Routing and Transport in Wireless Sensor Networks

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References

- **Adaptive Protocols for Information Dissemination in Wireless Sensor Networks**
  Wendi Rabiner Heinzelman, J. Kulik, and H. Balakrishnan
  Proceedings of the Fifth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom 1999), Seattle, Washington, August 15-20, 1999, pp. 174-185.

- **Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks**
  Chalermek Intanagonwiwat, Ramesh Govindan and Deborah Estrin
  Proceedings of the Sixth Annual International Conference on Mobile Computing and Networks (MobiCOM 2000), August 2000, Boston, Massachusetts.

- **Rumor Routing Algorithm For Sensor Networks**
  David Braginsky and Deborah Estrin
  First Workshop on Sensor Networks and Applications (WSNA), September 28, 2002, Atlanta, GA.

- **Highly Resilient, Energy Efficient Multipath Routing in Wireless Sensor Networks**
  Deepak Ganesan, Ramesh Govindan, Scott Shenker and Deborah Estrin
  Mobile Computing and Communications Review (MC2R), Vol 1., No. 2. 2002.

- **GRAdient Broadcast: A Robust Data Delivery Protocol for Large Scale Sensor Networks**
  Fan Ye, Gary Zhong, Songwu Lu, Lixia Zhang
  ACM WINET (Wireless Networks)

- **Energy-efficient Communication Protocol for Wireless Microsensor Networks**
  Wendi Heinzelman, Anantha Chandrakasan, Hari Balakrishnan
  Proceedings of the Hawaii International Conference on Systems Science, January 2000, Maui, HI.

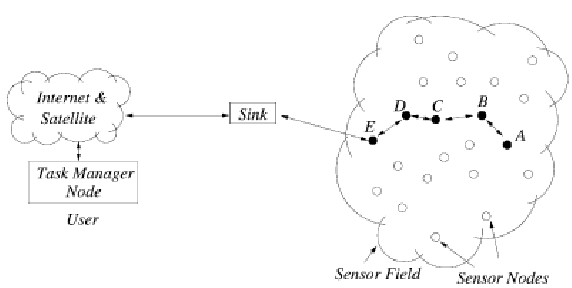
- **A Two-tier Data Dissemination Model for Large-scale Wireless Sensor Networks**
  Fan Ye, Haiyun Luo, Jerry Cheng, Songwu Lu, Lixia Zhang
  Proceedings of the Eighth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCOM 2002), September 2002, Atlanta, GA.

- **PSFQ: A Reliable Transport Protocol For Wireless Sensor Networks**
  Chieh-Yih Wan, Andrew Campbell, Lakshman Krishnamurthy
  First Workshop on Sensor Networks and Applications (WSNA), September 28, 2002, Atlanta, GA.

More References

- [redacted]
- **GPSR: Greedy Perimeter Stateless Routing for Wireless Networks**
  Brad Karp, H. T. Kung
  Proceedings of the Sixth Annual ACM/IEEE International Conference on Mobile Computing and Networks (MobiCOM 2000), August 2000, Boston, MA.
- **GeoMote: Geographic Multicast for Networked Sensors (2001)**
  http://citeseer.nj.nec.com/541776.html
- [redacted]
- Optimal Information Extraction in Energy-Limited Wireless Sensor Networks
  Fernando Ordonez and Bhaskar Krishnamachari
  June 2003.

Model



- Data flowing from sources (sensors) to “sink” is usually loss-tolerant
  - E.g., sensing temperature, light, acoustic, etc.
- Data flowing from “sink” to sensors is usually loss-sensitive
  - E.g., sensor management: re-tasking or re-programming sensors

Example Network Models

<table>
<tr><th>Sensors (Sources)</th><th>Users (Sinks)</th><th>Event</th><th>Interest Propagation</th><th>Data Dissemination</th></tr>
<tr><td rowspan="3">Stationary</td><td rowspan="3">Stationary</td><td rowspan="2">Query</td><td>Static</td><td rowspan="2">Unicast</td></tr>
<tr><td rowspan="2">Unicast</td></tr>
<tr><td rowspan="2">Continuous</td><td rowspan="2">Multicast</td></tr>
<tr><td rowspan="3">Mobile</td><td rowspan="3">Mobile</td><td rowspan="2">Multicast</td></tr>
<tr><td rowspan="2">Target Detection</td><td rowspan="2">Broadcast</td></tr>
<tr><td>Broadcast</td></tr>
</table>

