Energy-Efficient Communication Protocol for Wireless Micro-sensor Networks

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Outline

- Brief Introduction on Wireless Sensor Networks
- System Model and Assumptions
- Overview of Conventional Network Protocols and Properties
- Introduction to LEACH
- LEACH Algorithm
- Energy and Performance Analysis of LEACH
- Open Problems
- Related work and other energy efficient Network Protocols

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Brief Introduction on Wireless Sensor Networks

- Spread sensors monitoring a certain event
- No fixed topology or structure
- Variety of applications (medical monitoring, environmental monitoring, surveillance, security applications etc)
- Most important Design constraint: **Energy Consumption**
- Necessity of designing energy-efficient protocols for all layers

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System Model and Assumptions

- Base Station fixed and located far from the sensors
- All nodes are homogeneous and energy constrained
- Energy dissipated at the node radio:
  - Circuitry dissipation in J/bits (for Tx nodes and Rx nodes): E_{elec}
  - Dissipation due to transmit amplifier J/bits/m^2 (Tx nodes only): ϵ_{amp}
- Sensors only transmit data if some event occurs

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Overview of Conventional Network Protocols and Properties

- Direct Communication/Transmission Protocol
  - Every node communicates directly to the base station
  - Pros: No energy required to receive data
  - Cons: Large amount of transmit power if the base station is far from the sensor

Overview of Conventional Network Protocols and Properties (2)

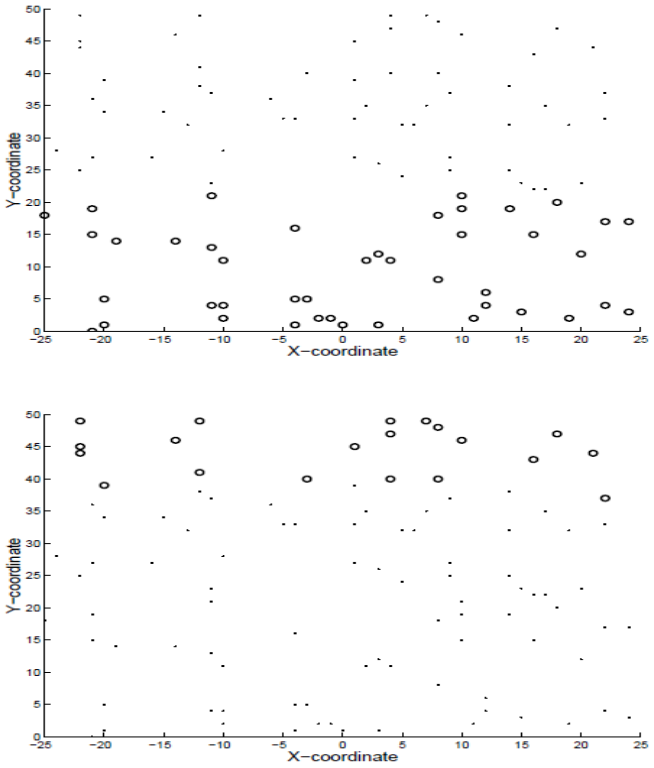
- "Minimum-energy" Routing Protocol
  - Protocol considered in the paper is the MTE protocol: Minimum-transmit-energy protocol
  - Multi-hop communication where intermediate node act as routers
  - Pros: Reduce transmit power at every node
  - Cons: Take energy dissipated at receiver node into consideration

Overview of Conventional Network Protocols and Properties (3)

