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Routing, Energy and Decentralized Decisions

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Sensor Network Architecture and Layering

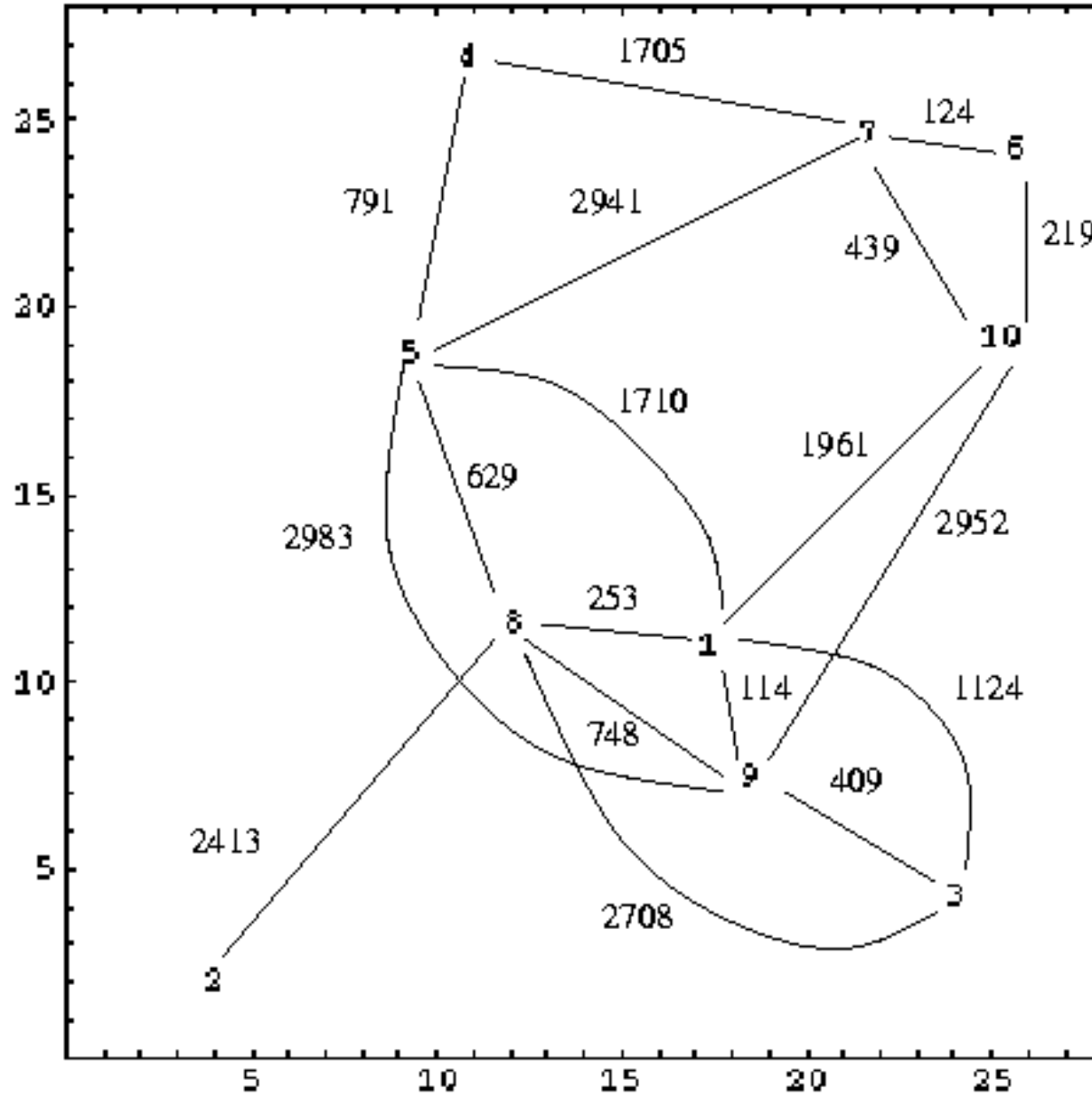
- Sensor network exists typically to do one thing (All custom built.)
- Expensive to pretend sensor is a general purpose computer
- Reduce costs and improve performance by eliminating unneeded functionality
- Layering is “original sin of networking”
- We have little idea how else to build a network
- While we gain experience, we maintain most of layering, with a few optimizations

