Grid-based Coordinated Routing in Wireless Sensor Networks

Robert Akl
Dept of Computer Science and Eng.
University of North Texas
Denton, Texas, 76207
rakl@cse.unt.edu

Uttara Sawant
Dept of Computer Science and Eng.
University of North Texas
Denton, Texas, 76207
uttara@unt.edu

Abstract— **This work explores grid-based coordinated routing in wireless sensor networks and compares the energy available in the network over time for different grid sizes. A test area is divided into square-shaped grids of certain length. Fully charged battery powered nodes are randomly placed in the area with a fixed source and sink nodes. One node per grid is elected as the coordinator which does the actual routing. The source node starts flooding the network with every coordinator joining in the routing. Once the flooding reaches the sink node, information is sent back to the source by finding the back route to the source. This process is continued until a node (coordinator) along that route runs out of energy. New coordinators are elected to replace the depleted ones. The source node refloods the network so that the sink can find a new back route to send information. This entire process continues until the network is partitioned and the connectivity between the source and the sink nodes is lost. We explore the quality of service of wireless sensor networks, how the coordinator nodes are elected, and the size of the grid area that will minimize the total energy consumption and extend the lifetime of the network.**

I. INTRODUCTION

Most of the work on routing in wireless sensor networks concentrates on finding and maintaining routes to the destination nodes. Routing protocols specifically designed for sensor networks are categorized into three types: data-centric, hierarchical, and location-based. In addition, slightly different approaches such as network flow and Quality of Service (QoS) are explored to consider end-to-end delay and energy efficiency while finding paths in the wireless sensor networks.

Flooding and gossiping [1] are the classic examples of data dissemination protocols in communication networks. In flooding, each sensor node broadcasts data packet to its neighbors and this process continues till the data packet reaches the destination node. However, the problem with flooding is that it results in unrestricted creation of duplicate packets throughout the network, thus leading to packet congestion and energy consumption. In gossiping, the receiving node transmits the data packet to a randomly selected neighbor which in turn selects another random neighbor until the destination node is reached. The drawback of gossiping is that, for two sensor nodes sensing overlapped regions, gossiping results in sending identical information to the receiver node.

The Low Energy Adaptive Clustering Hierarchy (LEACH) protocol [2] is a cluster-based routing protocol for wireless microsensor [3] networks that perform load balancing and ensure scalability and robustness by routing via cluster-heads and implement data fusion to reduce the amount of information overhead. Power-Efficient Gathering in Sensor Information Systems (PEGASIS) and Hierarchical-PEGASIS are improvements to the LEACH protocol. Instead of forming clusters as in LEACH, chains are formed by the nodes and data is transmitted along the chain to a node which transmits the aggregated data to the base station. For time-critical applications in sensor networks, routing protocols such as Threshold Sensitive Energy Efficient Sensor Network and Adaptive Threshold Sensitive Energy Efficient Sensor Network are developed [1].

In [4], the authors present algorithms simulated on static networks to maximize the system lifetime by selecting routes and adjusting the power levels of the nodes. The algorithms are based on the network flow approach. To minimize the end-to-end delay, an Energy-Aware QoS protocol is designed to select energy efficient paths in the network [1]. The Energy Aware Routing protocol developed in [5] keeps a set of good paths between source and sink nodes and selects one of them probabilistically for routing. It is reactive to topological changes, maintaining connectivity between communicating nodes and extending the lifetime of the network. In [6], the authors define a two-tiered WSN architecture consisting of sensor nodes that sense and send raw information to the application nodes which in turn relay it to the base stations. It is focused on topology control for base stations and application nodes that constitute the upper tier to extend the network lifetime. In [7], the authors adjust the transmit power of nodes to maintain topology and connectivity.

