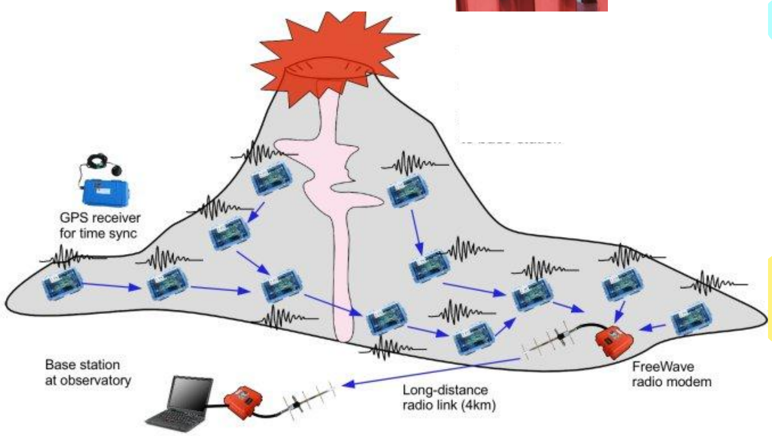
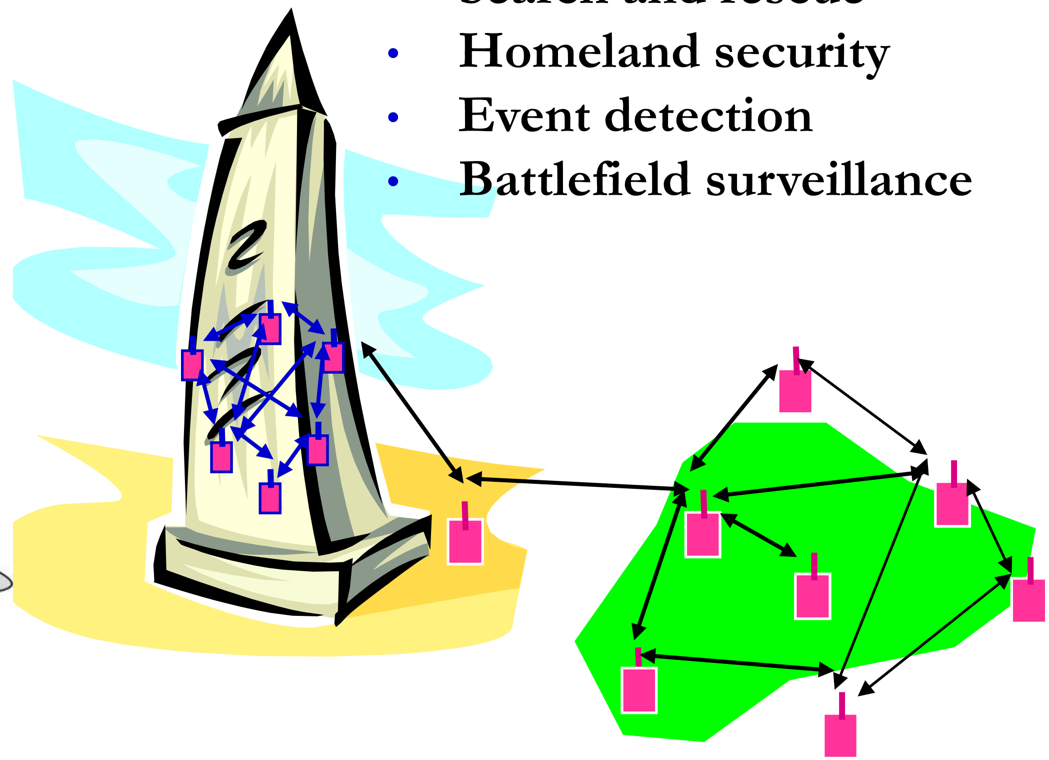
EE360: Lecture 14 Outline
Sensor Networks

- Announcements
  - Progress report deadline extended to 3/2 (11:59pm)
  - 2^{nd} paper summary due March 7 (extended)
  - Project poster session March 15 5pm?
- Overview of sensor networks
- Major Design Challenges
- Energy Considerations
- Energy-Constrained Link Layer Design
- Energy-Constrained MAC
- Energy-Constrained Routing

Wireless Sensor Networks

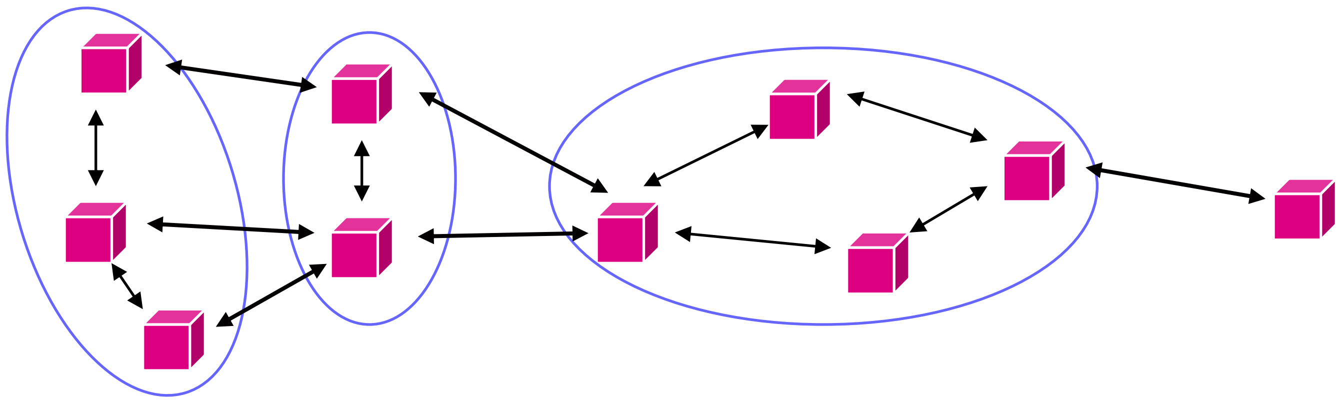
- Smart homes/buildings
- Smart structures
- Search and rescue
- Homeland security
- Event detection
- Battlefield surveillance





- Energy (transmit and processing) is the driving constraint
- Data generally flows to a centralized location for processing
- Intelligence is in the network rather than in the devices

Sensor Network Characteristics



- Energy a driving constraint
- Traffic patterns go towards a central node
- Low per-node rates but 10s to 1000s of nodes
- Data highly correlated in time and space.
- Nodes can cooperate in transmission, reception, and compression.

