CS649
Sensor Networks
Lectures 10-11: Topology Control

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Outline

- Topology Control
  - Introduction to topology control
    - High density deployment
    - Energy constraints
    - Power usage
  - Classification of algorithms
  - Examples
  - Performance comparison

High Density Deployment

- Smart and cheap sensors will be deployed to form ***densely*** distributed wireless networks.
  - Sensors are more effective when they are in close proximity to the phenomenon (~ r^{-2} -- r^{-4})
  - Similar to economics of stringing cables in wired networks.
  - Multiple sensing points can provide greater capability (sensor arrays such as in radar systems or binocular vision).
- Even with minimal sensor coverage, we get a high density communication network (radio range >> sensor range)

Energy Constraints

- Not always possible to do additional deployment (e.g. emergency services).
- Untethered operation due to lack of infrastructure precludes the use of high power wired sources (e.g. no infrastructure in lakes, forests, mountains, etc.)
- Nodes operate on batteries. They have a 5% rate of improvement every two years (compare to 100% improvement every 18 months of microprocessors).
- Alternative non-wired power sources are being investigated (solar panel, micro-engines, etc.), but not always practical or available.

Power Usage

- One of the nodes' subsystem that is critical in terms of power usage is the radio.
- Improvements in radio technology may improve the power usage by the radio, but there are physical limits to the energy required to send and receive a signal over a certain distance.
- Observation: radios consume about the same power in idle state as in Tx and Rx state.
- Chicken & egg problem: to save energy, radios must be turned off (not simply reduce packet transmissions); but if radios are turned off, nodes cannot receive messages.
- Name of the game: find a subset of nodes that provide communication coverage. Different schemes play different tricks to solve this problem.

Clustering Styles

- Minimal Connected Dominating Set (MCDS): Find the dominating set, and then find a subset of nodes that connect all the nodes in the dominating set. E.g.: AFECA, GAF, CEC, Span, and various theoretical algorithms.
- Density Estimation: Find a subset of nodes that provides a certain density threshold. E.g.: ASCENT, PEAS.
- Hybrid: E.g.: STEM.

Radio / MAC Assumptions

- Circular or Isotropic Models: various theoretical algorithms, PEAS, AFECA
- Grid-based connectivity: GAF
- Radio/MAC dependencies:
    - 802.11 Power Saving mode: Span
    - Promiscuous mode: ASCENT, CEC
    - 2 radios, one of them used as a wakeup component: STEM

Neighbor Information

- Locality:
  - 1-hop neighbor: AFECA, ASCENT, PEAS, STEM
  - n-hop neighbor (with various n > 1): GAF, CEC, Span and various theoretical schemes
- Dependency on routing: STEM, Span
- Measurement-based: ASCENT, CEC

Reaction to dynamics and load balancing

- Global re-calculation of the state: various theoretical schemes, STEM and Span (through routing)
- Local recovery: some theoretical schemes, GAF, CEC, ASCENT, PEAS
- Explicit load balancing mechanisms: Span, GAF, CEC.

SPAN

Benjie Chen, Kyle Jamieson, Robert Morris, Hari Balakrishnan
MIT
http://www.pdos.lcs.mit.edu/papers/span:wireless01

SPAN

- The goal is to preserve **fairness** and **capacity** while still providing energy savings.
- SPAN elects “coordinators” from all the nodes in the network to create the backbone topology.
- Other nodes remain in power-saving mode and periodically check if they should become coordinators.
- It tries to minimize the number of coordinators while still preserving network capacity.
- It depends on an ad-hoc routing protocol to get list of neighbors and the connectivity matrix between them.
- It runs above the MAC layer and alongside routing.

Coordinator Election & Announcement

- Rule: if 2 neighbors of a non-coordinator node cannot reach each other (either directly or via 1 or 2 coordinators), the node should become a coordinator.
- Announcement contention is resolved by delaying coordinator announcements with a randomized backoff delay.
- delay = ((1 – Er/Em) + (1 – Ci/(Ni pairs)) + R)*Ni*T
- Er/Em: energy remaining/max energy
- Ni: number of neighbors for node i
- Ci: number of connected nodes through node i
- R: Random[0,1]
- T: RTT for small packet over wireless link
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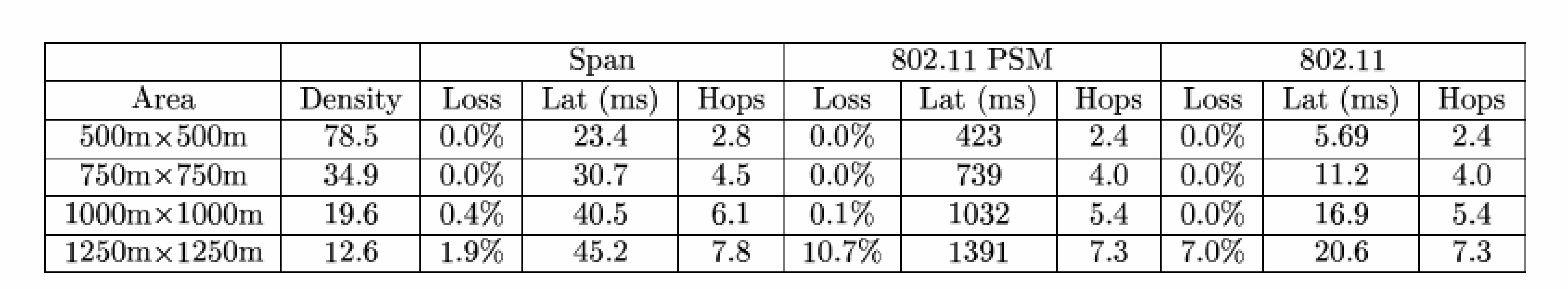
Coordinator Withdrawal

- Each coordinator periodically checks if it should withdraw as a coordinator (period ?)
- A node withdraws as a coordinator if every pair of neighbors can reach each other directly of via some other coordinators.
- To ensure fairness, after a node has been a coordinator for some period of time (period ?), it withdraws if every pair of nodes can reach each other through other neighbors (even if hey are not coordinators).
- After sending a withdraw message, the old coordinator remains active for a “grace period” to avoid routing loses until the new coordinator is elected.

