i(t) = 0 \\ 0 & C_i(t) = 1 \end{cases}$$

$C_i(t)$ = 1 if node i a CH in last *r* rounds

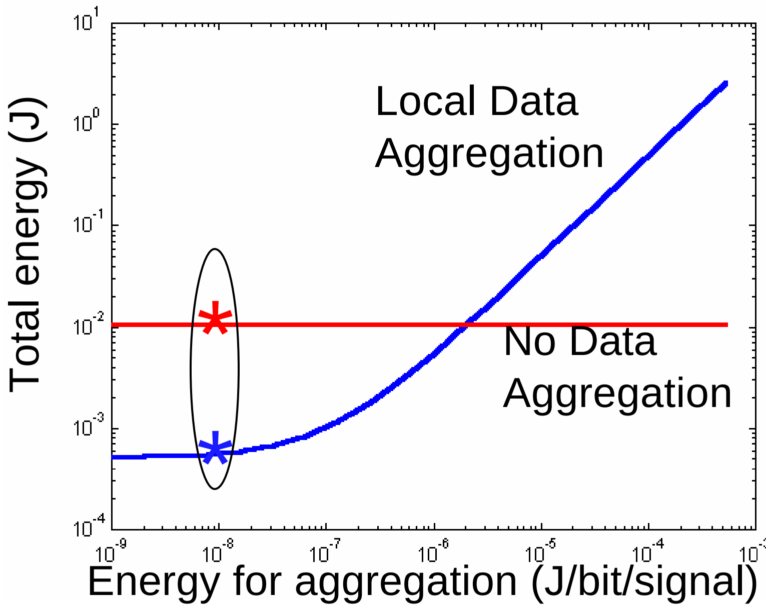
- Can determine $P_i(t)$ with unequal node energy

# LEACH Steady-State




- Cluster-head coordinates transmissions
  - Time Division Multiple Access (TDMA) schedule
  - Node i transmits once per frame
- Cluster-head broadcasts TDMA schedule
- Low-energy approach
  - No collisions
  - Maximum sleep time
  - Power control