Our application: event detection

- Wireless sensor network of battery-operated nodes.
- Exists to decide, “Does $H=1$ or $H=0$?” and report this decision to a user.
- Examples
 - tank has arrived
 - earthquake pre-tremor has occurred.
 - glacial ice temperature has exceeded a threshold.
- The sensors must organize to:
 - make a joint decision,
 - get the decision to a sink node.
- Two goals: accuracy and “lifetime.”
- Only one application → optimize node operation to achieve goals

Event detection sensor network: Assumptions

- N nodes, one distinguished as sink node. Sink makes final decision about whether event occurred.
- Observations $Y_i^t = 0$ or 1 arrive at each non-sink node in each sensation period t .
- $Y_i^t|H$ are independent Bernoulli random variables.
Given that $H=0$, $\Pr(Y=0)=p$.
Given that $H=1$, $\Pr(Y=1)=p$.
 $p > 0.5$ is known.
- All nodes know neighbors and distances.
- $P_r = P_t/d^a$ $2 < a < 4$
- Error-free communications \rightarrow SNR requirement \rightarrow energy-per-bit-transmitted requirement for each neighbor. The total energy cost to transmit 1 bit successfully on link (i,j) is known to i and j .
- Each node has some initial battery capacity B_i
- Nodes immobile, channel static.
- Delay not considered. Perfect MAC assumed.



Our contribution

- Routing metrics for Bellman-Ford that capture the notions of:
 - energy conservation (treat energy as cost)
 - residual energy (treat energy as non-renewable)
 - routing diversity (to support application)
- Routing metrics are a convenient place for layers to interact.

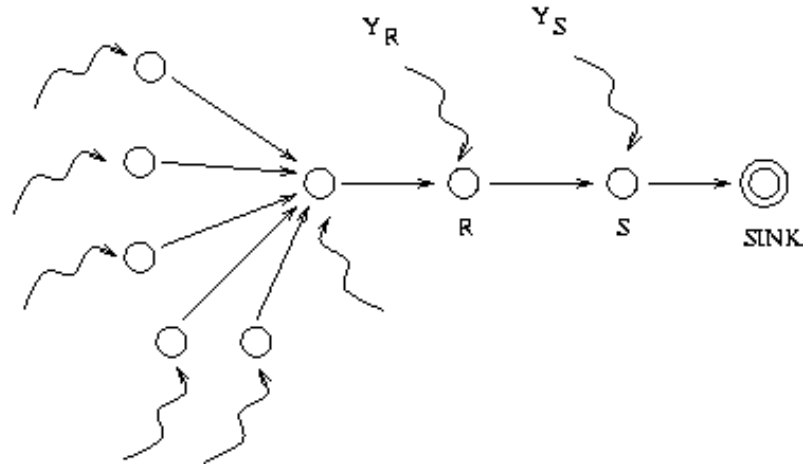
Bellman Ford routing

- Distributed algorithm
- Loop free
- Resulting routing from all nodes to the sink node is an oriented tree, with edges directed toward sink.