Evaluation

- Parameters
  - Density
  - Number of sending/receiving pairs
  - Sending mode
- Metrics
  - Packet delivery ratio
  - Path length
  - Latency
  - Power consumption

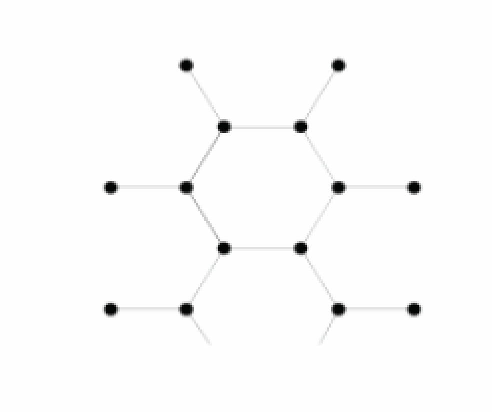
Comparison with 802.11 and 802.11 PSM

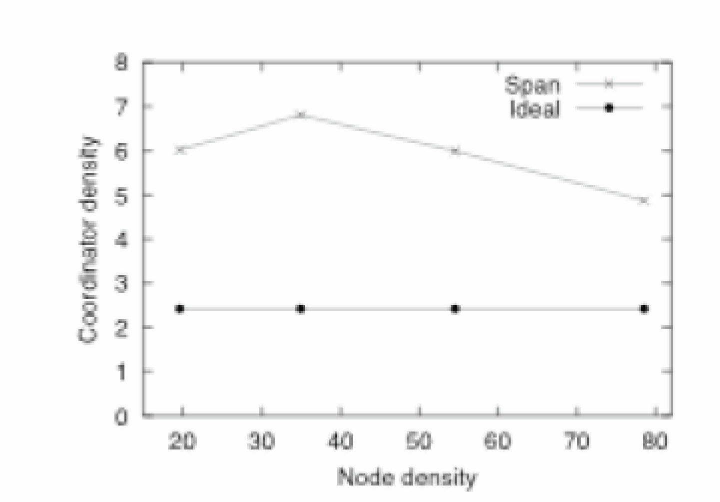


		Span			802.11 PSM			802.11		
Area	Density	Loss	Lat (ms)	Hops	Loss	Lat (ms)	Hops	Loss	Lat (ms)	Hops
500m×500m	78.5	0.0%	23.4	2.8	0.0%	423	2.4	0.0%	5.69	2.4
750m×750m	34.9	0.0%	30.7	4.5	0.0%	739	4.0	0.0%	11.2	4.0
1000m×1000m	19.6	0.4%	40.5	6.1	0.1%	1032	5.4	0.0%	16.9	5.4
1250m×1250m	12.6	1.9%	45.2	7.8	10.7%	1391	7.3	7.0%	20.6	7.3

Number of Coordinators

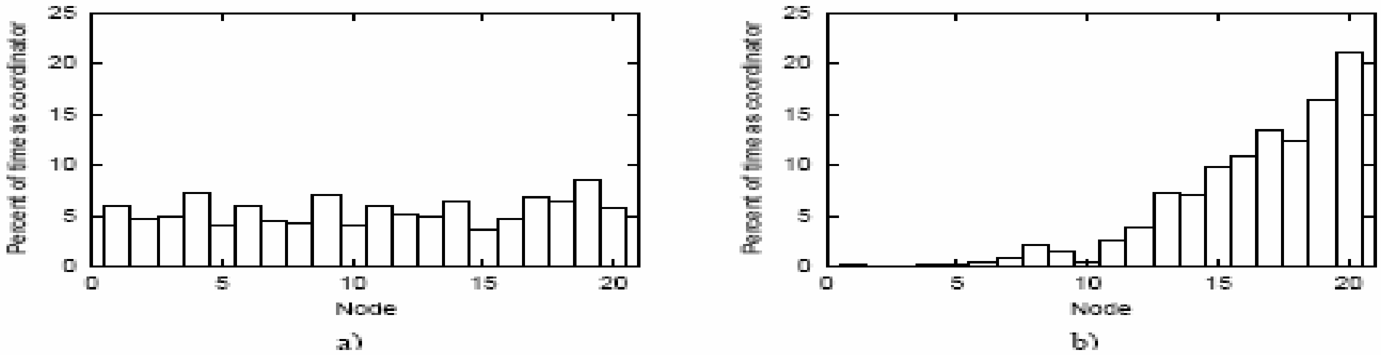
- Compared to “ideal” case
- Span elects more coordinators than hexagon scheme
  - Effect of density
  - Coordinator rotation





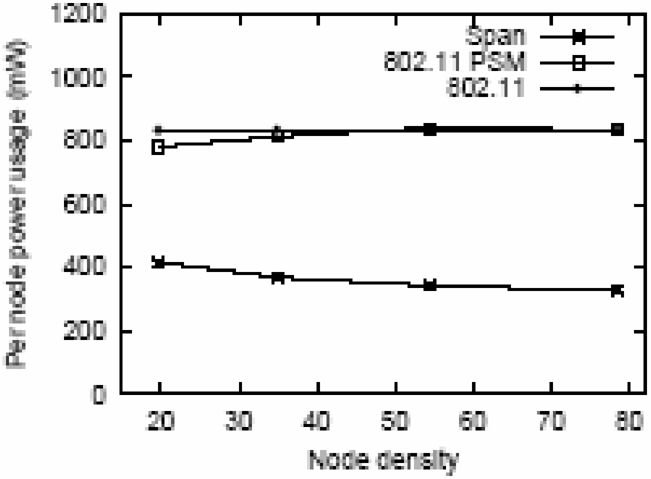
Coordinator Election as function of power

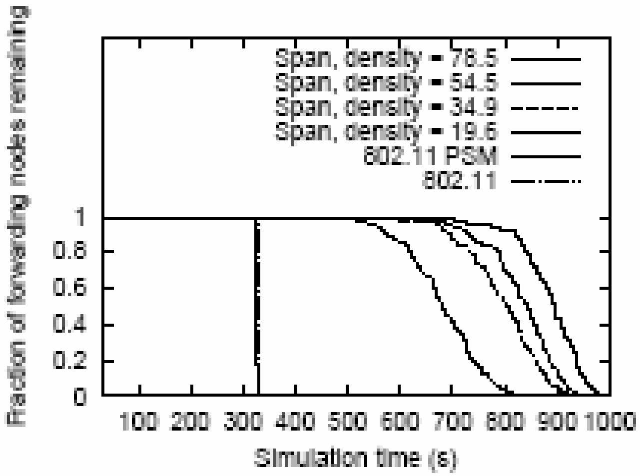
- Two models
  - All nodes have equal energy stores
  - Nodes has proportionally larger energy stores