Major Design Challenges

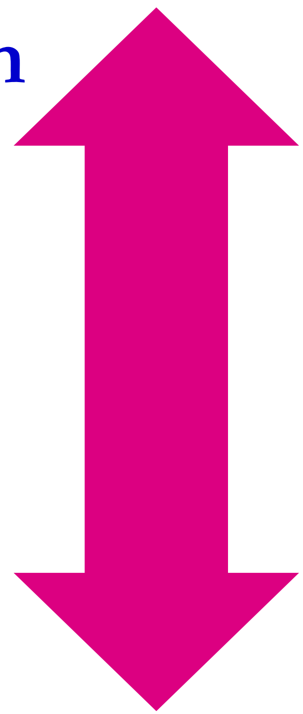
- Communication link and network design
  - Low-power communication, multiple access, and routing protocols
  - Scalability
  - Latency
- Information processing
  - Distributed compression
- Joint sensing, communication, and control

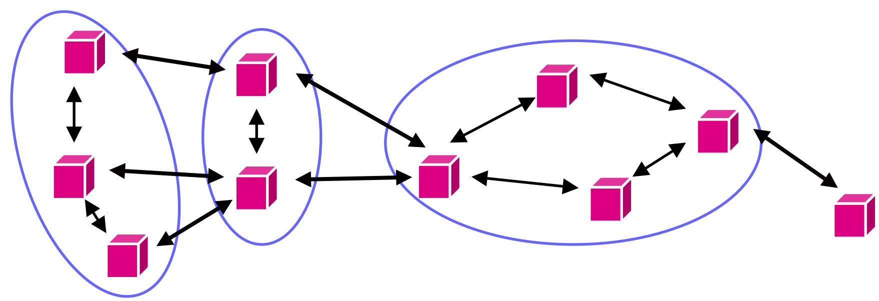
Energy-Constrained Nodes

- Each node can only send a finite number of bits.
  - TX energy minimized by sending each bit very slowly.
  - Introduces a delay versus energy tradeoff for each bit.
- Short-range networks must consider both transmit and processing/circuit energy.
  - Sophisticated techniques not necessarily energy-efficient.
  - Sleep modes can save energy but complicate networking.
- Changes everything about the network design:
  - Bit allocation must be optimized across all protocols.
  - Delay vs. throughput vs. node/network lifetime tradeoffs.
  - Optimization of node cooperation.

Crosslayer Design in Sensor Networks

- Application
- Network
- Access
- Link
- Hardware



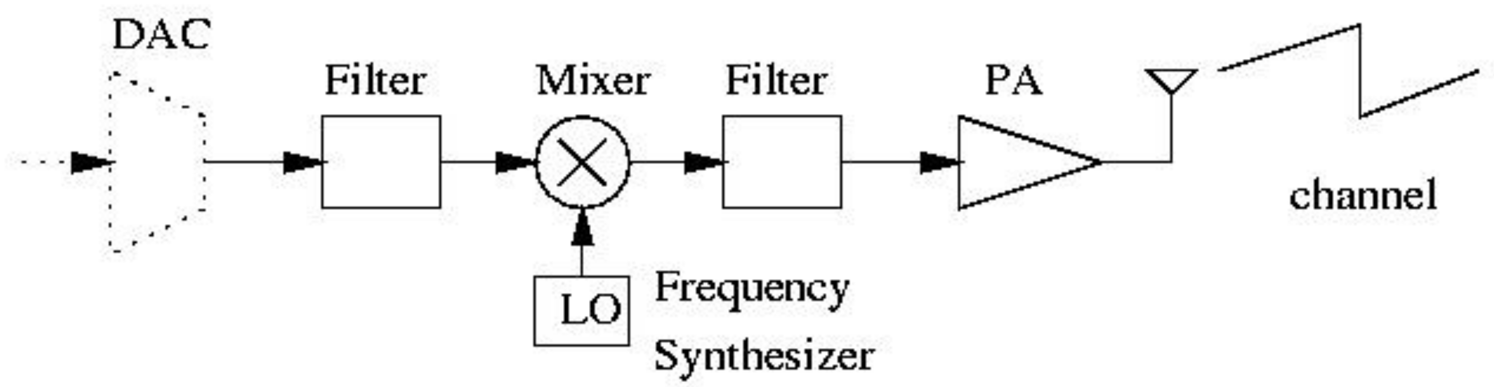


Energy consumption at each layer of the protocol stack must be considered in the design

Cross-Layer Tradeoffs under Energy Constraints

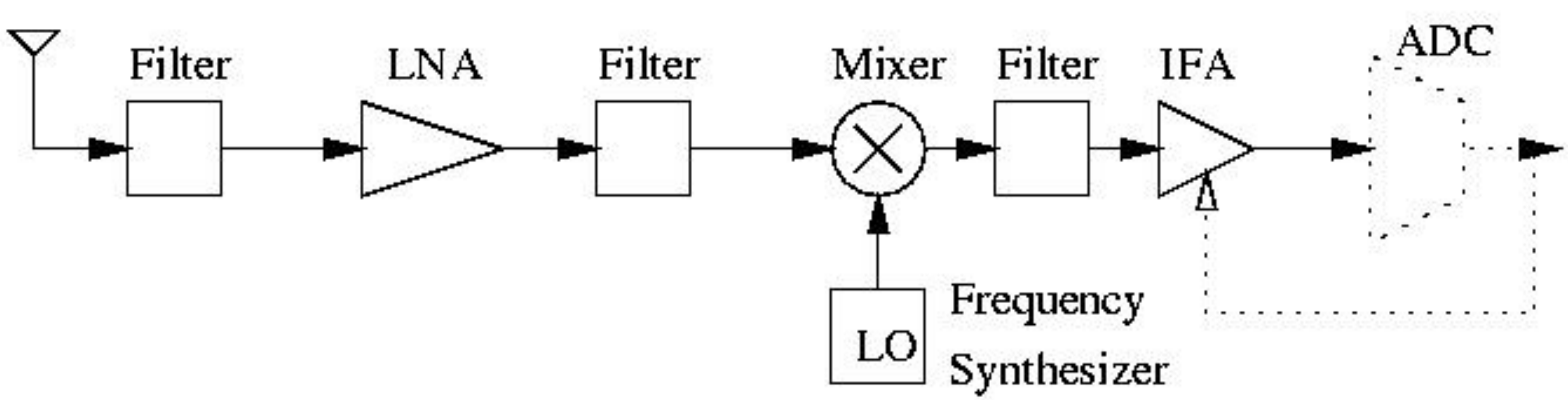
- Hardware
  - Models for circuit energy consumption highly variable
  - All nodes have transmit, sleep, and transient modes
  - Short distance transmissions require TD optimization
- Link
  - High-level modulation costs transmit energy but saves circuit energy (shorter transmission time)
  - Coding costs circuit energy but saves transmit energy
- Access
  - Transmission time (TD) for all nodes jointly optimized
  - Adaptive modulation adds another degree of freedom
- Routing:
  - Circuit energy costs can preclude multihop routing

