Analysis and Evaluation of Topological and Application Characteristics of Unreliable Mobile Wireless Ad-hoc Network

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Outline of Talk

- Motivation
- Definition of topological properties
- Mobility algorithms
- Application protocol – location determination
- Results
  - Without errors
  - With errors
- Observations
- Conclusions

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Motivation

- Topological characteristics of a network are important
  - Design of network protocols
  - Performance prediction of network protocols
  - Algorithms for improving topology
- Examples of topological properties
  - Connectivity
  - Coverage
  - Diameter
- Example scenario from US Department of Defense deployment of ad-hoc wireless network
  - Ad-hoc nodes carried by soldiers in a battlefield
  - Sensor nodes embedded in the battlefield for sensing properties of environment
  - Topological placement of the sensing nodes as well as the movement strategies affect the success of the military operation

Approach and Contributions

- Considered four topological properties that must **simultaneously** be satisfied in an ad-hoc network
  - Connectivity
  - Coverage
  - Diameter
  - Degree
- Proposed goal driven mobility algorithms for improving
  - Connectivity and diameter (Mean Shift Clustering or MSC)
  - Coverage (Shift Neighbors Away or SNA)
- Demonstrated requirement on node densities for required topological QoS values theoretically and through simulation
- Demonstrated the effect of topological characteristics on QoS of an application protocol (distributed location determination)

System Model

- Consider a sensor network model for the ad-hoc network
- Each node has a constant and limited transmission range
- Each node has a sensing range separate from transmission range
- Nodes can move in any direction in two-dimensional grid space
- Nodes can respond to control messages dictating direction and velocity of the motion
- Routing protocol: Dynamic Source Routing (DSR)
- Desired and minimum tolerable QoS values for the topological characteristics are specified to the system

Why Do We Care?

- Connectivity
  - Data dissemination from one part of the network to another
  - Minimum size of connected component for useful work
- Coverage
  - Can gather data about properties of covered region
- Diameter
  - Bounds the maximum delay in message communication
  - Important for data dissemination environments with real-time needs
- Degree
  - Higher degree means higher node connectivity
  - Higher node connectivity means higher resilience to node failures

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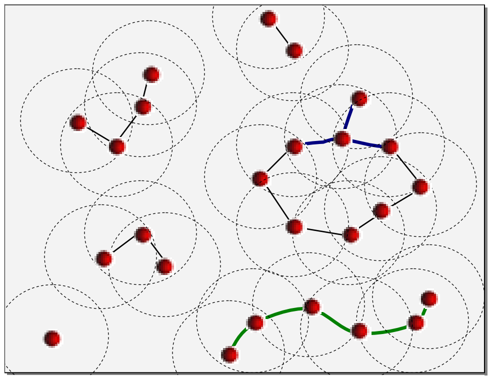
Definition of Topology Parameters



Connectivity
Size of maximum connected Component/Total number of nodes

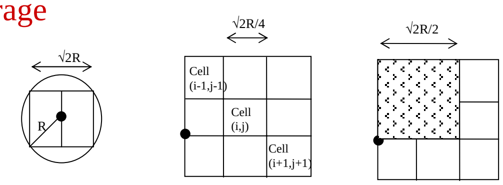
Coverage *(Σ / Area)*
Total area covered

Diameter *( )*
Max. number of hops

Degree *( )*
Max. degree of a node

Coverage Computation: Simplification

- Difficult to perform quick computation with circular coverage region
- Converted into a square coverage region which gives lower bound on coverage



- A node covers a square region of side √2.(Sensing radius) = √2R
- Split region into cells of side √2R/4
- Claim: If there is a node in any of the 8 adjacent cells to cell(i,j), then cell(i,j) is covered
- Coverage computed as number of covered cells/total number of cells ($=L^2/R_{eff}^2$)

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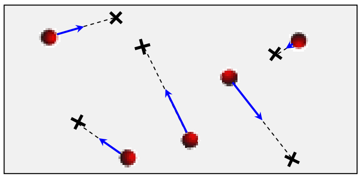
Mobility Models

.:: Random Way Point (RWP) ::.