Power Consumption

- 802.11 PSM provides no power savings(!)
- As density increases, SPAN saves more energy
  - Not linearly





GAF / CEC

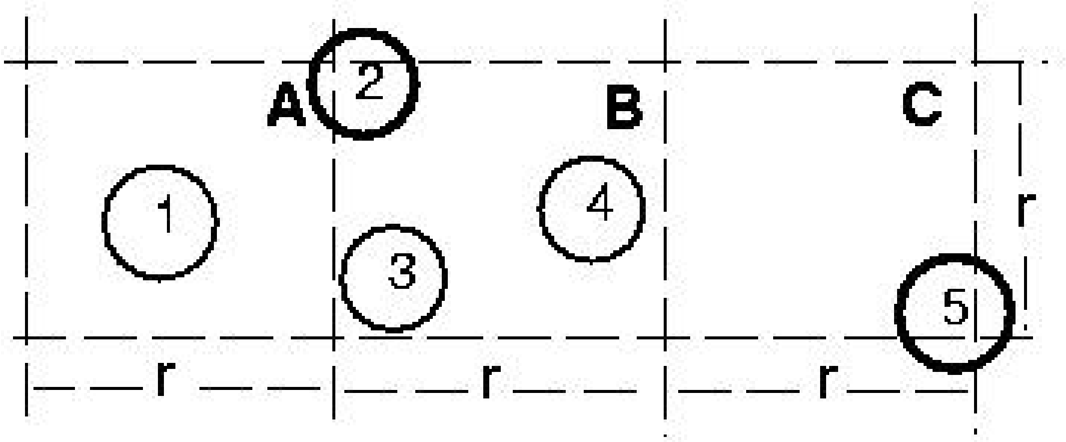
**Y. Xu, S. Bien, Y. Mori,
J. Heidemann & D. Estrin
USC/ISI – UCLA**

**http://www.isi.edu/scadds/papers/yaxu-mobicom2001.ps.gz
http://lecs.cs.ucla.edu/~sbien/papers/gaf-cec-journal.pdf**

Geographical Adaptive Fidelity

- Each node uses location information (provided by some orthogonal mechanism) to associate itself to a virtual grid.
- ***All*** nodes in a virtual grid ***must*** be able to communicate to ***all*** nodes in an adjacent grid.
- Assumes a deterministic radio range, a global coordinate system and global starting point for grid layout.
- GAF is independent of the underlying ad-hoc routing protocol.

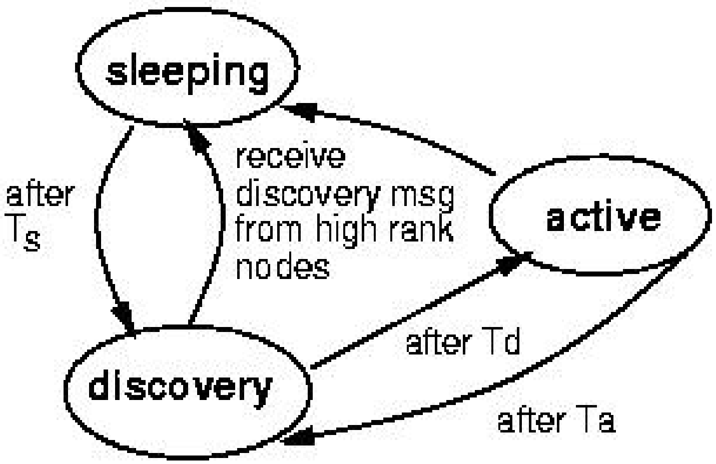
Virtual Grid Size Determination



- r: grid size, R: deterministic radio range
- $r^2 + (2r)^2 <= R^2$
- $r <= R/\text{sqrt}(5)$
- Number of grids: $A \big/ \left(R \big/ \sqrt{5} \right)^2$
- Best case savings: $nR^2 \big/ 5A$