Modulation Optimization



Tx

Rx



Key Assumptions

- **Narrow band, *i.e.* $B \ll f_c$**
  - **Power consumption of synthesizer and mixer independent of bandwidth B.**
- **Peak power constraint**
- **L bits to transmit with deadline T and bit error probability P_b.**
- **Square-law path loss for AWGN channel**

$$E_t = E_r G_d, \qquad G_d = \frac{(4\pi d)^2}{G\lambda^2}$$

Multi-Mode Operation
Transmit, Sleep, and Transient

- **Deadline *T*:** $T = T_{on} + T_{sp} + T_{tr}$
- **Total Energy:**

$$E = E_{on} + E_{sp} + E_{tr}$$

$$(E_{sp} \approx 0,\ E_{tr} \approx 2P_{syn}T_{tr})$$

Transmit — Circuit — Transient Energy

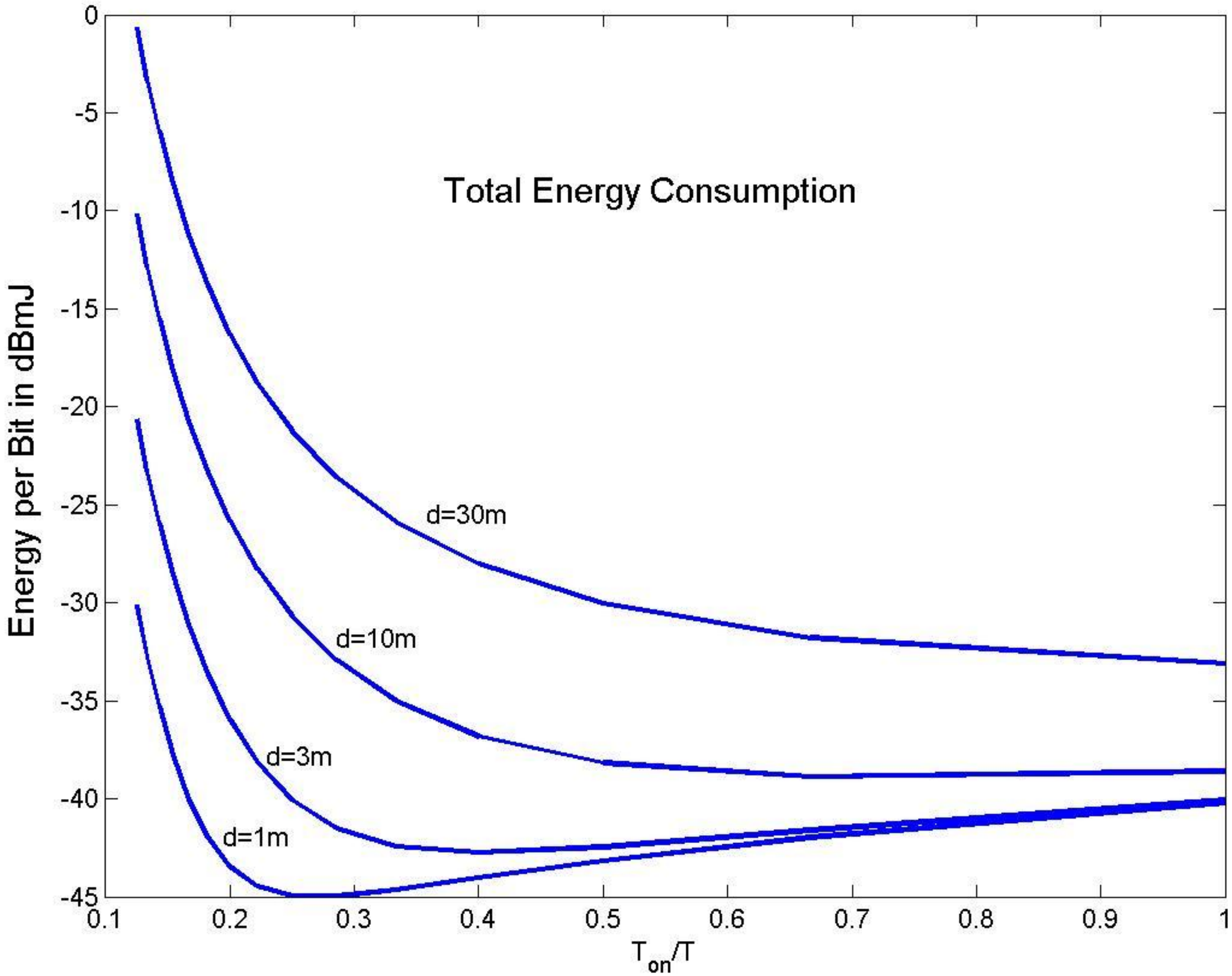
$$\approx (1+\alpha)P_tT_{on} + P_cT_{on} + 2P_{syn}T_{tr}$$