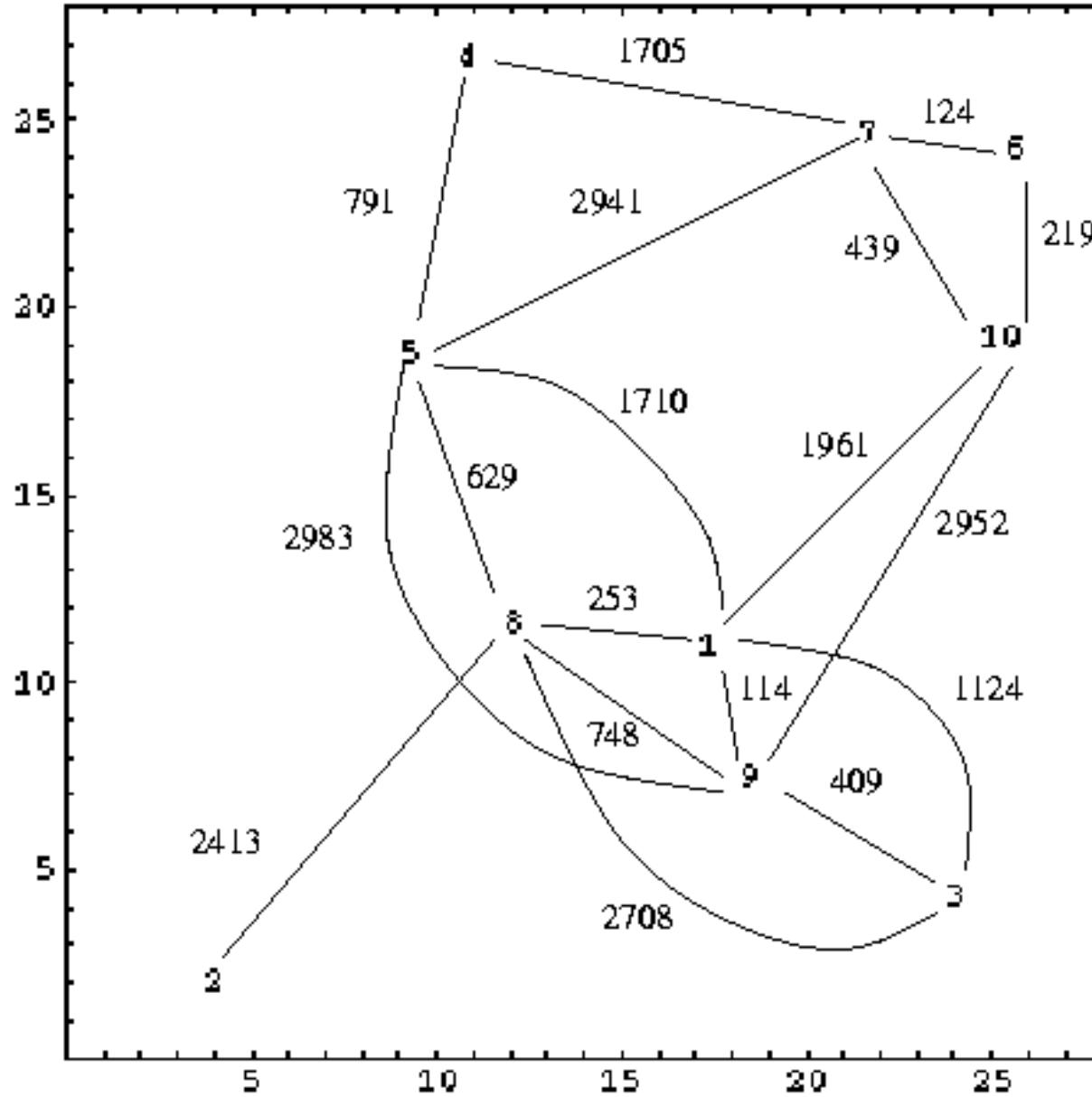
Two self-organization models

- M1
 - DATA HANDLING: each sensor transmits only 1 bit to its successor in routing tree. This bit is majority(own observation, bits received from predecessors)
 - ROUTING: Link cost $C1(i,j) = \text{Neighbors}(j) / B(i)$.
- M2
 - DATA HANDLING: each sensor transmits two integers to its successor in routing tree. These integers are the sums of all the 0-votes and 1-votes it has received, including its own observation.
 - ROUTING: Link cost $C2(i,j) = \text{power}(i,j) / B(i)$.
- In M1 and M2, sink node makes decision for whole network that minimizes $\text{Pr}(\text{error})$ locally.
- In M2 this is often a centralized decision.
- No claim of optimality.

Why is coalescence of routing paths bad in M1?