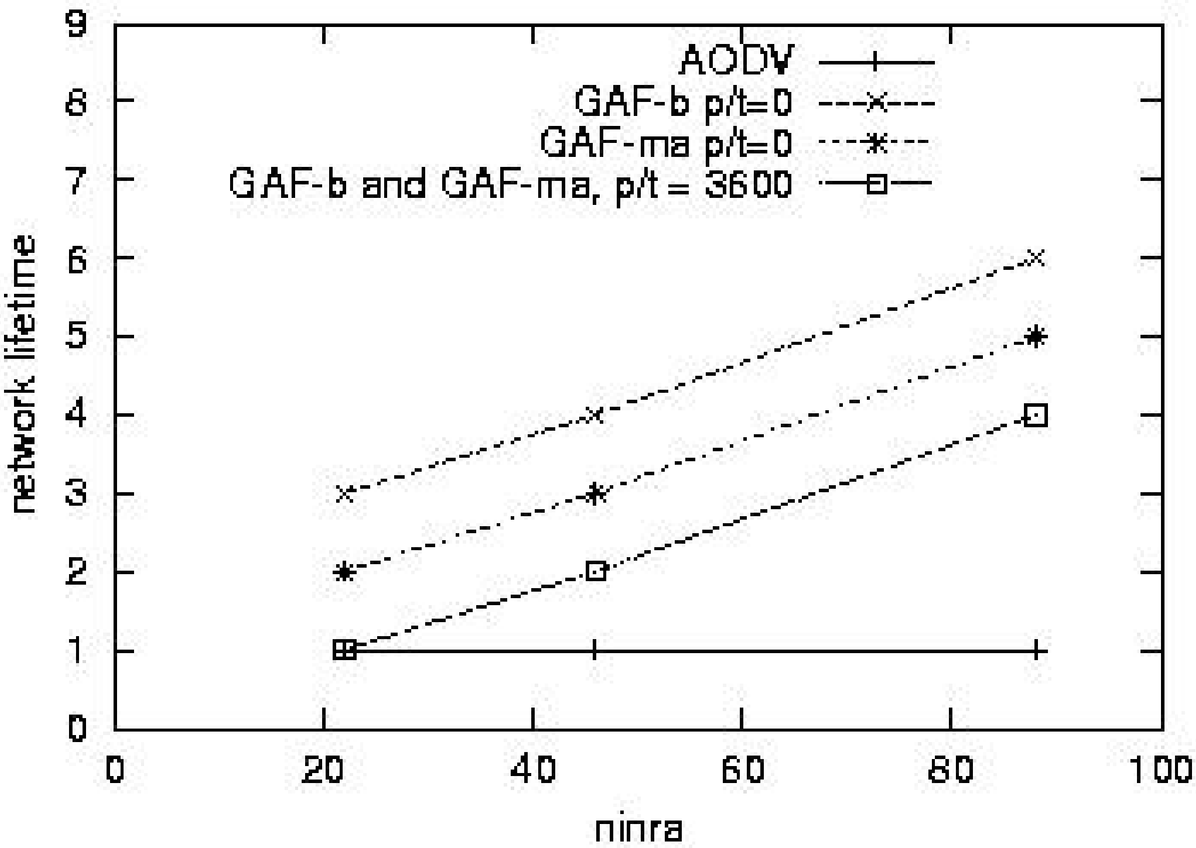
Parameters settings

- ***enat***: estimated node active time
- ***enlt***: estimated node lifetime
- ***Td,Ta, Ts***: discovery, active, and sleep timers.
- ***Ta*** = ***enlt*** || ***enlt***/2 (reason?)
- ***Ts*** = ***enlt***/2



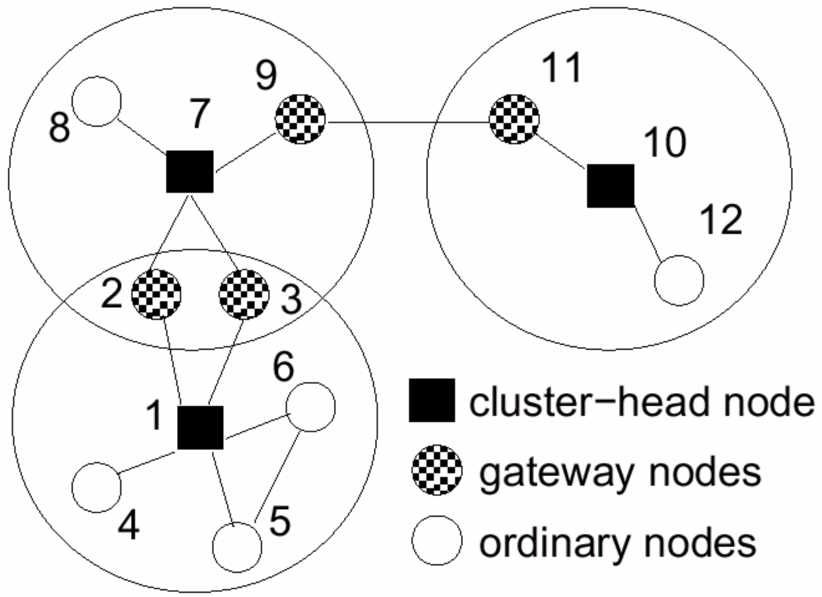
Performance Results

- Ninra: number of nodes in nominal radio range



CEC

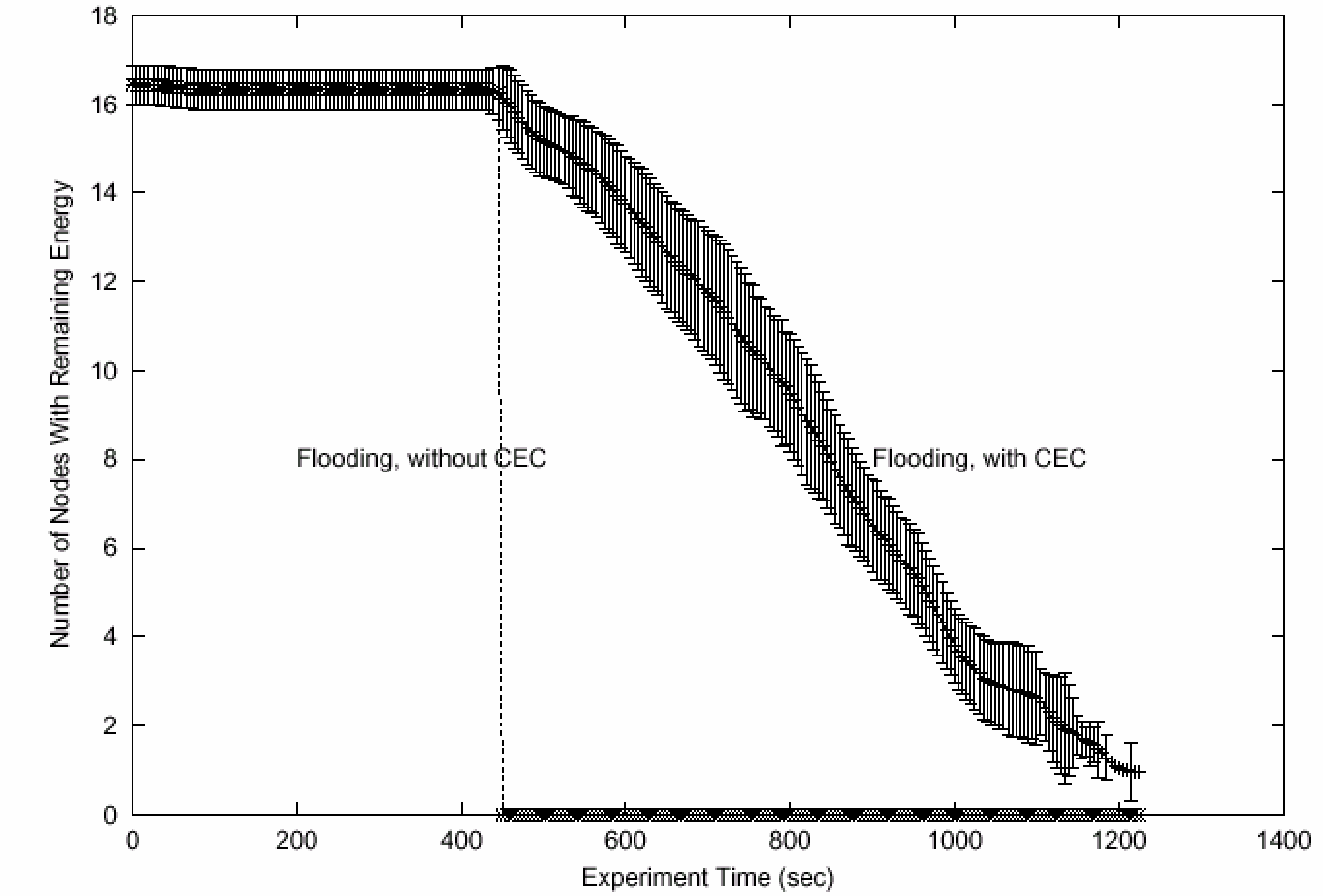
- Cluster-based Energy Conservation.
- Nodes are organized into overlapping clusters.
- A cluster is defined as a subset of nodes that are mutually reachable in at most 2 hops.