Protocols

- Flooding
- Gradient → Niky
- Clustering
- Reliable → George
- Geographic → Wei

- Analysis → Vijay

Flooding Based Approaches

- Flooding
- SPIN - Sensor Protocol for Information via Negotiation

"Adaptive Protocols for Information Dissemination in Wireless Sensor Networks," Wendi Rabiner Heinzelman, J. Kulik, and H. Balakrishnan, *MobiCom 1999.*

SPIN

Sensors (Sources)	Users (Sinks)	Event	Interest Propagation	Data Dissemination
Stationary	Stationary	Query	Static	Unicast
Mobile	Mobile	Continuous	Unicast	Multicast
		Target Detection	Multicast	Broadcast
			Broadcast	

Gradient Based Approaches

- Directed Diffusion

  "Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks," Chalermek Intanagonwiwat, Ramesh Govindan and Deborah Estrin, *MobiCOM 2000.*

- GRAB - GRadient Broadcast

  "GRAdient Broadcast: A Robust Data Delivery Protocol for Large Scale Sensor Networks," Fan Ye, Gary Zhong, Songwu Lu, Lixia Zhang, ACM Wireless Networks.

Directed Diffusion and GRAB

Sensors (Sources)	Users (Sinks)	Event	Interest Propagation	Data Dissemination
Stationary	Stationary	Query	Static	Unicast
			Unicast	
		Continuous		Multicast
Mobile	Mobile		Multicast	
		Target Detection	Broadcast	Broadcast

Is multi-path routing really fault-tolerant?

The Energy-Robustness Tradeoff for Routing in Wireless Sensor Networks

Bhaskar Krishnamachari,Yasser Mourtada and Stephen Wicker

Presented by Vijay Erramilli
Sensor Networks Seminar
Fall 2003
Boston University

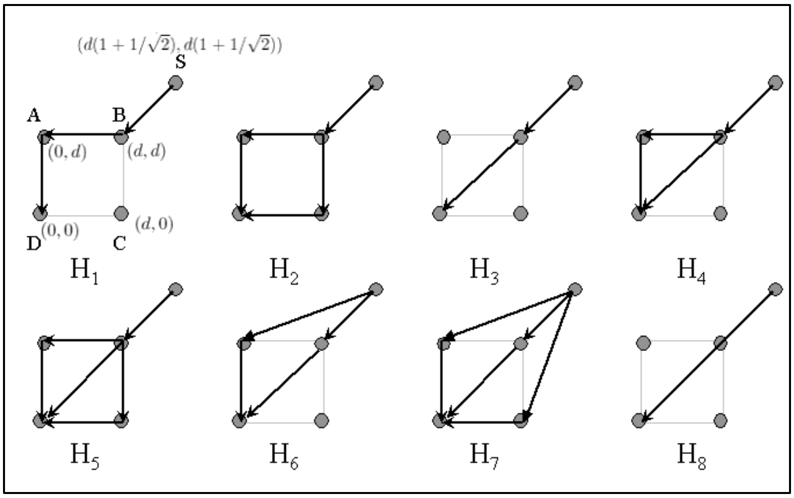
Motivation

- Differing views of providing fault-tolerant routing
  - Redundancy vs. Safeguard against node failures
- Multipath Routing introduces redundancy
  - E.g., Directed Diffusion, GRAB etc.
- What about Single Path?

Major Idea Studied

- Single Path Routing with high transmission powers
- Helps in fault-tolerance and conserving energy

Model Used



Model Used(Contd)

- **R_H = Minimum radius required**
- **$E_H = m_H R_H^a$ where m_H = no. of transmissions,**
  - a = **Path loss exponent**
- **p = prob. of node failure**