$$P_c = 2P_{mix} + 2P_{syn} + P_{LNA} + P_{IFA} + P_{fil} + P_{DSP},$$

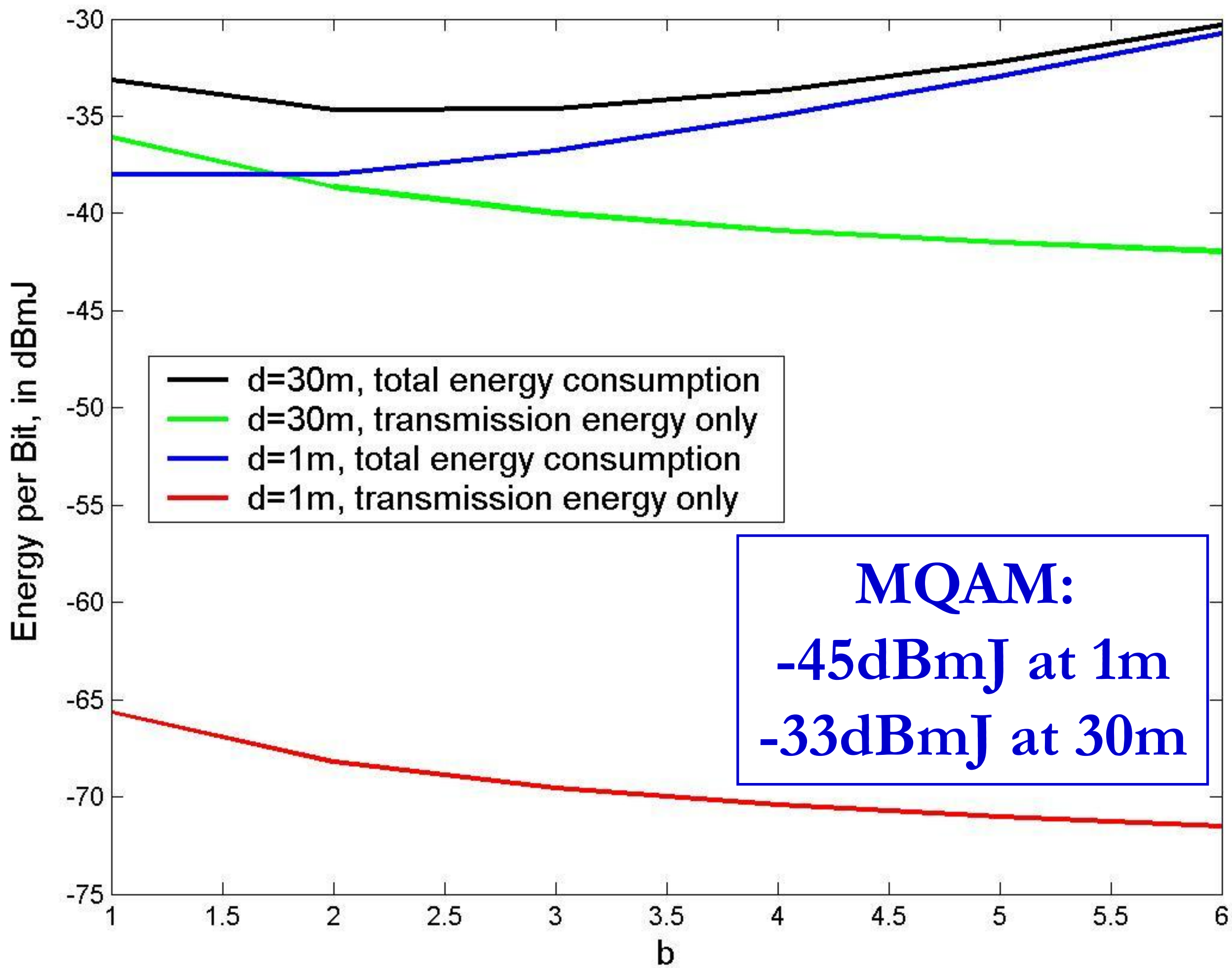
Energy Consumption: Uncoded

- Two Components
  - Transmission Energy: Decreases with T_{on} & B.
  - Circuit Energy: Increases with T_{on}
- Minimizing Energy Consumption
  - Finding the optimal pair (B, T_{on})
  - For MQAM, find optimal constellation size ($b=\log_2 M$)

Total Energy (MQAM)



Total Energy (MFSK)



Energy Consumption: Coded

- Coding reduces required E_b/N_0
- Reduced data rate increases T_{on} for block/convolutional codes
- Coding requires additional processing

  -Is coding energy-efficient

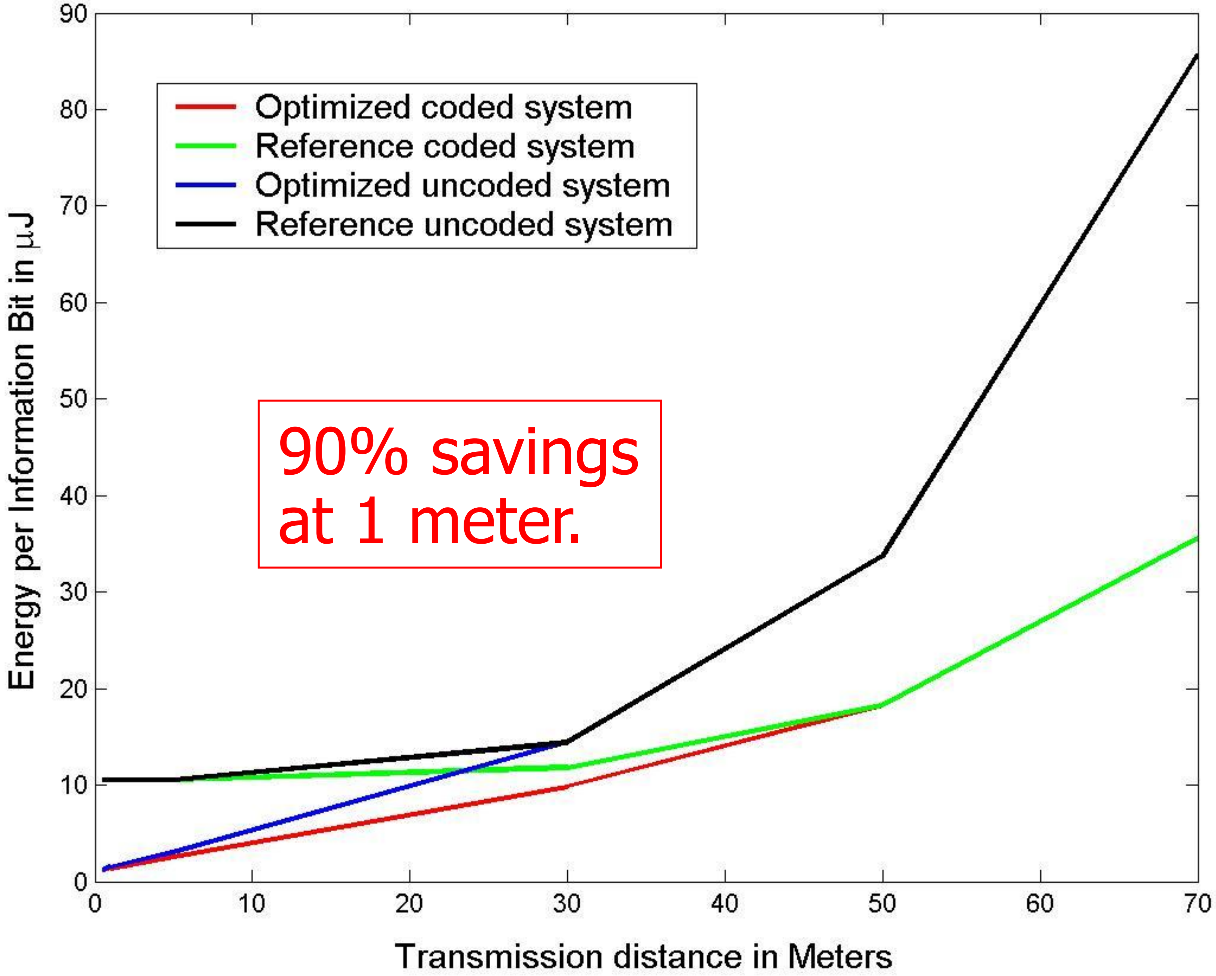
  -If so, how much total energy is saved.