Cluster Formation

- Cluster-head Selection: longest lifetime of all its neighbors (breaking ties by node id).
- Gateway Node Selection:
  - primary gateways have higher priority.
  - gateways with more cluster-head neighbors have higher priority.
  - gateways with longer lifetime have higher priority.
- Ts = enlt/2
- Ta= ?

Network Lifetime



ASCENT

Alberto Cerpa and Deborah Estrin
UCLA

http://lecs.cs.ucla.edu/Publications/papers/ASCENT-Infocom-2002.ps

ASCENT

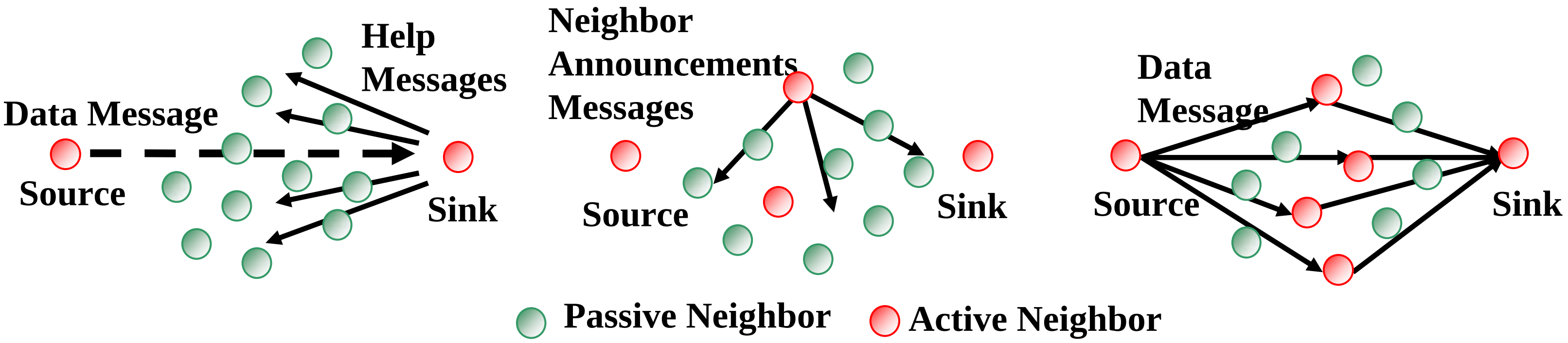
- Adaptive Self-Configuring sEnsor Networks Topologies.
- Observation: different applications may require the underlying topology to have different characteristics. For example:
  - Minimal.
  - Homogeneous with a certain degree of connectivity.
  - Heterogeneous with different degrees of connectivity in different regions. Examples of these different regions may be:
    - Along a data flow path.
    - Avoiding a data flow path.
    - In the border of an event of interest.
- The goal is to exploit the redundancy in the system (high density) to save energy while providing a topology that adapts to the application needs.

Practical connectivity issues

- Wireless connectivity is a very **complicated** matter in the real world. Multipath effects, asymmetries, obstacles, etc. make very difficult to have a precise propagation model.
- Instead, opted for **empirical adaptation**. Each node assesses its connectivity and adapts its participation into the multi-hop topology based on the measured operating region.
- Minimalist approach: ASCENT only needs to turn off the radio (sleep state) and to be able to turn the NIC/MAC in promiscuous mode (passive state).
- ASCENT runs on top of the MAC and below routing. It is independent of the routing protocol running on top, and it does not uses any information gathered by routing.