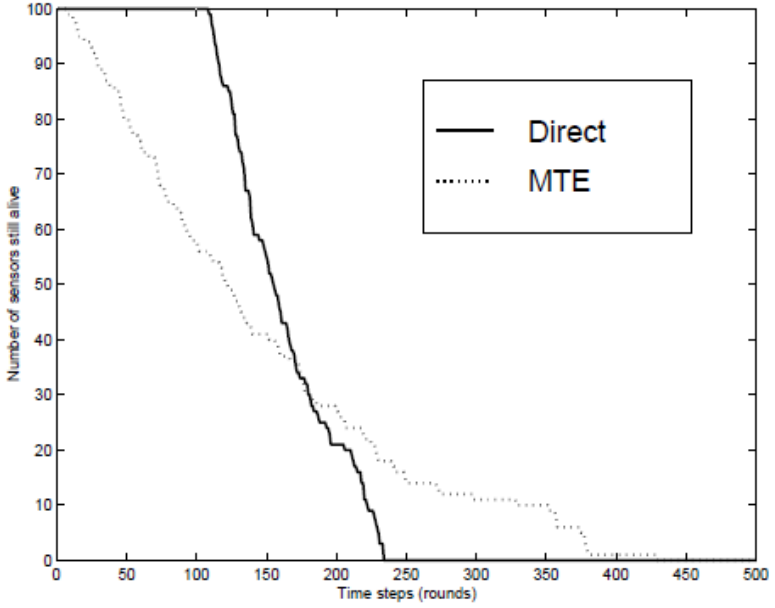
- Static Clustering Protocols
  - Nodes divided into clusters, with one node acting as local base station for each cluster
  - Local base stations communicate with the global base station
  - In each cluster, Nodes communicate directly to the local base station
  - Pros: Reduce transmit distance when compared to direct communication
  - Pros: No receive energy dissipated when compared to MTE protocols
  - Cons: local base station is a high energy node

Overview of Conventional Network Protocols and Properties (4)

Direct Communication VS MTE



Direct Communication VS MTE



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Introduction to LEACH: Low-Energy Adaptive Clustering Hierarchy

- Motivation:
  - None of the conventional models satisfy the proposed model requirements
  - Direct transmission requires very high transmit power
  - MTE requires taking into consideration receive energy, intermediate nodes die quickly
  - Conventional clustering requires high-energy nodes to act as local base stations; nodes in clusters without local BS are considered dead

Introduction to LEACH: Low-Energy Adaptive Clustering Hierarchy (2)

- Main Features:
  - Self-Organizing, **Adaptive clustering** protocol
  - **Randomized rotation** of the high energy cluster head
  - Sensors elect themselves to chose a cluster head
  - Each node chooses its own cluster
  - Local **data fusion** at local BS – **Compresses** data to send, **reduces** transmit power
  - Within each clusters, nodes access the channel using TDMA (MAC)
  - Each local BS picks a CDMA code at random for communication inside the cluster

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LEACH Algorithm

- **Advertisement Phase (1):** Node n chooses a number between 0 and 1, if the number is less than the threshold, then n becomes a cluster head

$$T(n) = \begin{cases} \frac{P}{1 - P * (r \bmod \frac{1}{P})} & \text{if n} \in \text{G} \\ 0 & \text{otherwise} \end{cases}$$

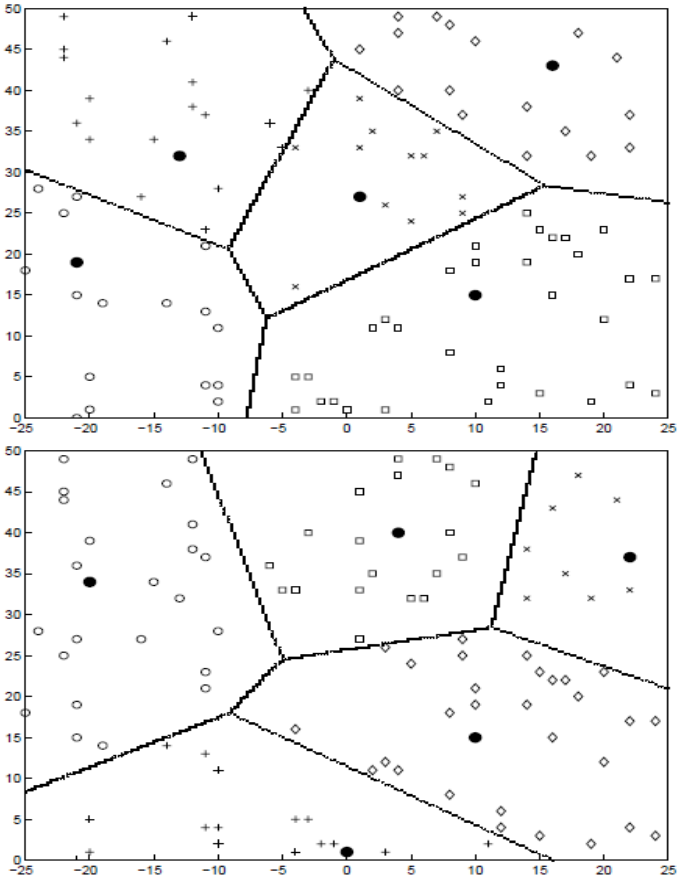
- Notations:
  - T(n) is the threshold number
  - P = the desired percentage of cluster heads
  - r = the current round
  - G is the set of nodes that have not been cluster-heads in the last 1/P rounds