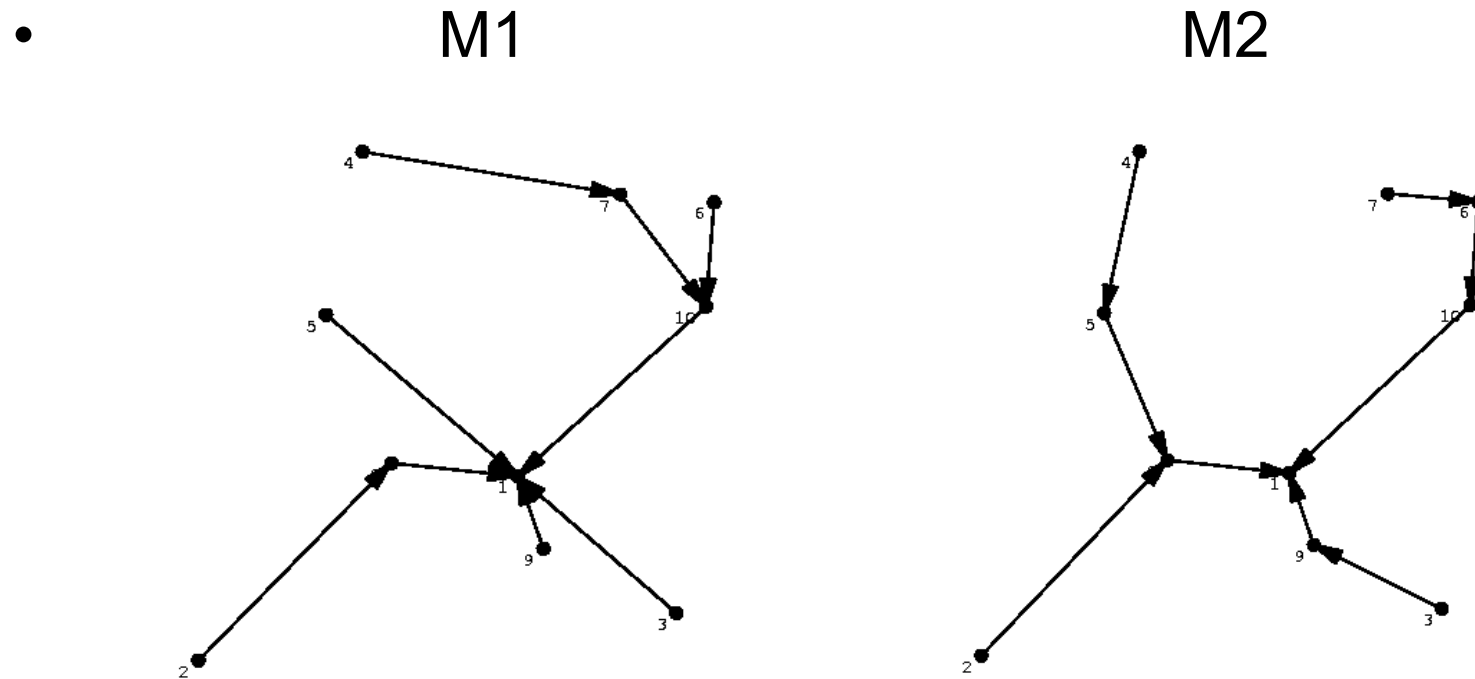


- According to data handling rules of M1:
 - if $Y_R \neq U_Q$ then R flips a coin--BAD
 - if $Y_S \neq U_R$ then S flips a coin--BAD
- Want routing tree to be bushy and balanced, especially at sink.
- Let $C1(i,j) = \text{num nbors}(j) / \text{resid battery}(i)$