Finding efficient routes in networks using the location of the sensor nodes is the focus of most of the location-based protocols. Minimum Energy Communication Network (MECN) [1] sets up routes by determining the position of the sensor nodes using low-power Global Positioning System (GPS). The Small Minimum Energy Communication Network protocol is an improvement of MECN by constructing a smaller backbone of sensor nodes for routing [1]. The Geographic Adaptive Fidelity (GAF) algorithm [8] classifies nodes into equivalent groups

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based on their locations which are determined using GPS. Cluster-based Energy Conservation [9] is an improvement over GAF since it eliminates location dependence.

Adaptive Fidelity Energy-Conserving Algorithm [10] is a topology control protocol based on the concept of adaptive routing fidelity. Radios are turned off to reduce energy consumption and node deployment density is exploited to extend the network lifetime. Span [11] selects coordinators which route packets. Each node running Span determines which of its neighboring nodes will become the coordinator. The coordinator role is rotated among the neighboring nodes to achieve load balancing.

In [12], each node determines its connectivity and decides whether or not to join the network by locally assessing the environment. Active nodes stay awake to route packets while passive nodes periodically check when to become active. This protocol was designed to save energy and extend lifetime in networks with high-density node deployment. Geographic and Energy Aware Routing suggests sending data queries to specific regions of interest by exploiting the location information of the sensor nodes. Thus, it combines the qualities of a location-based protocol and data-centric communication mechanism. In [13], five new metrics are defined based on battery power consumption at the nodes. These metrics are used to determine the routes in the network. The hierarchical power aware routing algorithm [14] discusses a zone-based scheme that groups nodes into zones and allowing the zones to route packets. Zoning requires nodes to be GPS-enabled.

Sensor Protocols for Information via Negotiation (SPIN) [1] is the classic example of data-centric communication protocol for sensor networks. The idea behind SPIN is that data is named using high-level descriptors or meta-data. This meta-data is exchanged between sensor nodes before transmission. Specific data is requested by the nodes using the information specified in the meta-data. Directed diffusion communication paradigm [15] also focuses on inherent data-centric property of a sensor application. It enables communication of named data by selecting paths and by caching and managing the data in-network.

This work is focused on energy analysis and simulation of routing and flooding in densely populated wireless sensor networks. Keeping simulation parameters such as transmit power, path loss factor, and sensitivity constant, energy consumption for different grid sizes is determined. Based on the results, we can infer which grid sizes yield the best energy savings and longer network lifetime.

The objectives of this work are to:

- Design grid-based coordinated routing based on flooding in ad hoc wireless sensor networks.
- Extend network lifetime by only routing through coordinator nodes.
- Maintain network connectivity and prolong network partition time.
- Verify through simulation the results for our algorithm and compare with traditional flooding algorithms.

The remainder of this paper is organized as follows. Traditional flooding is presented in Section II. Our grid-based coordinated routing algorithm is described in Section III. Numerical results are presented in Section IV, and finally Section V concludes the paper.

II. TRADITIONAL FLOODING

Flooding algorithms are one of the most widely used and simplest algorithms to distribute data in a connected network. In these algorithms, every node acts as a transmitter and a receiver. Flooding starts with the source broadcasting the information. When the receiver node receives the information, it rebroadcasts it. This process continues until the information reaches every part of the network. Real-world flooding is more complex than this, since precautions have to be taken to avoid uncontrolled transmission of data packets, duplicate transmissions and infinite loops in the network. Usually flags and message identification numbers (ID) are used to identify whether the node has received a data packet.

Flooding gives rise to a tree structure to denote the parent and the child node in the network. Algorithm 1 shows a flooding-based tree construction protocol [16].