# Data Aggregation

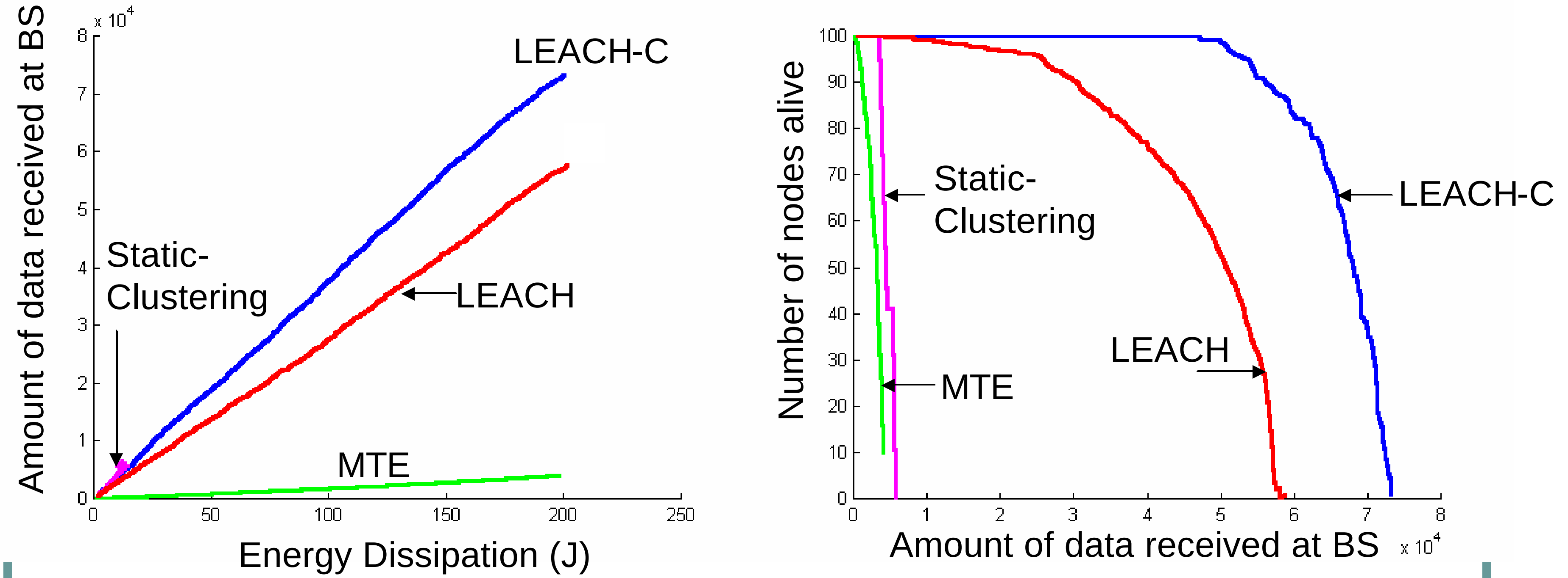



- Clusters exhibit spatial locality
  - Local data aggregation
- Computation vs. communication tradeoff
  - Depends on cost of computation and communication
  - Signal processing within the network

# Base Station Cluster Formation

- Get optimal clusters for comparison
- LEACH-C
  - Requires communication with base station
  - Nodes send base station current position
  - Base station runs optimization algorithm to determine best clusters
- Need GPS or other location-tracking method