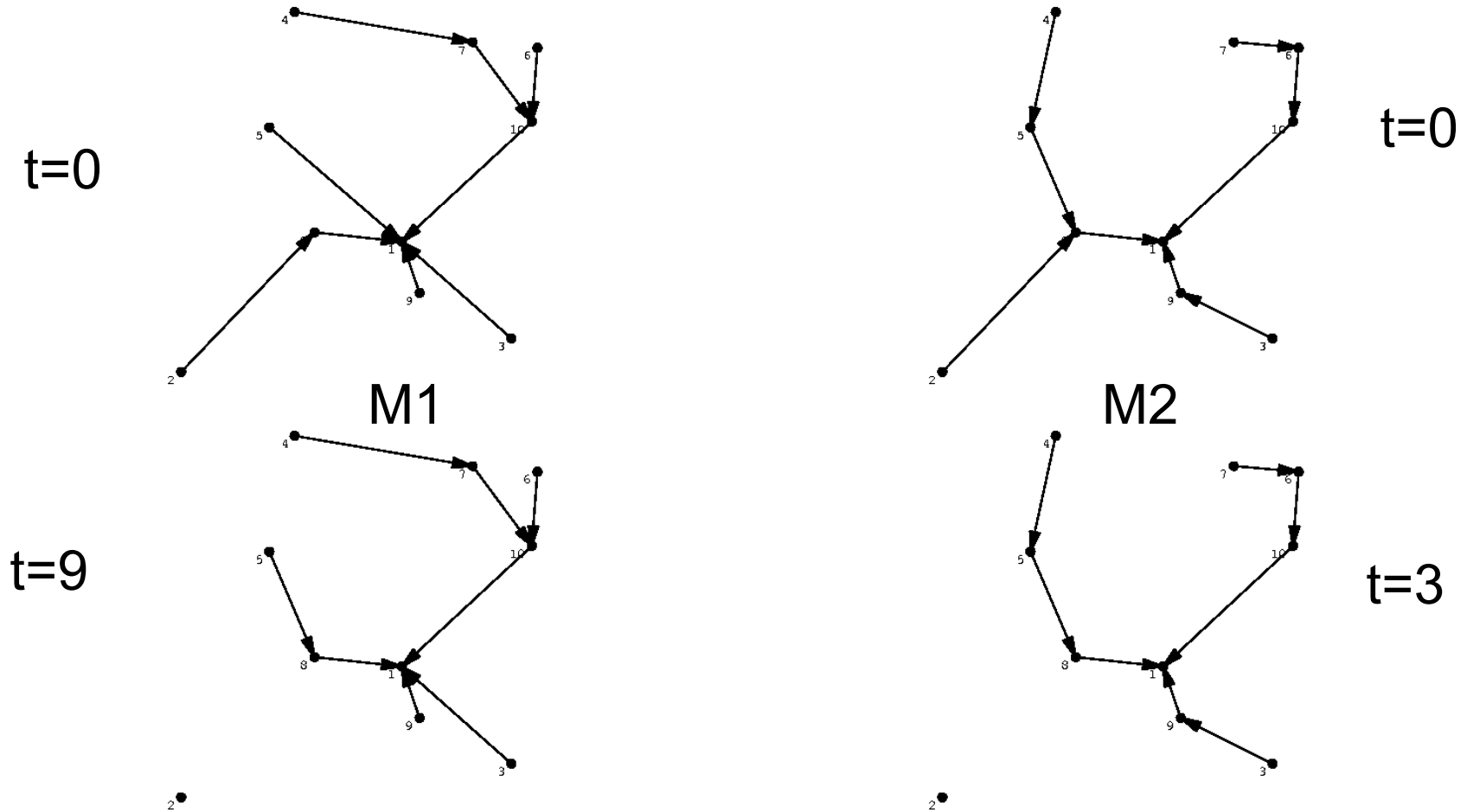


Network evolves over time

- Routing below based on battery capacities (10000, 20000, 30000, ..., 100 000)



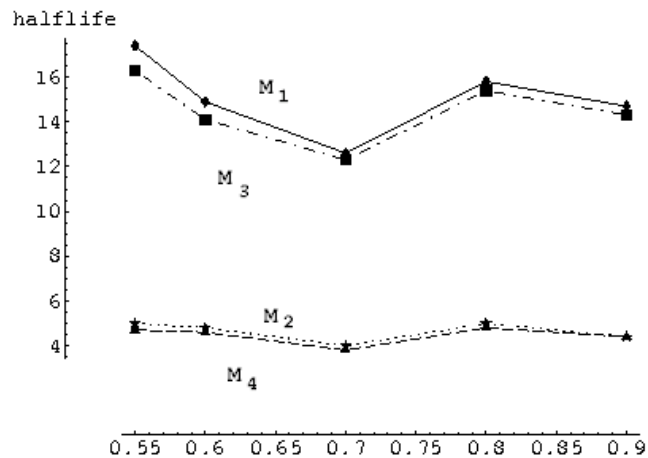
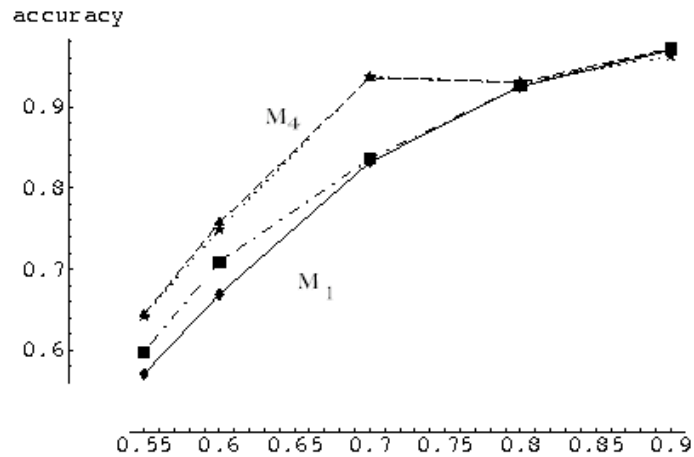
Network evolves over time