Routing Scheme H	Minimum Radius R_H	Energy Cost E_H	E_H $(\alpha = 2)$	E_H $(\alpha = 4)$	Robustness Π_H
H_1	d	$3d^{\alpha}$	$3d^2$	$3d^4$	$(1-p)^2$
H_2	d	$4d^{\alpha}$	$4d^2$	$4d^4$	$(1-p)(1-p^2)$
H_3	$d\sqrt{2}$	$2(d\sqrt{2})^{\alpha}$	$4d^2$	$8d^4$	$(1-p)$
H_4	$d\sqrt{2}$	$3(d\sqrt{2})^{\alpha}$	$6d^2$	$12d^4$	$(1-p)$
H_5	$d\sqrt{2}$	$4(d\sqrt{2})^{\alpha}$	$8d^2$	$16d^4$	$(1-p)$
H_6	$d\sqrt{2(1+1/\sqrt{2})}$	$3(d\sqrt{2(1+1/\sqrt{2})})^{\alpha}$	$10.2d^2$	$35.0d^4$	$(1-p^2)$
H_7	$d\sqrt{2(1+1/\sqrt{2})}$	$4(d\sqrt{2(1+1/\sqrt{2})})^{\alpha}$	$13.7d^2$	$46.6d^4$	$(1-p^3)$
H_8	$d(1+\sqrt{2})$	$(d(1+\sqrt{2}))^{\alpha}$	$5.2d^2$	$34.0d^4$	1

TABLE I
ENERGY AND ROBUSTNESS MEASURES FOR ALTERNATIVE ROUTING CONFIGURATIONS

Model Used (cont'd)

- How to compare Robustness w/ Energy-efficiency?
- Pareto Optimality!
- Notion of Domination:

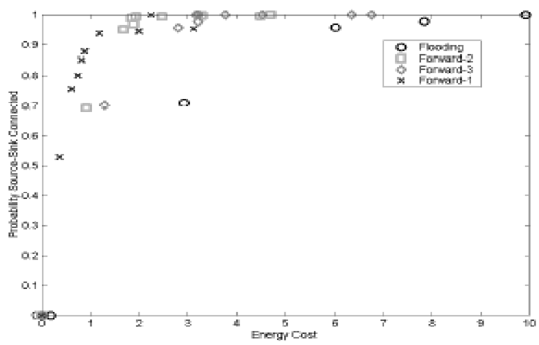
  $\Pi_{Hi} >= \Pi_{Hj}$, $E_{Hi} < E_{Hj}$ or $\Pi_{Hi} > \Pi_{Hj}$, $E_{Hi} <= E_{Hj}$
- Not dominated ➔ Pareto Set
- Example for $\alpha = 2$, Set $= \{H_1, H_3, H_8\}$

Analytical Results

- All Pareto Optimal Sets are Single Path!
- Multipath not the best solution!

Simulation Setup and Results

- 50 Nodes, S & D fixed
- Simulating forward-*k* routing algorithms including flooding



Probability that a route exists with respect to normalized energy cost (5 % failure rate)

Analysis of Energy-Efficient Fair Routing in Wireless Sensor Networks through Non-Linear Optimization

Bhaskar Krishnamachari, Fernando Ordonez

Presented by Vijay Erramilli
Sensor Networks Seminar,
Fall 2003
Boston University

Motivation

- Current Work: Protocol Development/Simulations/Testing
- Need for theoretical performance bounds
  - help in defining standards
- Non-linear convex optimization methods used to obtain bounds

Related Work

- Simulation Studies like Directed Diffusion, GRAB, etc.
- Bhardwaj and Chandrakasan find upper bounds on lifetime of sensor networks
- Kalpakis et al. give LP formulation to schedule flows to maximize network lifetime

References

•M. Bhardwaj and A.P. Chandrakasan"Bounding the lifetime of Sensor Networks via Optimal Role Assignments," *INFOCOM 2002*

• K. Kalpakis, K. Dasgupta and P. Namjoshi, Maximum Lifetime Data Gathering and Aggregation in Wireless Sensor Networks," *ICN 2002*

Model Used

- **Fairness** : % of total information that can be sent by each source node to sink

- n nodes, each node :
  - E_i - Energy
  - R_i - max source rate
  - f_{ij} - info flow rate b/w nodes i and j
  - P_{ij} - Transmission power b/w nodes i and j
  - C - per-bit reception power
  - d_{ij} - distance b/w nodes i and j

  α_i - fairness proportion of total info sent to the sink

  η - noise in channel

Model Used (cont'd)

- Formulation 1 - Max. Information Extraction

$$\max \sum_{j=1}^{n} f_{jn+1} \quad (1)$$

$$\text{s.t.} \sum_{j=1}^{n} f_{ji} \leq \sum_{j=1}^{n+1} f_{ij} \quad (1a)$$

Info Outflow >= Info Inflow

$$\sum_{j=1}^{n} f_{ji} + R_i \geq \sum_{j=1}^{n+1} f_{ij} \quad (1b)$$

Outflow <= Inflow + Max. Source rate

$$\sum_{j=1}^{n+1} f_{ij} - \sum_{j=1}^{n} f_{ji} \leq \alpha_i \sum_{j=1}^{n} f_{jn+1} \quad (1c)$$