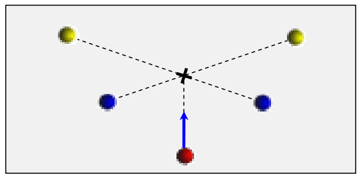
- Uniformly random movement
- Max velocity and epoch interval specified
- In each epoch interval, a random destination is chosen for each node
- Velocities are assigned in a way that all the nodes finish their movements before the epoch interval ends.



Mobility Models

.:: Mean-Shift Clustering (MSC) ::.

- Diameter decreasing algorithm
- Move to the centroid of neighbors
- *k-and-less* hop neighbors are considered in determining the centroid
- Problem: Causes coverage to go down to zero

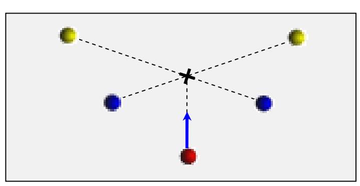


Mobility Models

.:: Mean-Shift Clustering (MSC) ::.

- To preserve the coverage property, following evaluation function is used.

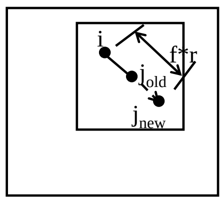
  LEF = w1 * Sum of distances from k-and-less neighbors – w2 * Distance from centroid
- If LEF is positive, then move is accepted
- The weights are adjusted depending on which property's QoS has not been satisfied



Mobility Models

.:: Shift Neighbors Away (SNA)

- Coverage increasing algorithm
- Pushes neighboring nodes outwards appropriately
- In each iteration, the nodes are traversed once left to right, and once top to bottom



Mobility Models

.:: Global evaluation function ::.

- **Choose one of MSC or SNA and apply evaluation function to determine whether rollback is required**
*GEF = W1 * Connectivity + W2 * Coverage - W3 * Diameter*
- **Relative changes are considered in each measure**
- **Accept move if the relative change is positive**
- **Else rollback**
- **In actuality, the nodes will perform the evaluation before movement, therefore no physical rollback is required**
- **Question: Who is to perform the GEF computation?**

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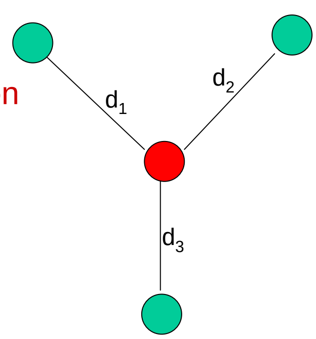
Application Protocol: Location Determination

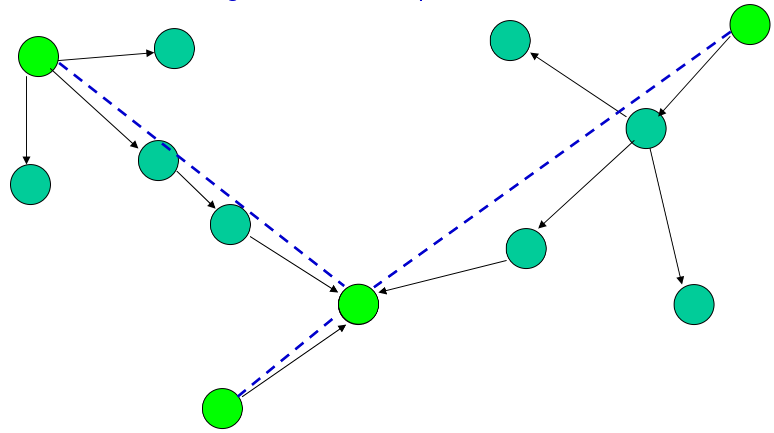
- To explore effect of topology on an application's QoS
- Problem Statement:
  - A large sensor network where a small fraction of nodes (typically 5 %) called *anchors* have special hardware to determine their location
  - To deduce location of all sensor nodes based on location information of anchors
  - Important and critical service
- Basic technique used: Triangulation