Simulations

- $\min_{\text{tree}} \Pr(\text{error})$ is intractable analytically. Therefore, simulate.
- Create a square area such that average number of neighbors per node is 4. Place nodes randomly, including sink node.
- Let T_{death} be the smallest t such that half the nodes lack the energy to successfully transmit a message to any neighbor. Randomly generate the “state of nature” H and a 1-bit observation $Y_i^t|H$ for each node i for $t=1, 2, 3, \dots, T_{\text{death}}$
- Compute T_{death} and accuracy = $|\{t : U_{\text{sink}} = H\}| / T_{\text{death}}$
- Did at least 200 trials for each combination of $N=10,20,40$ and models $M1,M2$ and $p=.55,.6,.7,.8,.9$

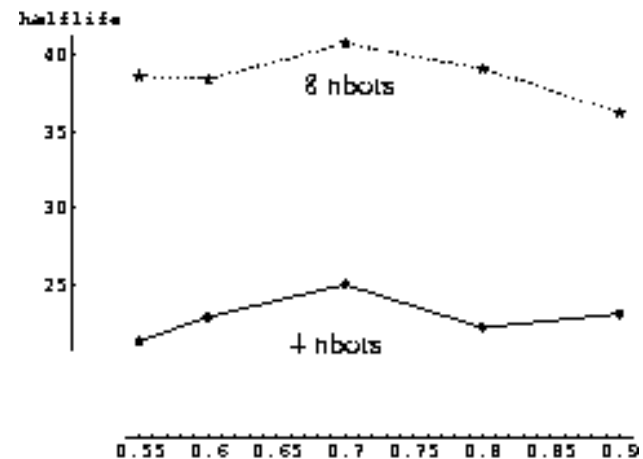
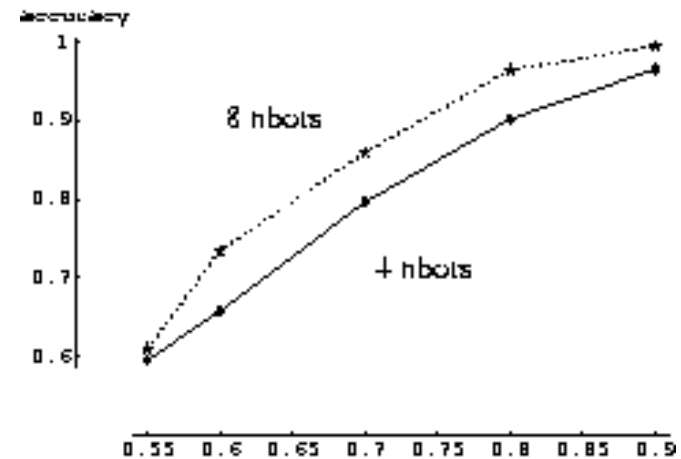
Simulation results



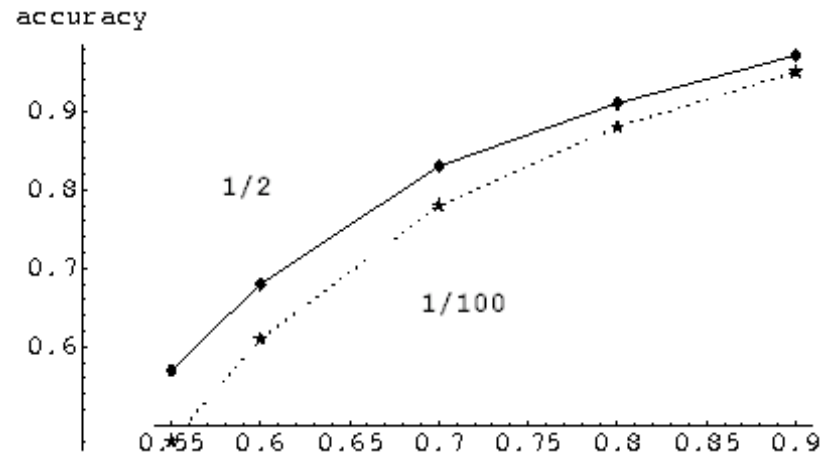
- X-axis is $p = \Pr(Y_i^t = H)$
- M2 has better accuracy (centralized)
- Difference not as pronounced for high p
- M1 has longer life

Simulation results

- denser network: make square area smaller so that average number of neighbors is 8 not 4.
- improves accuracy and lifetime
- increasing network size while keeping density constant hurts lifetime and accuracy