Fairness Constraint

Model Used (cont'd)

$$\sum_{j=1}^{n+1} P_{ij} + \sum_{j=1}^{n} f_{ji} C \leq E_i \qquad (1d)$$ Energy Constraint

$$f_{ij} \leq \log\left(1 + \frac{P_{ij} d_{ij}^{-2}}{\eta}\right) \qquad (1e)$$ Power Constraint

$$f_{ij} \geq 0, P_{ij} \geq 0 \qquad (1f)$$ Non-Negativity Constraints

Results

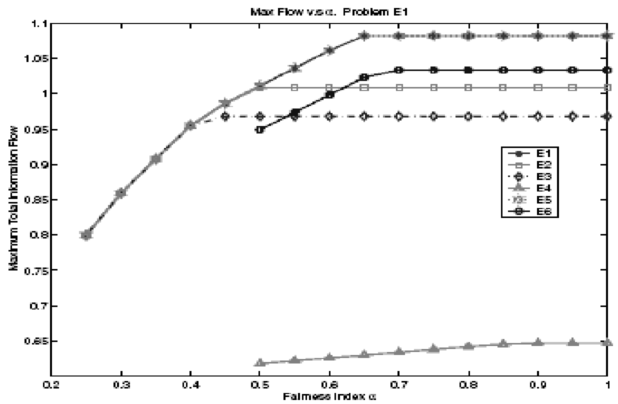
- Solved using LOQO
- Four nodes located at (1,0),(2,0),(3,0),(4,0), sink - (0,0)

Experiment	Node 1	Node 2	Node 3	Node 4
E1	1.0	1.0	1.0	1.0
E2	0.5	1.5	1.5	0.5
E3	0.4	0.8	1.2	1.6
E4	0.0	0.0	1.0	3.0
E5	1.6	1.2	0.8	0.4
E6	3.0	1.0	0.0	0.0

TABLE I
DESCRIPTION OF EXPERIMENTS: MAXIMUM SOURCE RATES FOR EACH NODE IN THE NETWORK

Reference: R.J. Vanderbei, "LOQO- A User's Manual- version 3.10," *Optimization Methods and Software, 1999*

Results



Maximum total information flow to sink versus the fairness proportion index α for each experiment

Conclusions & Future Work

- High fairness constraint results in decrease in information extraction and high energy usage
- Need to incorporate aggregation and other constraints

Clustering and Cellular Based Approaches

- LEACH - Low Energy Adaptive Clustering Hierarchy

  "Energy-efficient Communication Protocol for Wireless Microsensor Networks," Wendi Heinzelman, Anantha Chandrakasan, Hari Balakrishnan, *Proc. Hawaii International Conference on Systems Science*, 2000.

- TTDD - Two Tier Data Dissemination

  "A Two-tier Data Dissemination Model for Large-scale Wireless Sensor Networks," Fan Ye, Haiyun Luo, Jerry Cheng, Songwu Lu, Lixia Zhang, MobiCOM 2002.

LEACH

- Motivation of the work
  - Direct transmission to sink, min-energy routing, and static clustering may not be optimal
- Single major idea in paper
  - Clustering where cluster heads are randomly selected and rotated
  - Cluster heads send TDMA schedule to members
  - Cluster heads aggregate and send directly to sink
- Model provided in paper
  - Data delivery phase longer than setup phase
- Related work
  - Direct, min-energy routing, static clustering

Which one, Direct or MER, is more efficient?

LEACH

Cluster head selection:

Node n chooses random number, s, between 0 and 1.