MQAM Optimization

- Find BER expression for coded MQAM
  - Assume trellis coding with 4.7 dB coding gain
  - Yields required E_b/N_0
  - Depends on constellation size (b_k)
- Find transmit energy for sending L bits in T_{on} sec.
- Find circuit energy consumption based on uncoded system and codec model
- Optimize T_{on} and b_k to minimize energy

Coded MQAM

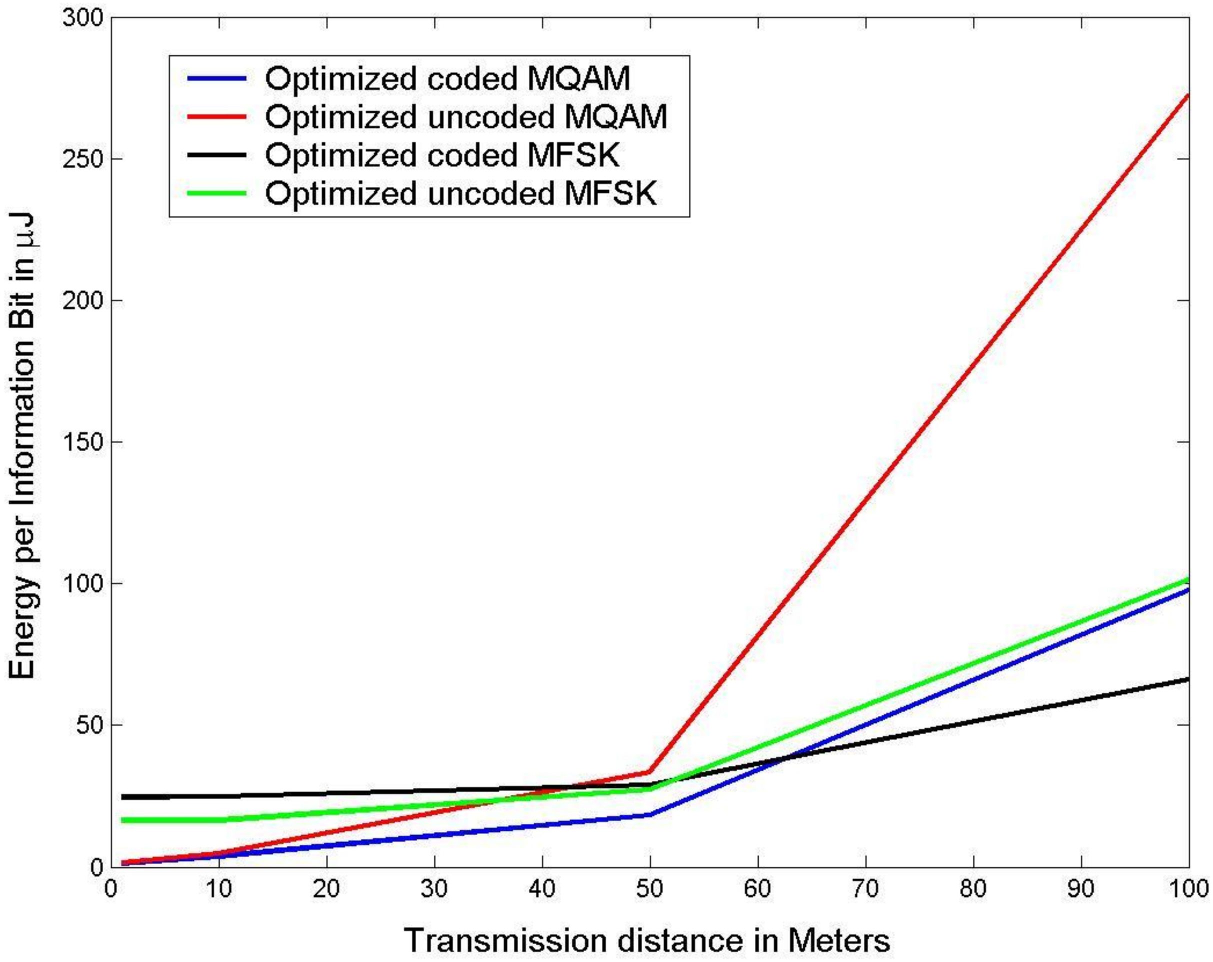
Reference system has b_k=3 (coded) or 2 (uncoded)