LEACH Algorithm (2)

- Advertisement Phase (2):
  - Elected node broadcasts advertisement using CSMA-MAC protocol
  - All elected nodes transmit with same energy
  - Based on the received advertisement signal strength, the non-cluster-head node chooses its cluster
  - The node chooses the cluster-head whose advertisement has the highest received power Since the amount of transmit energy needed to communicate to this cluster head is minimal

LEACH Algorithm (3)

- Cluster Set-Up Phase:
  - Each node informs the cluster-head node about its choice
  - Each node uses CSMA-MAC protocol to transmit this information
  - Cluster heads must keep receivers on



LEACH Algorithm (4)

- Schedule Creation:
  - Cluster head creates A TDMA schedule based on the number of nodes in the cluster
  - The head broadcasts the schedule back to his nodes
- Data Transmission:
  - Nodes send with minimal required energy to the local cluster head, and turn off their radio when not sending
  - Local cluster heads receive data, compress it into a single signal
  - At the end of the round (decided upon before), Start from the beginning
  - To avoid interference between clusters, CDMA codes are picked at random by local cluster heads and broadcasted to their cluster nodes

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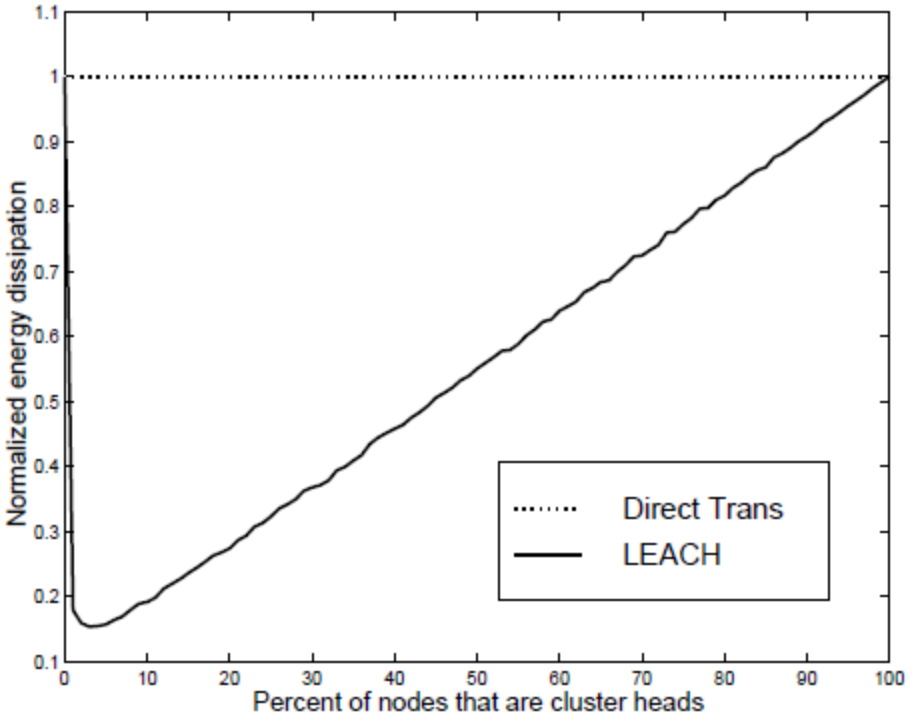
Energy and Performance Analysis of LEACH