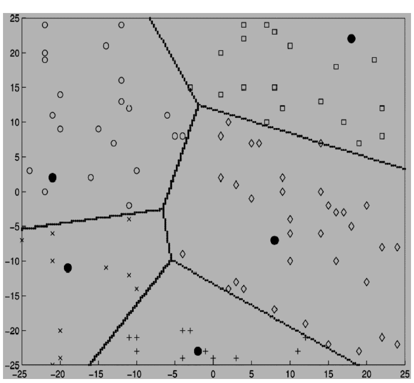
If $s < T(n)$, node n becomes a cluster head in current round where:

where: P = desired percentage of cluster heads

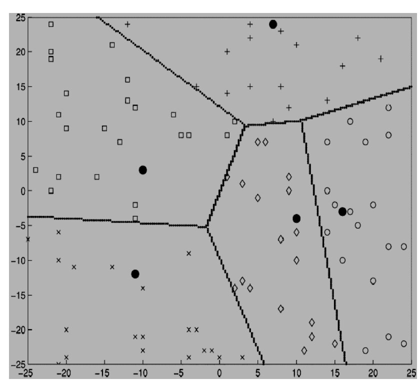
G = set of nodes that have not been a cluster head in the last $1/P$ rounds

LEACH

Cluster Head Rotation:



Round r



Round $r + 1$

Nodes "randomly" die!

LEACH

- Advantages of the work
  - Scalability: local interactions
  - Energy-efficient: members only wake up during their scheduled transmission
- Improvements to the work
  - Cluster selection aware of energy left
- Single major result
  - Order of magnitude reduction in energy consumption and network lifetime compared to direct, min-energy routing and static clustering
- Future research
  - How to dynamically use the “right” number of cluster heads?
  - What if cluster heads fail?
  - Can it be extended to multiple levels of hierarchy?

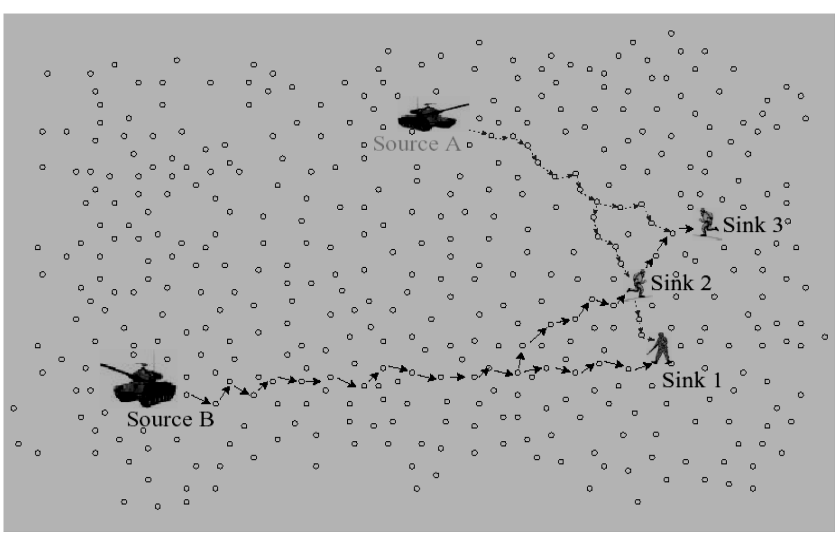
LEACH

Sensors (Sources)	Users (Sinks)	Event	Interest Propagation	Data Dissemination
Stationary	Stationary	Query	Static	Unicast
		Continuous	Unicast	Multicast
Mobile	Mobile		Multicast	
		Target Detection	Broadcast	Broadcast

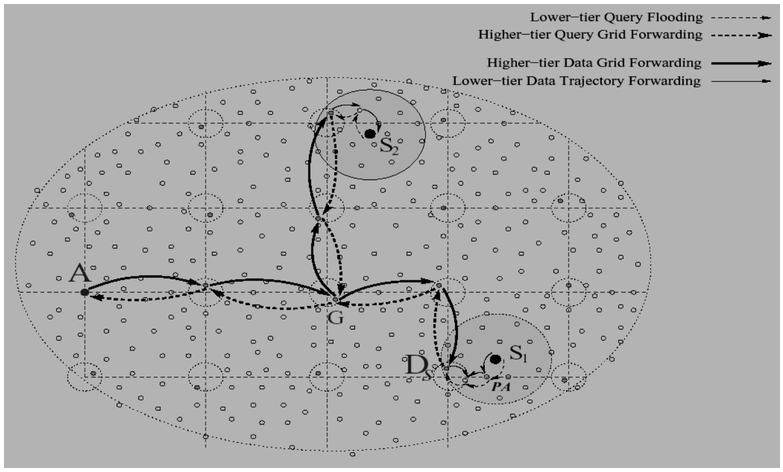
TDD

- Motivation of the work
  - Deal with mobile sinks, avoiding the overhead of global re-flooding by the sink as it moves
- Single major idea in paper
  - Source proactively builds a virtual grid of dissemination nodes
  - Query locally flooded, then forwarded upstream
  - Source sends data on reverse path (upper tier)
  - Trajectory forwarding hides sink mobility from immediate dissemination node (lower tier)
- Model provided in paper
  - Mobile sinks in a stationary sensor field
  - Geographic routing
- Related work
  - DVMRP: source periodically floods the network
  - Rumor routing