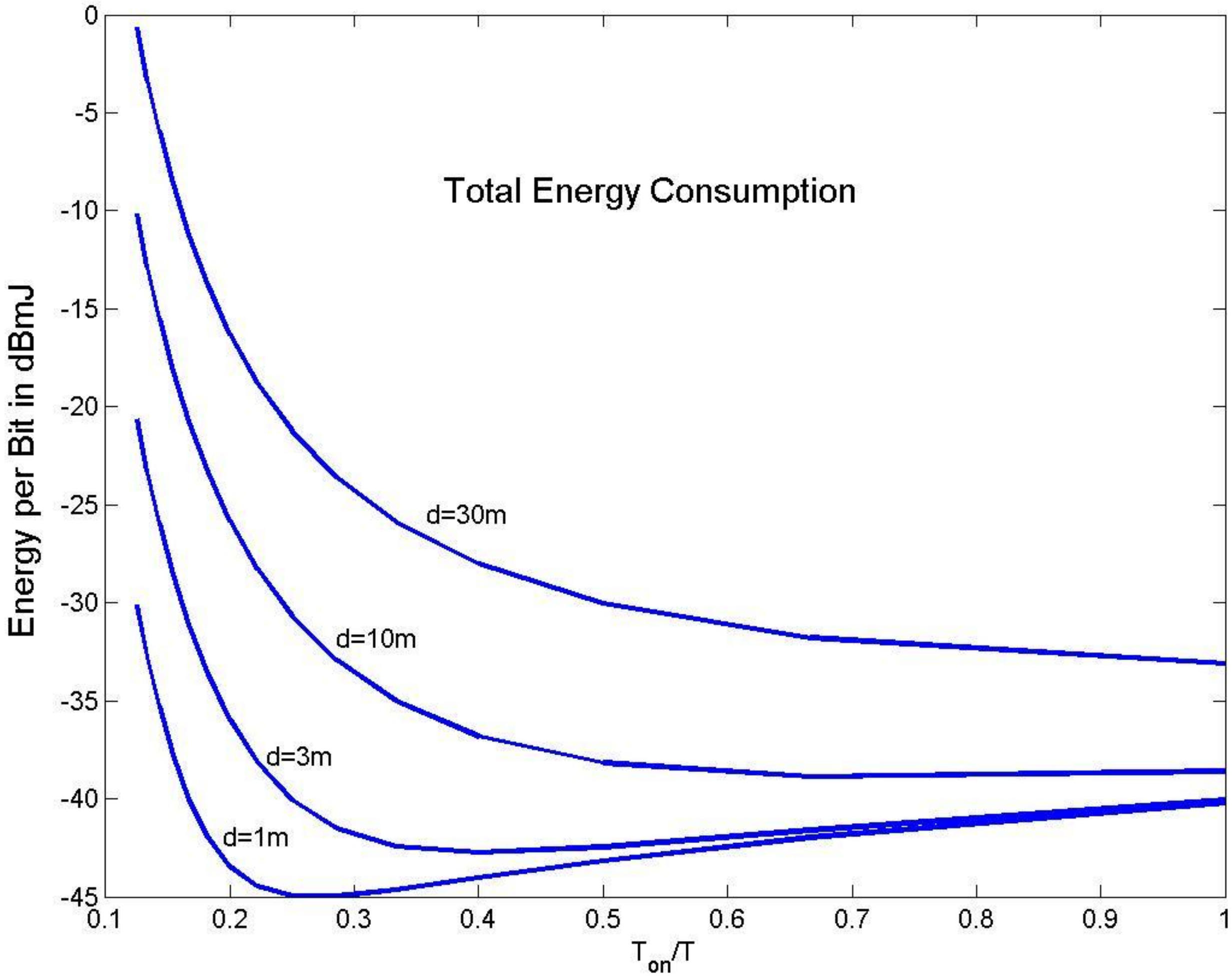
MFSK Optimization

- Find BER expression for uncoded MFSK
  - Yields required E_b/N_0 (uncoded)
  - Depends on b, T_{on} a function of b.
- Assume 2/3 CC with 32 states
  - Coding gain of 4.2 dB
  - Bandwidth expansion of 3/2 (increase T_{on})
- Find circuit energy consumption based on uncoded system and codec model
- Optimize b to minimize total energy

Comparison: MQAM and MFSK

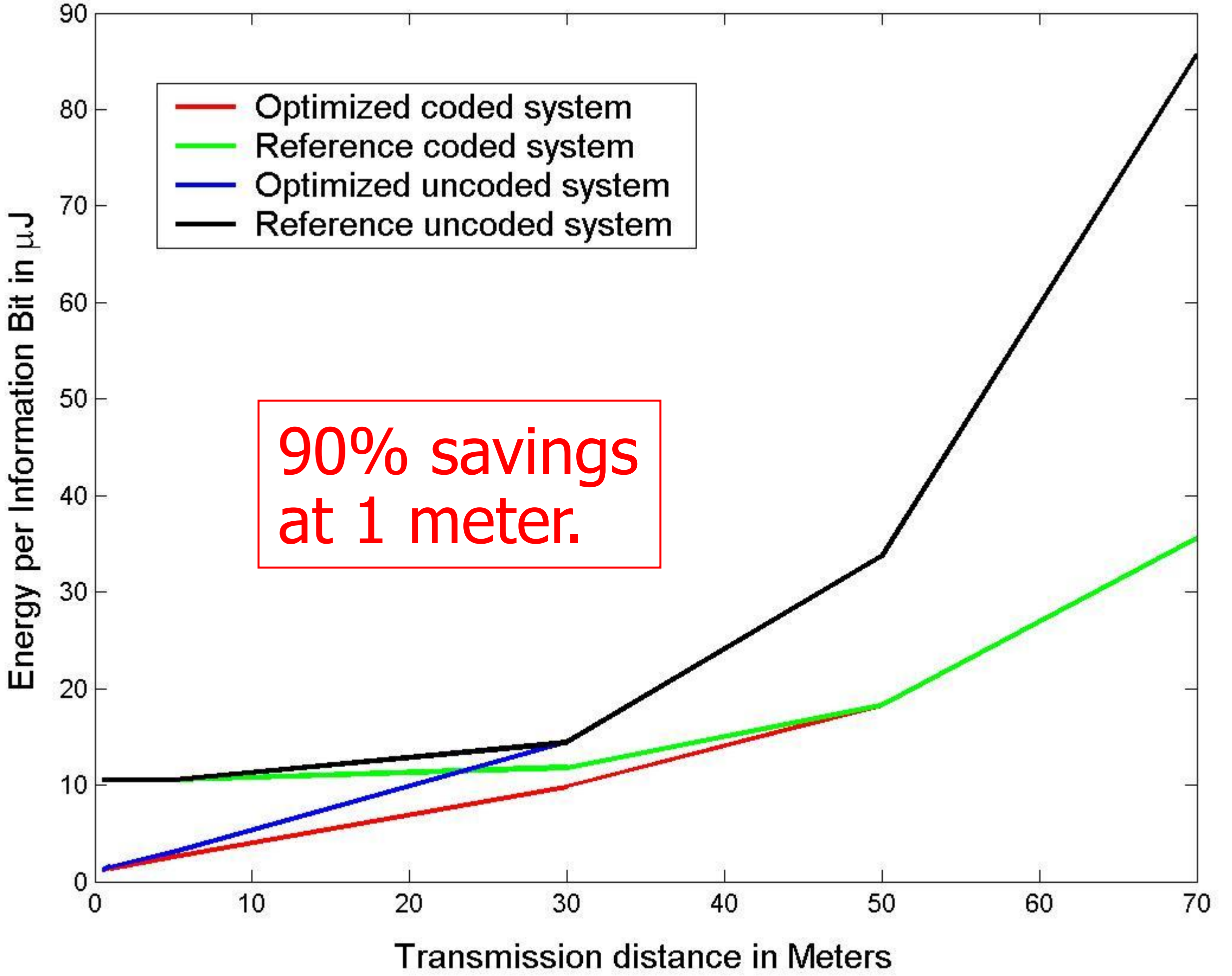


Total Energy (MQAM)



Adaptive Coded MQAM

Reference system has $\log_2(M)=3$ (coded) or 2 (uncoded)



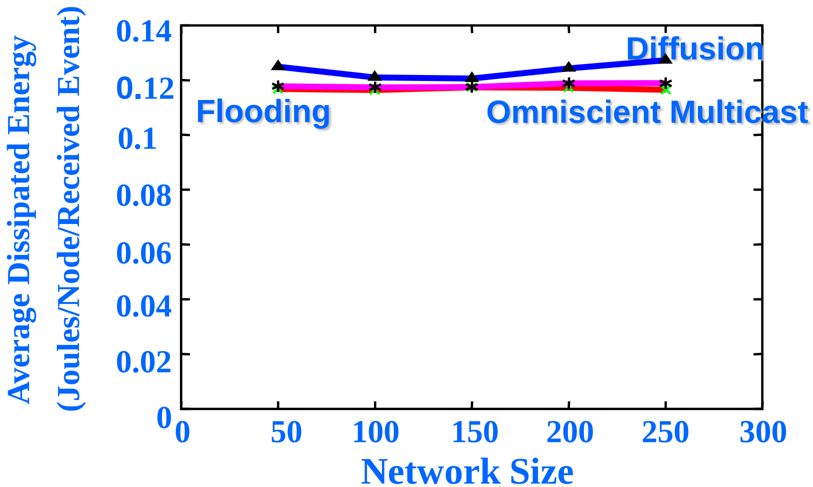
Medium Access Control in Sensor Nets

- Important attributes of MAC protocols
  1. Collision avoidance
  2. Energy efficiency
  3. Scalability in node density
  4. Latency
  5. Fairness
  6. Throughput
  7. Bandwidth utilization