  Given locations of three anchor nodes and distances from each of them the location of the sensor node can be calculated



Location Determination Protocol

- Hop-Terrain and Refinement (Savarese & Rabaey)
  - Deduce how many hops away from multiple anchors
  - Use this knowledge to determine position and now act as an anchor



Theoretical Analysis: Connectivity and Coverage

- Mapping our scenario to stationary unreliable sensor grid
  - Impact of mobility: A position in the network may not be covered by any node
  - Impact of Unreliability: A position in the network may not be covered due to node failures
  - Impact of Largeness: Assuming a *Virtual* node at each position, asymptotic result can be deduced from the stationary case
- Result is sufficient condition for sensing and transmission radius for 100% connectivity and coverage
- Implication of our result
  - Impact of Mobility is not significant: The sufficient condition for connectivity and coverage differs from the stationary case only by a constant factor
  - Our result gives engineering heuristics on how to ensure connectivity and coverage in a large sensor network with unreliable mobile nodes.

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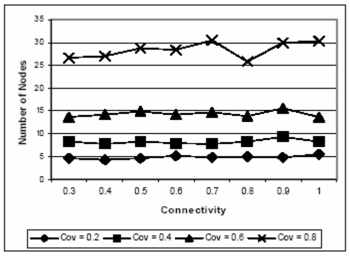
Experiments

Parameter	Value
Sensor field dimension	500 m X 500 m (1 m grid)
Initial placement regions	Two bands: (0,0) – (70,70). (430,430) – (500,500).
Node transmission range	125 m
Mean epoch length (T_E)	200 ms
Mean Time to Failure	200 ms
Mean Time to Repair	20 ms
Permanent:Transient failures	10:90
Number of runs (N_r)	5
Epoch iterations (E_N)	40

The simulation parameters

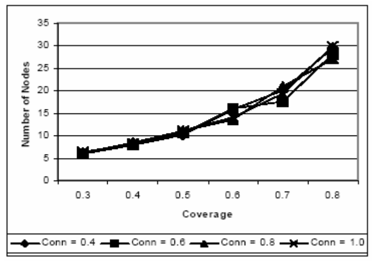
We perform two sets of experiments: one with no errors and one with node failures (permanent and temporary).

Experimental Results – Without Errors

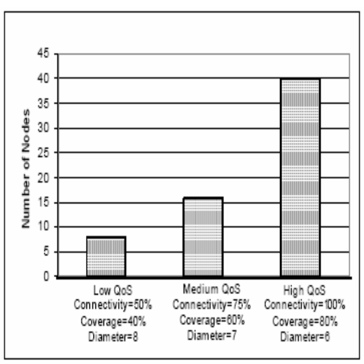


Connectivity: The number of nodes is pretty much stable in different desired network connectivity. Connectivity not sensitive to number of nodes.

Coverage: The required number of nodes drastically increases as the desired level of coverage increases. 60% coverage is guaranteed by 13 nodes, while 26 nodes are needed to guarantee 80%.



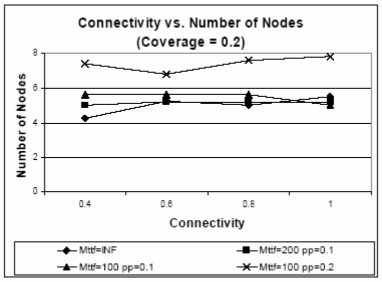
Experimental Results – Without Errors



QoS: Number of sufficient nodes to comply three QoS levels

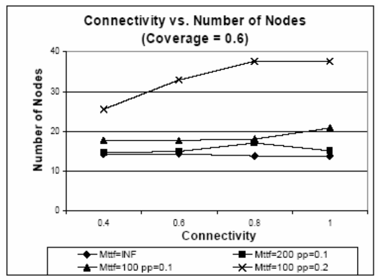
- **QoS_{low}** can be achieved with 8 nodes
- **QoS_{medium}** can be achieved with 16 nodes
- **QoS_{high}** can be achieved with 40 nodes