TTDD



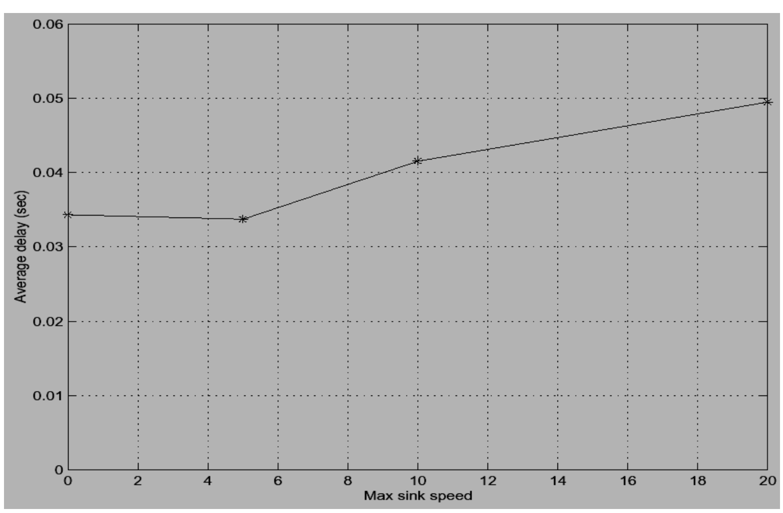
TTDD



Does this really scale to multiple sources?
How bad are these paths?

TTDD

Latency with Mobility:



TDD

- Advantages of the work
  - Scalable: local flooding of queries, which are aggregated along dissemination path
- Improvements to the work
  - Flood query using expanded ring search
- Single major result
  - For static sinks, energy and latency comparable to directed diffusion
- Future research
  - What should be the grid size? *Why is it important?*

Grid size controls balance between local query flooding and grid construction overhead

  - How to deal with mobile targets?
  - How to build a non-uniform grid based on sinks' locations?
  - How to maintain the grid if sensors are moving?
  - Can sources use other existing (close by) grids?

TTDD

Sensors (Sources)	Users (Sinks)	Event	Interest Propagation	Data Dissemination
Stationary	Stationary	Query	Static	Unicast
		Continuous	Unicast	Multicast
Mobile	Mobile		Multicast	
		Target Detection	Broadcast (localized)	Broadcast

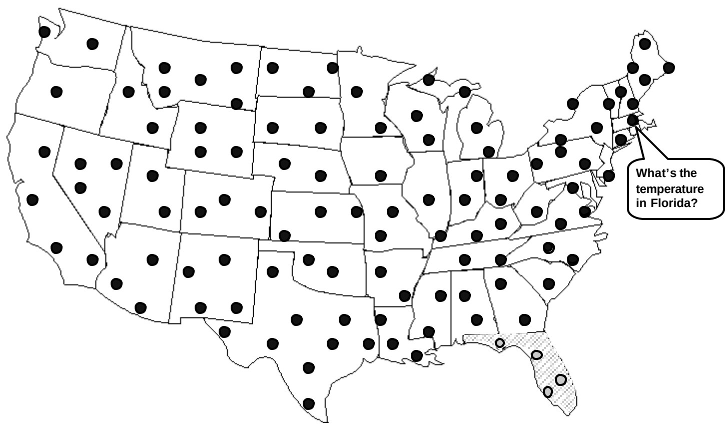
Why don't we just use distance-vector or link-state routing?

A review on Geographic Routing

Wei Li
Boston University
Oct 21, 2003

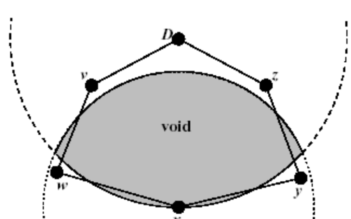
Motivation

- Sending information to a specified geographic region is a very useful application in sensor networks.