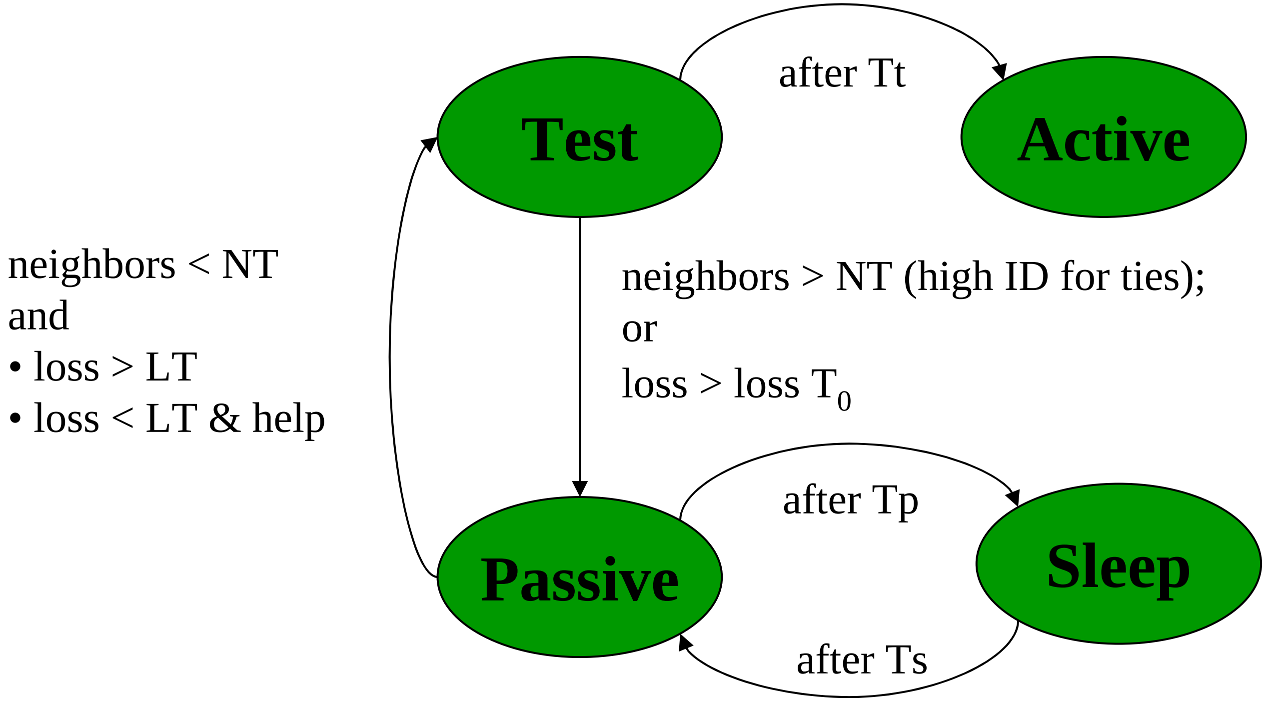
ASCENT Basics

- The nodes can be in active or passive state.
    - Active nodes are part of the topology and forward data packets (using an orthogonal routing mechanism that runs on the topology).
    - Nodes in passive state can be sleeping or collecting network measurements. They do not forward any packets.
- Each node measures the number of neighbors and packet loss locally.
- Each node then makes an informed decision to join the network topology or to perform some form of adaptation (e.g. reducing its duty cycle to save energy).



(a) Communication Hole (b) Self-configuration transition (c) Final State

State Transitions



NT: neighbor threshold

LT: loss threshold

Tx: state timer values (x = p: passive, s: sleep, t: test)

Gory Details

- Each node adds a sequence number to each packet (this allows packet loss detection)
- Neighbor estimator: based on a neighbor loss threshold (NLT) = 1 – 1/N (N: number of neighbors in the previous cycle).
- The neighbor threshold value (NT) determines the average degree of connectivity in the network.
- The loss threshold determines the maximum amount of data loss an application can tolerate.
- Relation between Tp/Ts (passive & sleep timers) determines the amount of energy savings and convergence time in case of dynamics.

ASCENT Energy Savings Analysis

$$ES(n)=\frac{n*Idle}{NT*Idle+(n-NT)*Idle*\frac{Tp}{Tp+Ts}+(n-NT)*Sleep*\frac{Ts}{Tp+Ts}}$$