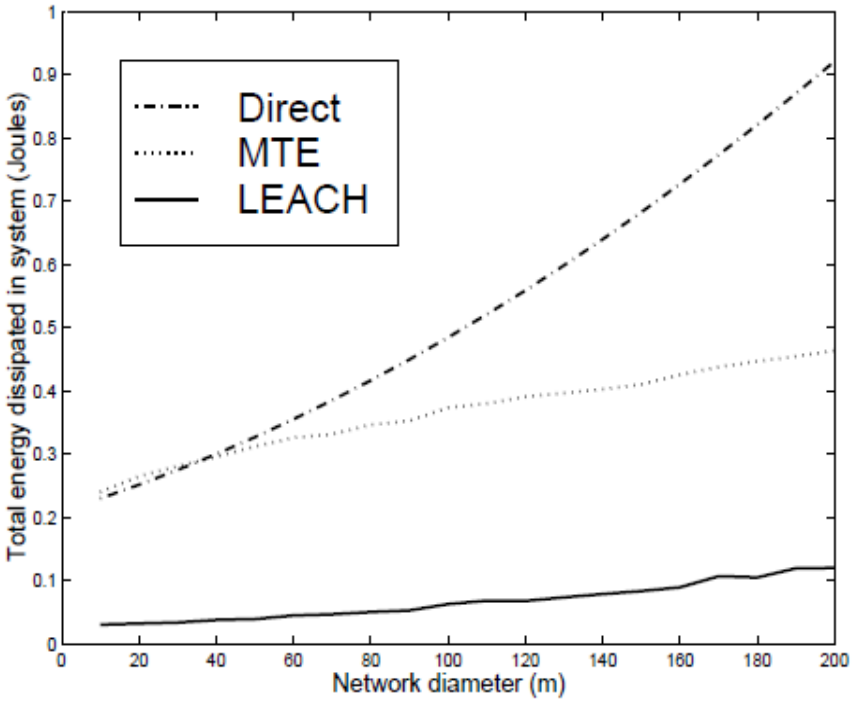
- Deciding on P is done by plotting the total system energy dissipated versus to percent of nodes that are cluster heads at once

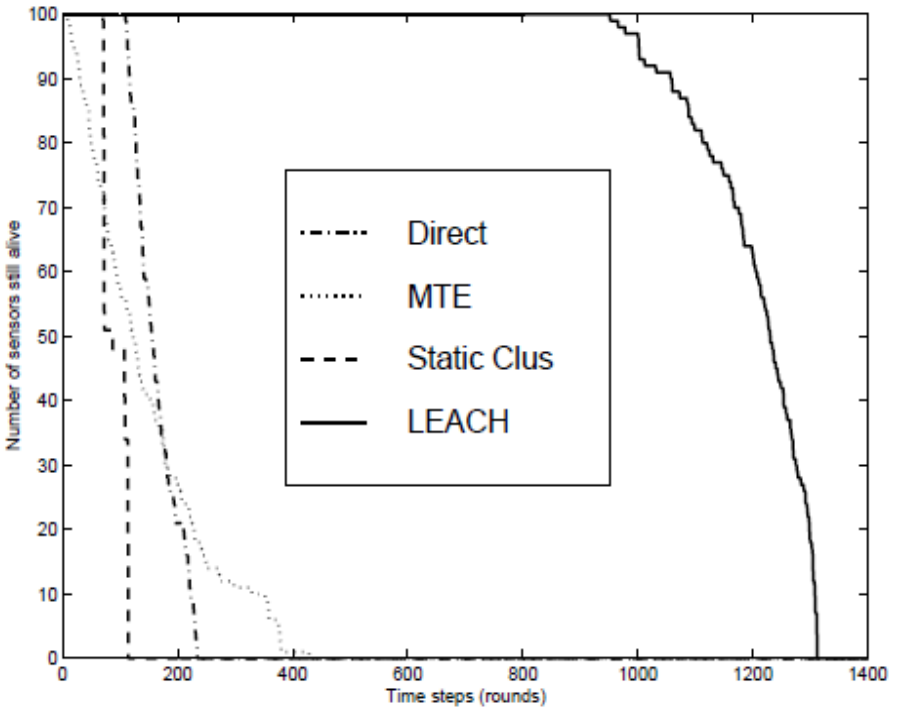


For our model, we will choose **P = 0.05**

Energy and Performance Analysis of LEACH (2)

- Assumptions:
  - Same random **100–node** network model, messages are **2000 bits**, $\mathbf{E_{elec}}$ **= 50 nJ/bit** and $\mathbf{\epsilon_{amp}}$**= 100pJ/bit/m²**, initial energy of **0.5 J/node,** computation cost **5 nJ/bit/message**