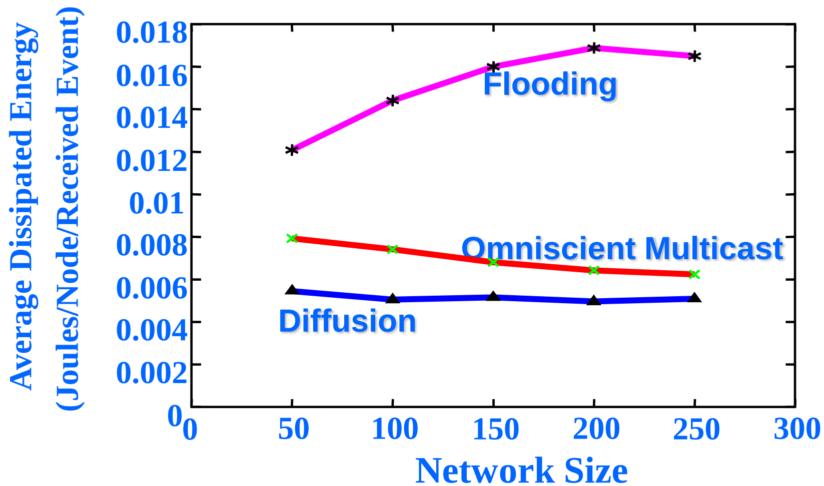
MAC Impact on Sensor Networks

(Intanago et al, 2000)

- Major sources of energy waste
  - Idle listening when no sensing events, Collisions, Control overhead, Overhearing

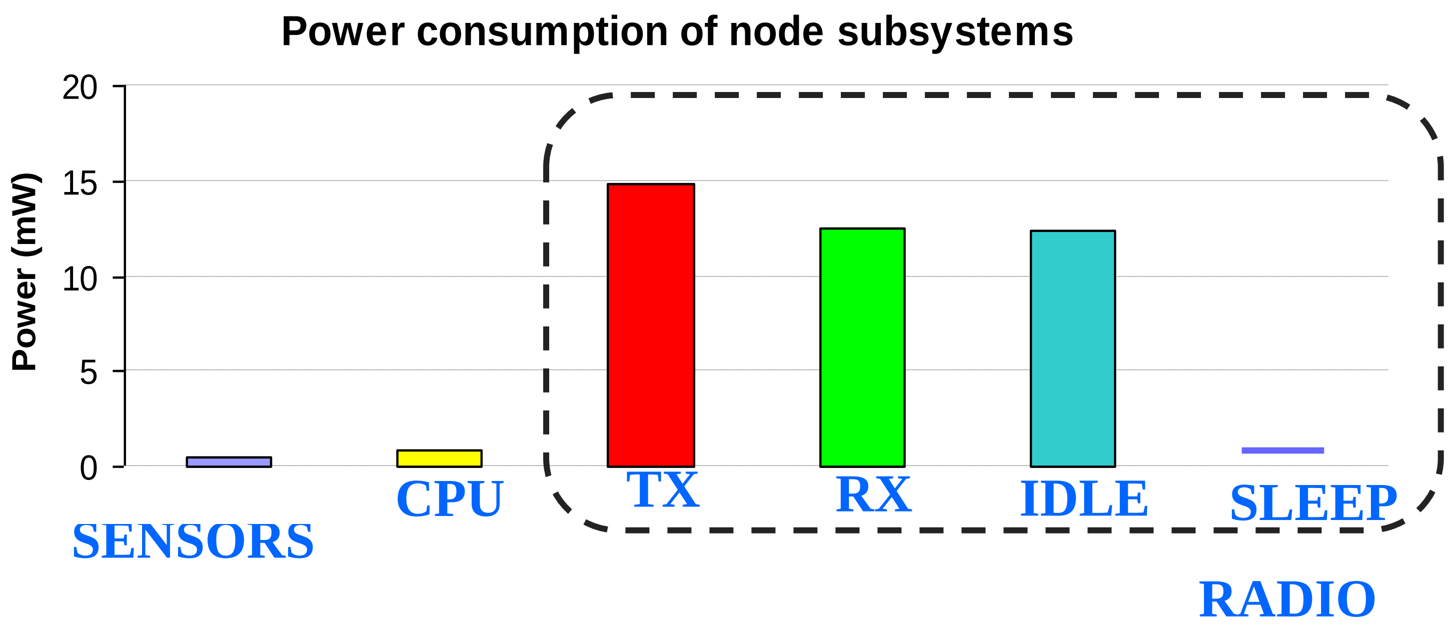


Over 802.11-like MAC



Over energy-aware MAC

Identifying the Energy Consumers



$$E_{TX} \approx E_{RX} \approx E_{IDLE} >> E_{SLEEP}$$

- Need to shutdown the radio

Energy Efficiency in MAC

- Major sources of energy waste
  - Idle listening
    - Long idle time when no sensing event happens
    - Collisions
    - Control overhead
    - Overhearing

  } Common to all wireless networks
- Try to reduce energy consumption from all above sources
- TDMA requires slot allocation and time synchronization
- Combine benefits of TDMA + contention protocols

Periodic Listen and Sleep

- Schedule maintenance
  - Remember neighbors' schedules
    - — to know when to send to them
  - Each node broadcasts its schedule every few periods
  - Refresh on neighbor's schedule when receiving an update
  - Schedule packets also serve as beacons for new nodes to join a neighborhood

Collision Avoidance

- **Problem:** Multiple senders want to talk
- **Options:** Contention vs. TDMA
- **Possible Solution:** Similar to IEEE 802.11 ad hoc mode (DCF)
  - Physical and virtual carrier sense
  - Randomized backoff time
  - RTS/CTS for hidden terminal problem
  - RTS/CTS/DATA/ACK sequence

Overhearing Avoidance

- Problem: Receive packets destined to others
- Solution: Sleep when neighbors talk
  - Basic idea from PAMAS (Singh 1998)
  - But we only use in-channel signaling
- Who should sleep?
  - **All immediate neighbors of sender and receiver**
- **How long to sleep?**
  - **The *duration* field in each packet informs other nodes the sleep interval**

Message Passing

- Problem: In-network processing requires *entire* message
- Solution: Don't interleave different messages
  - Long message is fragmented & sent in burst
  - RTS/CTS reserve medium for entire message
  - Fragment-level error recovery
    — extend Tx time and re-transmit immediately
- Other nodes sleep for whole message time

Routing

- Given a topology, how to route data?
  - MANET: Reactive[DSR], proactive[AODV], TORA, GPSR[KarpKung00]
  - Location-aided routing: Geocast[Navas97], Cartesian-LAR, [KOVaidya98]
  - Energy-budget routing
  - Geographical Routing (GRAB, curve routing)
  - Data-directed routing

GRAB: Field Based Minimum Cost Forwarding (Lu et al 2002)

- Each node broadcasts only once
- Cost Function is a measure of how expensive it is to get a message back to the sink.
  - Could be based on Energy needed in radio communication, hop count, or other considerations
- Node Cost
  - Each node keeps best estimate on its minimum cost.
  - Estimate updated upon receipt of every ADV message.
  - ADV message forwarding deferred for time proportional to nodes cost estimate.