Basic method

- The idea of *greedy forwarding*
- Advantage—only needs local information
- Difficulty—how to go around a *hole*



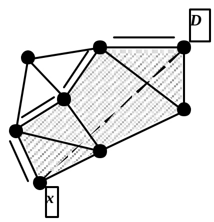
Related work

- FINN, G. G. Routing and addressing problems in large metropolitan-scale internetworks. Tech. Rep. ISI/RR-87-180, Information Sciences Institute, Mar. 1987.

  —— Greedy forwarding + Flooding (to eschew holes)

- Brad Karp and H. T. Kung. GPSR: Greedy perimeter stateless routing for wireless networks. In Proc. ACM Mobicom, Boston, MA, 2000.

  —— Greedy forwarding + Perimeter forwarding



What's missing in previous work?

- Energy aware routing
- How to forward the packet to ALL the nodes in the target region?

GEAR—Geographical and Energy Aware Routing protocol

Yan Yu, Ramesh Govindan and Deborah Estrin, Geographical and Energy Aware Routing: A Recursive Data Dissemination Protocol for Wireless Sensor Networks, UCLA Computer Science Department Technical Report UCLA/CSD-TR-01-0023, May 2001.

- GEAR consists of two phases:
  - Forwarding the packet towards the target region
  - Disseminating the packet within the target region

1^{st} phase's routing algorithm

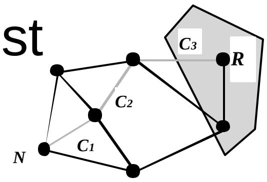
- GEAR makes "next-hop decision" by considering:
  Geographic info **+** Transmission cost info

- When "closer neighbors" exist:
  Next hop=*arg min* {*Transmission cost* (**closer** neighbors)}

- Otherwise (hole):
  Next hop=*arg min* {*Transmission cost* (**all** neighbors)}

  CAN skirt the hole by this method. WHY?

Transmission cost



- Node *N* is forwarding a packet to region *R*. Then:

Transmission cost *h*(*N*,*R*)

= total cost for forwarding a packet along the best path from N to R

= $C_1 + C_2 + C_3$ (in example)

- Obtaining transmission cost needs global info about the network
- The paper designs a "self-learning" process to gradually obtain transmission costs

The self-learning process for transmission cost

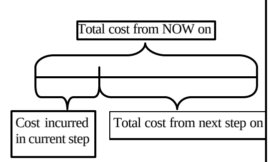
- To start up, computes a estimated cost *c*(*N*,*R*) for each node and use it as initial value for *h*(*N*,*R*):

$$c(N,R) = ad(N,R) + (1-a)e(N) \Rightarrow h(N,R)$$

- Updating *h*(*N*,*R*) from time to time:

After forwarding a packet from *N* to *M*

$$h(N,R) = h(M,R) + C(N,M)$$

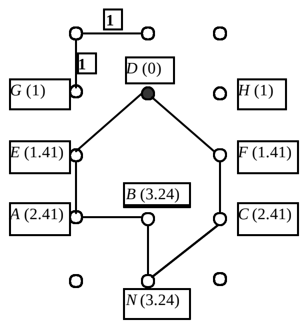


- The paper argues, by applying this self-learning:
  - *h*(*N*,*R*) at each node will finally converge to its real value
  - a node can skirt the hole it may face

An example for the 1st phase

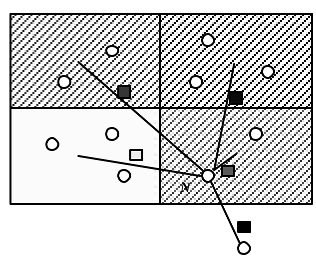
To simply the discussion, assume:

Forwarding cost *C*(*N*,*M*)=|*NM*|; estimated cost *c*(*N*,*D*)=|*ND*|.



2nd Phase—recursive packet dissemination

- In the 2nd phase, the packet will be disseminated to all the nodes in the target region.



Final Remarks

- Geographic routing is a scalable routing method, which uses the positions of routers and destination to make routing decisions
- The basic method of geographic routing is Greedy Forwarding. But other method must be proposed to skirt the hole.
- GEAR is an energy aware routing protocol which use transmission cost to make routing decisions
- GEAR's recursive packet disseminating procedure can forward a packet to all the nodes within the target region

Thanks! & Questions?

Bravo! Chinese space ship...