Experimental Results – With Errors

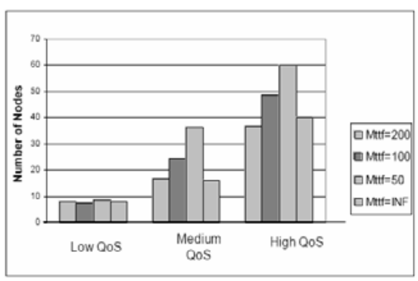


- Different MTTFs employed for transient node failure, but only marginal effect on the number of nodes.
- Permanent failures have significant effect on this number

Same graph with 60% coverage. Again MTTF values are not having much effect, while the permanent failures increases the node requirement drastically.



Experimental Results – With Errors



- Different levels of QoS and MTTF.
- Observe that when MTTF gets smaller values, its effect becomes more significant

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Observations

- Number of nodes required most strongly dependent on the coverage
  - The achievable coverage plateaus around 80% and beyond that increasing the number of nodes leads to fluctuating system behavior
- Achieving a high QoS level combining high thresholds for all the metrics requires a very large number of nodes
- With node failures, the permanent failures have a drastic effect on the coverage metric
  - The results are a function of the network lifetime
- Improved topological characteristics through goal-directed motion have marked improvement on the error in location estimation
  - With the requirement of a high coverage of 80%, the improvement is 45% for 30 nodes and shows an increasing trend with the number of nodes
  - With lower coverage, improvements of up to 68% are obtainable

Contributions

- Proposed goal-directed mobility algorithms for simultaneously satisfying multiple topological QoS parameters
- Evaluated node density required to achieve desired topology for a sensor network.
- Demonstrated that coverage requirements have the greatest effect on sensor density.
- Showed that small changes in permanent node failure rates have significant effect on a sensor network's topological characteristics.
- Studied the impact of desirable topological characteristics in improving the performance of an application layer location determination protocol

Further Details, Late-breaking news,
Pointers to presentations at the home
page of
DCSL : Dependable Computing
Systems Lab
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Backup Slides

Theoretical Result of Connectivity and Coverage

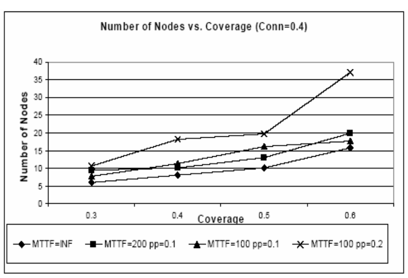
- Understanding the impact of mobility and unreliability: How to ensure connectivity and coverage in a large network?
- System model
  - Discrete System: Large number of sensor nodes arranged on a grid; Node movement in discrete time
  - Unreliable Nodes: Independent node failure with certain probability
  - Mobility Model: Individual node chooses speed and destination in a distributed fashion
- Goal of our analysis
  - How to design the network parameters (transmission radius, etc) to ensure connectivity and coverage statistically
  - How does our result scale with the network size
  - Verification of how the simplifying assumptions affect simulation results

SNA – calculation of coverage improvement

- **Theorem 1: After SNA converges, the coverage increases by a factor *(n-k)/k.***
  - After SNA converges, there is at least one node in each initially covered cell.
  - After SNA converges, there is at most one node in every cell.

- **Theorem 2:** After SNA converges, the coverage is improved over the Random Way Point (RWP) model of motion.
  - P_{SNA}(greater than one node in a cell) = 0
  - P_{RWP}(> one node in a cell)
    = 1 – P(one node in cell) – P(no node in a cell) > 0

Experimental Results – With Errors



Coverage graph for MTTF. Again permanent failures play important role while MTTF values do not affect the number of sufficient nodes.

Different levels of QoS and MTTF. Observe that when MTTF gets smaller values, its effect becomes more significant