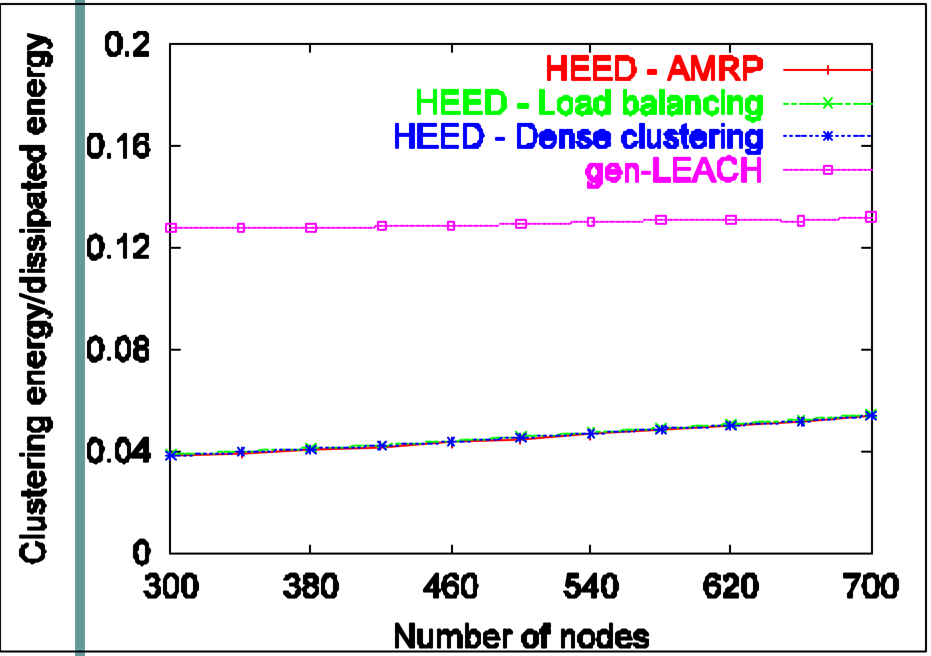
# LEACH Performance

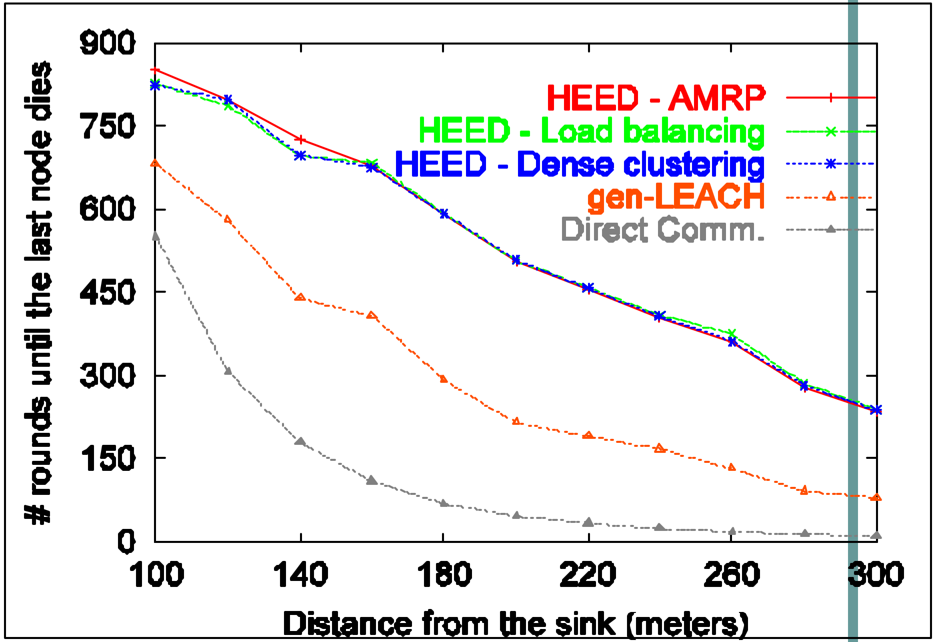


# HEED

- Node costs
  - Cluster head probability
    - Function of residual energy
  - Communication cost
    - Function of neighbor proximity
- Iterative approach where nodes with lowest cost advertise themselves as cluster head
  - Nodes associate with cluster heads
  - At each iteration, cluster head probability increased
- Advantages
  - Creates well distributed clusters
  - Terminates in constant time
  - Requires only local communication

# HEED Performance




- HEED produces well distributed clusters
  - Reduces energy load
  - Extends network lifetime

[http://www.cs.purdue.edu/homes/fahmy/talks/infocom04.ppt]

# Querying a Distributed Database

- WSNs can be thought of as distributed databases
- Can query sensors using SQL-like language
  - TAG
  - TinyDB
  - GHT
  - Cougar
- Careful thought needed for execution of queries

# Database Query Languages

- TAG
  - Unlike standard database queries where data gathered by central processor, allows queries to be executed in distributed manner
- TinyDB
  - Provides optimizations of aggregation trees, sensing task scheduling and query processing
- GHT
  - Data-centric means for storing sensor data

# Research Issues

# Research Issues (1)

- Appropriate QoS model
  - Traditional networks: delay, packet delivery ratio, jitter
  - Sensor networks: probability of missed detection of an event, signal-to-noise ratio, network sensing coverage, others
  - Difficult to translate these data-specific QoS parameters into meaningful protocol parameters
  - What are good QoS parameters and how can these be described efficiently for use in protocol optimizations?

# Research Issues (2)

- Appropriate architecture
  - Cross-layer
    - Entire protocol stack tailored to specific needs of WSN application
    - Trade-off: generality and ease of network design to achieve lifetime increases
  - Layered
    - Generality leads to worse system performance
  - Hybrid approaches
  - What is best architecture to meet WSN needs?

# Research Issues (3)

- Reliability
  - Links and sensors may fail, temporarily or permanently
  - Must design protocols to provide reliable service with these failures
  - How can reliability be achieved at all levels of the protocol stack?
- Self-powered sensors
  - Using vibration, solar, heat
  - How should protocols be modified for time-varying energy capacities?

# Research Issues (4)

- Heterogeneous applications
  - Sensor nodes may be shared by multiple applications with differing goals
  - How to ensure protocols efficiently serve multiple applications simultaneously?
- Heterogeneous sensors
  - How to make best use of resources in heterogeneous sensor networks?

# Research Issues (5)

- Security
  - How much and what type of security is really needed?
  - How can data be authenticated?
  - How can misbehaving nodes be prevented from providing false data?
  - Can energy and security be traded-off such that the level of network security can be easily adapted?

# Research Issues (6)

- Actuation
  - Eventually sensor networks will “close the loop”
  - Data do not need to reach base station
  - Current models for sensor networks may not be valid– what new models are needed?
- Distributed and collaborative data processing
  - How to best process heterogeneous data?
  - How much data and what type of data should be processed to meet application QoS goals while minimizing energy drain?

# Research Issues (7)

- New medium
  - Underground sensor networks
    - Agriculture monitoring
    - Structural monitoring
  - Underwater sensor networks
    - Tsunami warnings
    - Ocean monitoring
  - What changes do these channels pose for existing protocols and algorithms?
  - What architectures should be used?

# Research Issues (8)

- Integration with other networks
  - Sensor networks may interface with other networks, such as a WiFi network, a cellular network, or the Internet
  - What is the best way to interface these networks?
  - Should the sensor network protocols support (or at least not compete with) the protocols of the other networks?
  - Or should the sensors have dual network interface capabilities?

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