Energy and Performance Analysis of LEACH (3)

- Conclusions:
  - **LEACH** reduces communication energy by as much as **8x** compared with **Direct transmission** and **MTE routing**
  - **First** node death in **LEACH** occurs over **8 times** less than the **first** node death in **direct transmission, MTE,** or **static routing**
  - **Last** node death occurs over **3 times** later than the **last** node death in the other protocols

Energy (J/node)	Protocol	Round first node dies	Round last node dies
0.25	Direct	55	117
	MTE	5	221
	Static Clustering	41	67
	LEACH	394	665
0.5	Direct	109	234
	MTE	8	429
	Static Clustering	80	110
	LEACH	932	1312
1	Direct	217	468
	MTE	15	843
	Static Clustering	106	240
	LEACH	1848	2608

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Open Problems in LEACH

- No Guaranteeing that the cluster head nodes are weel distributed through the network
  - LEACH-C has been proposed but cannot scale for large number of nodes
- Hierarchical Clustering:
  - Creation of super-cluster-heads
  - Cluster heads will communicate with super cluster heads and so on, until data is sent to the global base station
  - Seems promising for larger networks, could save a lot of energy

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Related work and other energy efficient Network Protocols

- Hybrid Energy-Efficient Distributed Clustering (HEED)
  - Similar to LEACH
  - The distinctive feature is in the clustering algorithm
  - HEED uses an iterative cluster formation algorithm
  - Sensor Assign themselves a cluster head probability
  - The cluster head probability is a function of the residual energy, and a communication cost that depends of the neighbors proximity
  - Based on this value, nodes decide or not to advertise/'run' as candidates for being the cluster head
  - Each sensor picks the candidate with the lowest communication cost (the closest)
  - This process iterates; at each iteration the cluster head probability is increased until it converges to one and the corresponding node would be declared the head of the cluster

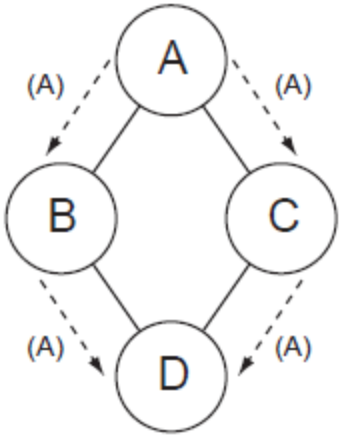
Related work and other energy efficient Network Protocols (2)

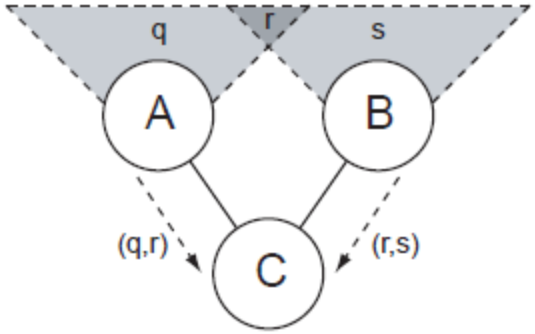
- Sensor Protocol for Information via Negotiation (SPIN)
  - Sensors don't blindly broadcast data
  - Sensors advertise their data first through short ADV messages
  - ADV messages contain information about data itself (Type, location etc.)
  - Nodes interested by this data will send request (REQ) messages back
  - SPIN avoids implosion, overlap and resource blindness

Related work and other energy efficient Network Protocols (3)

Implosion: occurs in a highly connected network

Overlap: occurs due to the redundant nature of sensor data





Related work and other energy efficient Network Protocols (4)