Energy-Budget Routing

- A node with interesting data broadcasts two things (besides data)
  - Total budget to get back to sink.
  - Amount of budget used in initial broadcast.

- A node receiving a data message will only forward a data message if

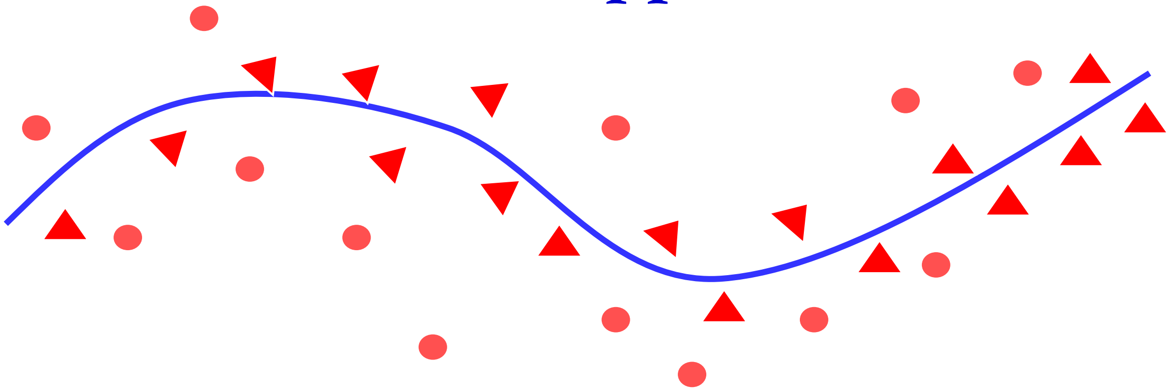
  Total Budget ≥ Budget Spent So Far + My Cost

  - If the inequality holds then Budget Spent So Far is updated.
  - Otherwise the message is dropped.

Routing on a Curve

(Nath et al 2002)

- Route trajectories based on network structure
- By definition, network structure mimics physical structure that is instrumented
  - Stress along a column
  - Flooding along a river
  - Pollution along a road
- Trajectories come from application domain



In-Network Processing

The Key to Sensor Network scalability and Realization

- **Gupta and Kumar pointed out fundamental limits of large scale wireless networks (per node throughput O(1/sqrtN)**
- **However, S. Servetto shows that result holds only for independent nodes (Mobicom 2002)**
  - ***Densely deployed sensor network data will be correlated and can be aggregated***
- **Scalability and lifetime will depend on techniques for in-network processing of data**
  - **Directed Diffusion: *Routing+aggregation/processing***
  - **Data base perspectives:TAG, Sylph**
  - **Programming mechanisms: Sensorware, Mate**

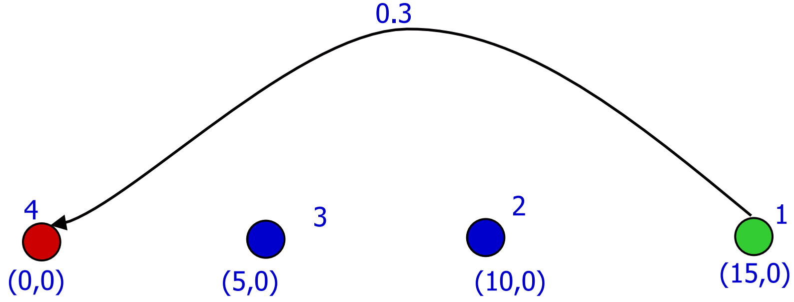
Minimum-Energy Routing Optimization Model

$$\begin{aligned} \text{Min} \quad & f_0(x_1, x_2, \ldots) \\ \text{s.t.} \quad & f_i(x_1, x_2, \ldots) \le 0, \quad i = 1, \cdots, M \\ & g_j(x_1, x_2, \ldots) = 0, \quad j = 1, \cdots, K \end{aligned}$$

- **The cost function $f_0(.)$ is energy consumption.**
- **The design variables $(x_1, x_2, \ldots)$ are parameters that affect energy consumption, e.g. transmission time.**
- **$f_i(x_1, x_2, \ldots) \le 0$ and $g_j(x_1, x_2, \ldots) = 0$ are system constraints, such as a delay or rate constraints.**
- **If not convex, relaxation methods can be used.**
- **Focus on TD systems**

Minimum Energy Routing

- **Transmission and Circuit Energy**



Red: hub node
Blue: relay only
Green: source

$$R_1 = 60\,pps$$

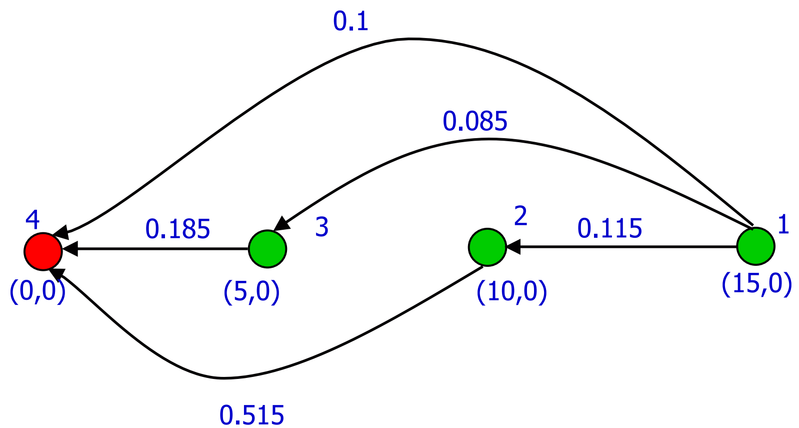
$$R_2 = R_3 = 0$$

$$\upsilon = 100 bits$$

Multihop routing may not be optimal when circuit energy consumption is considered

Relay Nodes with Data to Send

- Transmission energy only



Red: hub node
Green: relay/source

$$R_1 = 60\,pps$$
$$R_2 = 80\,pps$$
$$R_3 = 20\,pps$$

- **Optimal routing uses single and multiple hops**
- **Link adaptation yields additional 70% energy savings**

Summary

- In sensor networks energy (transmit and processing) is the driving constraint
  - Impacts all layers of the protocol stack
- Data generally flows to a centralized location for processing:
  - Impacts routing and in-network processing
- Intelligence is in the network rather than in the devices

Presentation

- **"Energy aware routing for low energy ad hoc sensor networks"**

- Authors: Rahul C. Shah and Jan M. Rabaey

- ***Presented by Eric Lam***