NT: neighbor threshold

Tp: passive state timer

Ts: sleep state timer

Sleep: power radio off

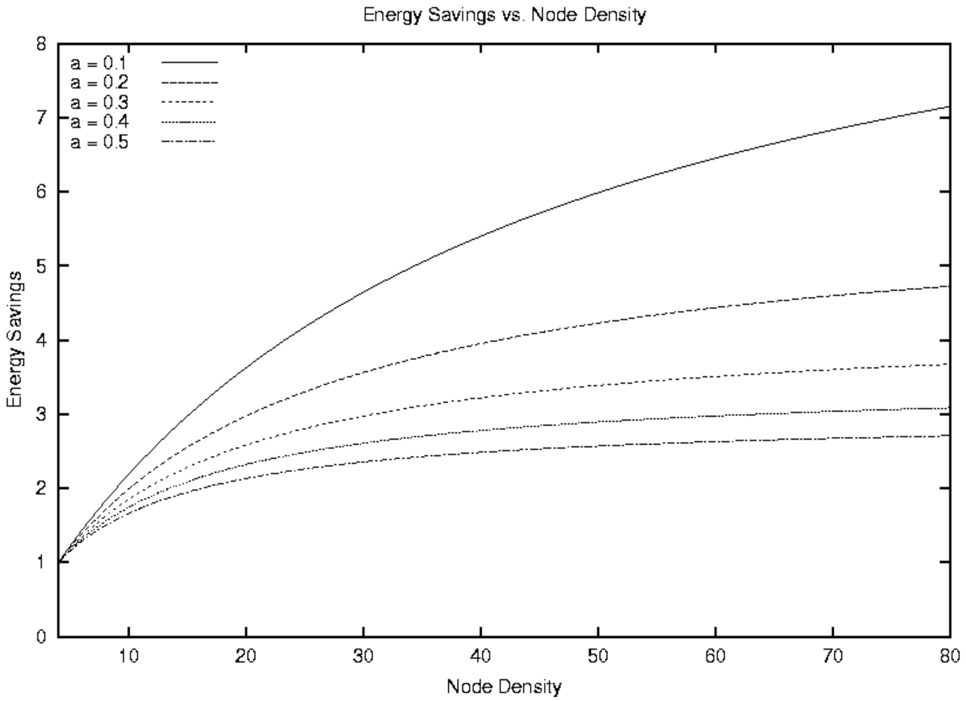
Idle: power radio on

α = ***Tp***/***Ts***

β = ***Sleep***/***Idle*** = 0.004

$$ES(n)=\frac{n}{NT+(n-NT)*\frac{\alpha+\beta}{\alpha+1}}$$

$$\lim_{n\to\infty} ES=\frac{\alpha+1}{\alpha+\beta}$$



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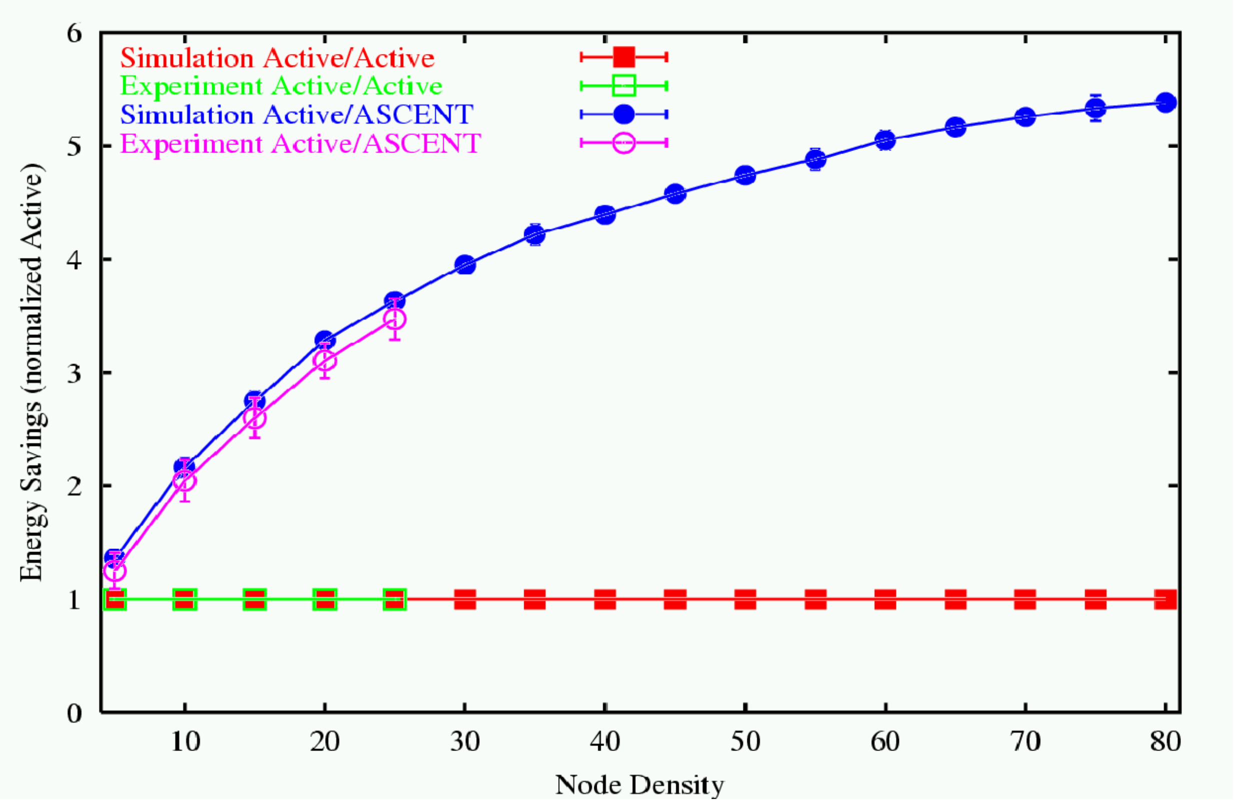
Performance Results



Energy Savings (normalized to the Active case, all nodes turn on) as a function of density. ASCENT ***provides*** significant amount of ***energy savings***, up to a ***factor of 5.5*** for high density scenarios.

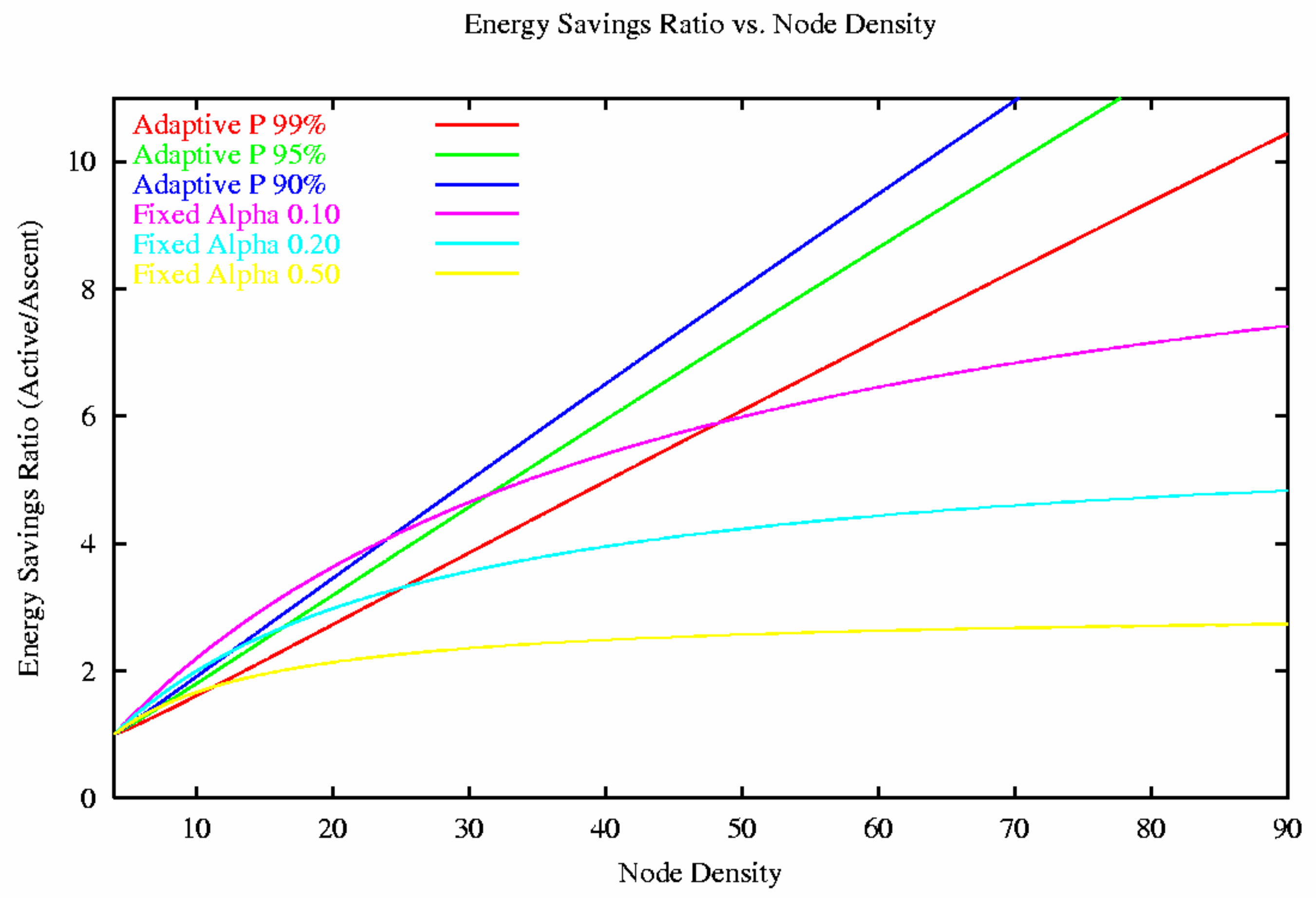
Adaptive Timers

$$Pk(\text{at least k passive nodes}) = 1 - \left(\left(\frac{1}{\alpha - 1} \right)^{n} * \left(\frac{\alpha^{k} - 1}{\alpha - 1} \right) \right)$$