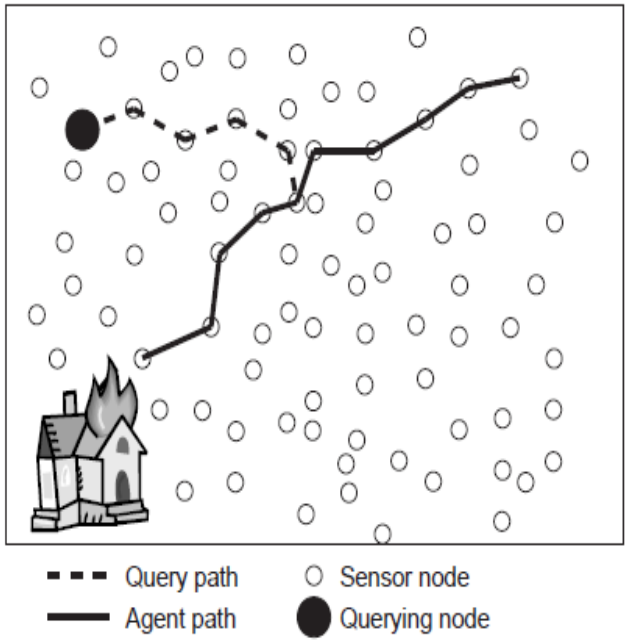
- Sensor Protocol for Information via Negotiation (SPIN) (2)
  - SPIN reduces the waste of energy due to **implosion** since only the small ADV messages suffer from implosion
  - SPIN solves data **overlap** since nodes name data in ADV messages. Hence nodes only ask for the data they are interested in (in the REQ messages)
  - SPIN solves the problem of **resource blindness** since nodes that are low on resources are allowed not to send ADV messages
  - Depending on the application, SPIN might require complex processing at the node level

Related work and other energy efficient Network Protocols (5)

- Directed Diffusion
  - Similar to SPIN but uses a 'PULL' mode
  - A querying node creates an interest and let's corresponding nodes know about its interest by broadcasting them an interest message with specific details (type, duration etc.)
  - Node memory caches interest and nodes are aware that an interest has been created
  - Nodes that can answer this interest send back corresponding data
  - Could be inefficient for certain applications that have monitor sudden events

Related work and other energy efficient Network Protocols (6)

- Rumor Routing
  - When an event is detected by a sensor, it probabilistically creates an agent in the form of a data packet, and forwards it throughout the network in a random manner
  - Nodes through whom the agent is forwarded maintain local state information about the event (direction, distance)
  - If another agent goes through the same node, it adds information to past cached information
  - When a node sends a query related to a given event, it simply forwards a query packet in a random direction throughout the network
  - The two lines (random walks) are likely to meet, and hence the query will reach a node with information about the event
  - Might not be efficient in large networks



Related work and other energy efficient Network Protocols (7)

- Treating the sensor network as a Database:
  - Tiny Aggregation (TAG) service: minimizes number of messages for a certain query
  - Acquisitional Query Processing (ACQP): provide a generic SQL-like interface
  - Geographic Hash Tables (GHT)

Related work and other energy efficient Network Protocols (8)

- Other Protocols:
  - Span
  - Energy-Aware Data Centric Routing (EAD)
  - Greedy Perimeter Stateless routing (GPSR)
  - Trajectory based Forwarding (TBF)
  - Geographic Adaptive Fidelity (GAF)
  - Adaptive Self-Configuring Sensor Networks Topologies (ASCENT)

References

- Wendi Rabiner Heinzelman, Anantha Chandrakasan, and Hari Balakrishnan, “Energy-efficient communication protocols for wireless microsensor networks,” in Proceedings of the Hawaii International Conference on Systems Sciences, Jan. 2000
- M. Perillo and W. Heinzelman. DAPR: A protocol for wireless sensor networks utilizing an application-based routing cost. In Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC), 2004.
- W. Heinzelman, J. Kulik, and H. Balakrishnan. Adaptive protocols for information dissemination in wireless sensor networks. In Proceedings of the Fifth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom), 1999.
- C. Intanagonwiwat, R. Govindan, and Estrin D. Directed diffusion: A scalable and robust communication paradigm for sensor networks. In Proceedings of the Sixth Annual International Conference on Mobile Computing and Networks (MobiCom), 2000.
- D. Braginsky and D. Estrin. Rumor routing algorithm for sensor networks. In Proceedings of the First ACM International Workshop on Wireless Sensor Networks and Applications (WSNA),2002.
- D. Niculescu and B. Nath. Trajectory based forwarding and its applications. In Proceedings of the Ninth Annual International Conference on Mobile Computing and Networking (MobiCom),2003.
- O. Younis and S. Fahmy. Distributed clustering in ad-hoc sensor networks: A hybrid, energy efficient approach. In Proceedings of the Twenty-Third Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM), 2004.