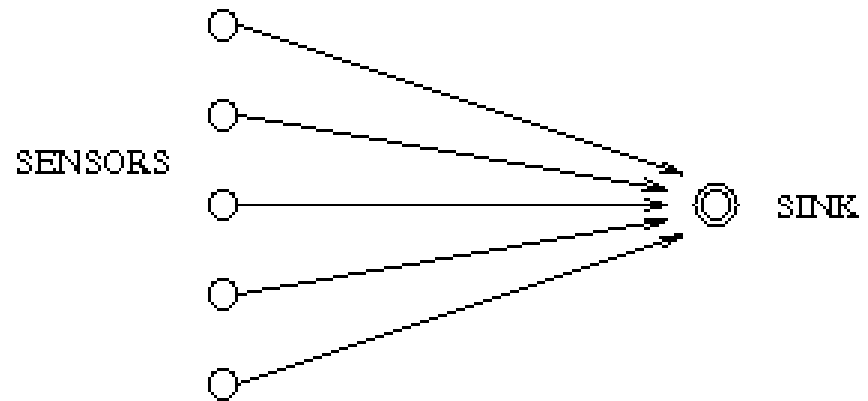
Simulation results



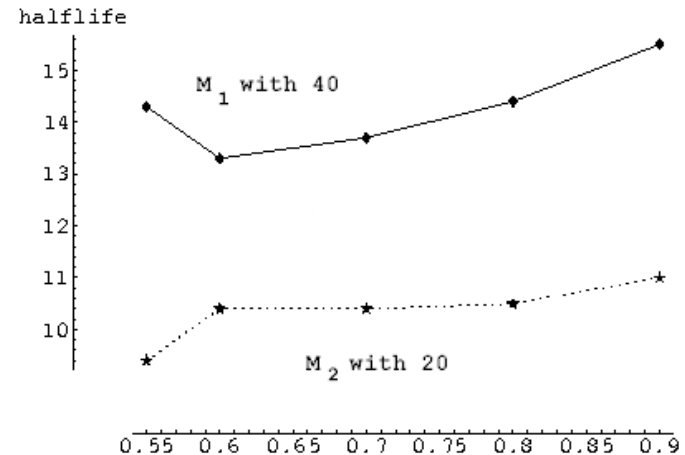
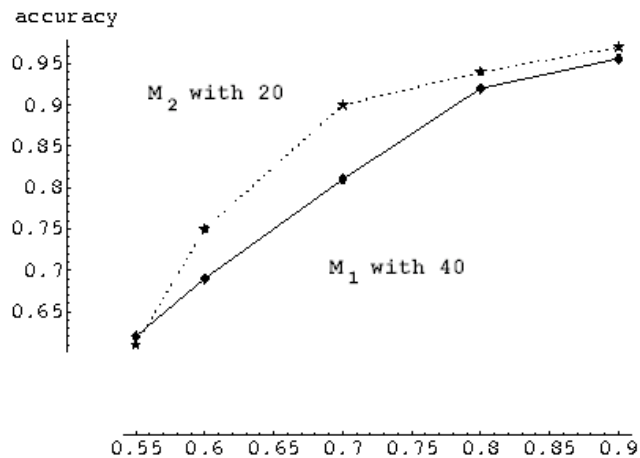
- Unequal prior $\Pr(H=1) \neq 1/2$ (corresponding to rare events) hurts M1 accuracy, because M1 uses majority vote.
- does not affect M2
- does not affect lifetime

Comparison to theory of decentralized decisions

- Shi, Sun & Wesel, Trans Info Th. 2001
- 1-hop (star) network
- “It takes fewer than twice as many sensors transmitting a single bit to give the performance of infinite precision sensors.”
- Rough translation: “M1 with 40 sensors should perform better than M2 with 20 sensors.”



Comparison to result of Shi et al



- M1 less accurate than theory predicts
- Multihop network: may include wrong local decisions in M1; local weightings may be wrong
- We do not use optimal thresholds--no way to compute them in a distributed fashion.
- Lifetime is offsetting advantage for M1

Conclusions

- Sensor network doing event detection studied. Trying to optimize (a) accuracy of detection, and (b) network lifetime.
- Cross-layer optimizations: achieved through routing metric: routing interacts with data aggregation (application) and with battery level (physical layer)
- Routing appears to be a convenient place for layers to interact.