$$\alpha(n) = 10^{-\left(\frac{\log(1 - Pk)}{n} \right)} - 1$$

- For any given probability target Pk and given the number of passive nodes in the area, nodes could calculate the optimal relation between the passive and sleep timers (α)
- The larger the Pk target, the larger the alpha for any given density.
- The larger the k, the larger the alpha (although it grows VERY slowly).

Adaptive vs Fixed Timers

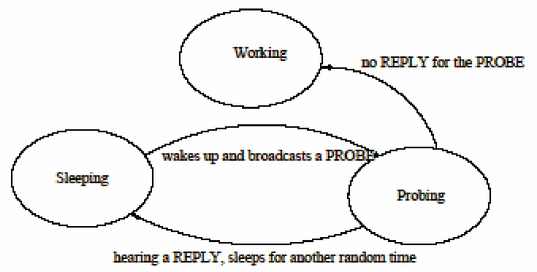


Another example: PEAS

PEAS: A Robust Energy Conserving Protocol for Long-lived Sensor Networks
Fan Ye et al
Presented in ICDCS 2003

Summary

- Assumed environment
    - Static network, high density, unexpected failures, radios with adjustable power savings
- Constraints
    - No per neighbor state, difficult to predict node lifetime
- Main idea
    - Probing Environment
        - Nodes periodically wake up and probe for the existence of other active nodes within range R_p
    - Adaptive Sleeping
        - If active nodes exist, node goes back to sleep for time drawn from $f(t_s) = \lambda e^{-\lambda t_s}$



Adaptive Sleeping

- Adjust probing rate λ, to keep aggregate probing rate at a desired value.
- Mechanism
  - Each working node estimates aggregate probing rate
  - Reply with estimate when sending REPLY
  - New probing rate $\lambda_{new} = \lambda \frac{\lambda_d}{\overline{\lambda}}$

Experimental Results

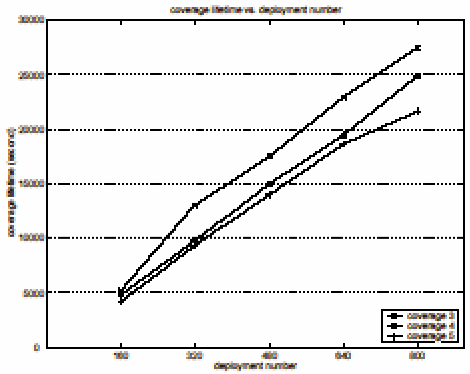


Figure 9. Extension of Coverage Lifetime

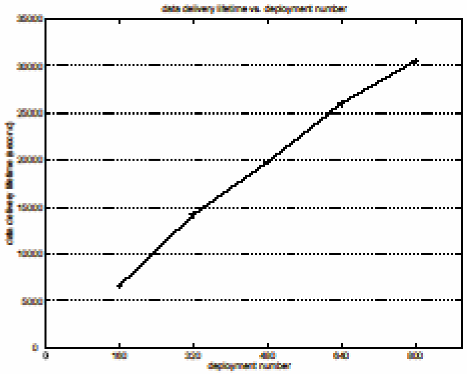


Figure 10. Extension of Data Delivery Lifetime

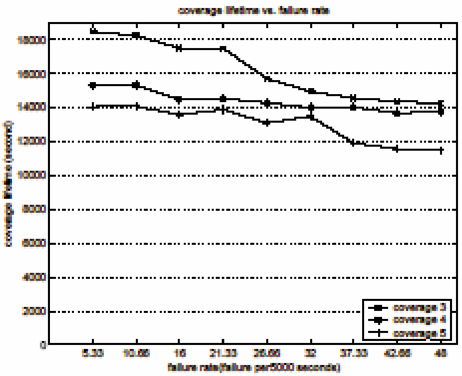


Figure 12. Coverage Lifetime with Failures

- Lifetime increases linearly with density
- Coverage lifetime drops between 12% to 20% when 38% of nodes fails

Comparison: Goals

- GAF, and SPAN share a similar goal: save as much energy as possible while still providing fairness and routing fidelity between any node in the network.
- ASCENT goal is to save as much energy as possible while establishing a topology of a certain characteristic. It does not necessarily preserve capacity from any node to any other node in the network.

Comparison: Interaction with routing

- SPAN gets the connectivity matrix and the neighbor list from a routing protocol. In addition, it needs to modify the route lookup process such that routing uses only coordinators to route packets.
- GAF/CEC and ASCENT do not depend on the routing mechanisms, nor they need to modify them.

Comparison: Other issues

- None of the previous schemes required any particular MAC.
- It would be interesting to study the synergy effect that these schemes may have with energy savings MACs (S-MAC, UCB MAC, etc).

Comparison: Energy Savings

- SPAN (2), GAF(3), CEC(3.5), and ASCENT (5.5) achieve comparable energy savings, albeit their goals are different.
- SPAN and ASCENT have sublinear energy savings as a function of density (because they periodically check the status of the network). GAF/CEC and ASCENT (w/adaptive timers) have linear energy savings as a function of density.
- Further studies are required to make more conclusive statements.

Comparison: Summary

	Goal (energy savings)	Routing dependency	Assumptions
GAF/CEC	preserve routing fidelity	none	geographic information for grid placement radio connectivity directly correlated with geography (gaf)
SPAN	preserve capacity of the raw topology	gets connectivity matrix and neighbors from routing requires modifications in the routing lookup process	802.11 MAC with Power Savings mode
ASCENT	adapt topology based on application needs	none	radio supports promiscuous mode