Algorithm 1 FLOOD()

```
if $Node$ receives packet for the first time then
    Mark $Node$ as received
    $Parent \Leftarrow Sourceofpacket$
    $Source \Leftarrow Node$
    Increment $Level$ Field
    Rebroadcast packet
end if
```

In this algorithm, the node sets its parent to be the node from whom it received the packet for the first time. Then, it increments the $Level$ field by one and rebroadcasts the packet. The $Level$ field denotes how many hops the node is away from the original source. A node is selected as a receiver only if it has not received the packet. This helps to avoid duplicate deliveries. Also, every node has a unique parent and each node can have any number of children, if they are within its transmission range. Since sensor nodes are battery-powered, flooding through all the nodes in the network is not efficient. Keeping a small number of nodes active will consume less energy and improve the network lifetime.

III. GRID-BASED COORDINATED ROUTING ALGORITHM

Our grid-based coordinated routing protocol is based on flooding. Unlike traditional flooding, grid-based coordinated routing is designed to reach only selected nodes in the field. Fully charged battery powered sensor nodes are randomly placed in the field with a fixed source and a sink. The sensor field is divided into square-shaped grids of user defined grid size. The algorithm then selects one node per grid as a coordinator which stays active until it runs out of energy. Remaining nodes power down their radios to save energy. The source node starts flooding the network with a query message to every coordinator. When the sink node receives the message,

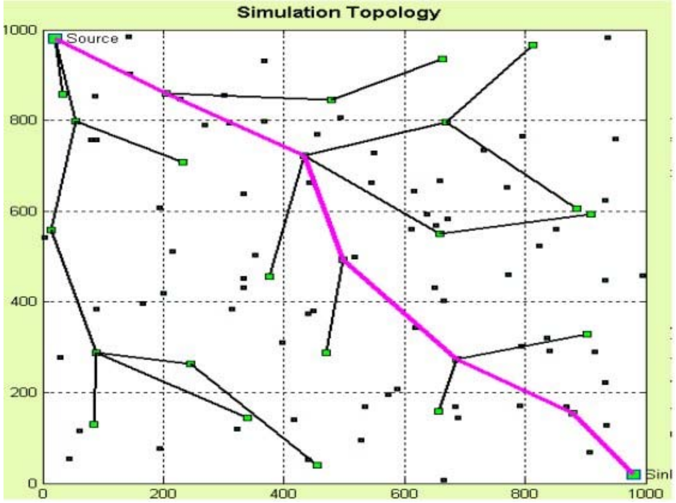

Fig. 1. Simulation topology showing sink sending information to the source through a back route.

it sends information by finding a route back to the source. This process repeats until a node (coordinator) along that route runs out of energy. Fig. 1 shows the sink sending information to the source. New coordinators are elected to replace the depleted ones. The source node refloods the network so that the sink can find a new route to send information. This entire process continues until the network is partitioned and connectivity between the source and the sink node is lost. Algorithm 2 shows our grid-based coordinated routing algorithm.

Algorithm 2 GRID-BASED COORDINATED ROUTING ALGORITHM

```
$C \Leftarrow setofcoordinatornodes$
while network is not partitioned do
  while $C \neq \phi$ or sink node not reached do
    Pick a node randomly from $C$
    FLOOD()
  end while
  Send information from the sink to the source node
  Elect new coordinator nodes, $C'$
  $C \Leftarrow C'$
end while
```

As the source refloods the network, every coordinator goes through three states based on its remaining energy. If the remaining energy is greater than 25% of battery life, the coordinators are said to be in routing state. If the remaining energy is less than or equal to 25% of battery life, the coordinators are said to be in warning state. Finally, they are in depleted state when the remaining energy is equal to zero.

A. Coordinator Election

Nodes are elected as coordinators to route packets in the network. Non-coordinator nodes sleep while coordinator nodes route the packets. Since the non-coordinator nodes power down their radios, the overall energy is conserved.

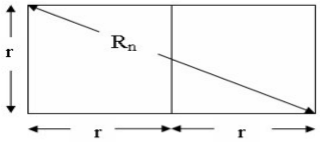

Fig. 2. Calculation of grid width.

Coordinator election is as follows. All the nodes are randomly assigned IDs. The node with largest ID in a grid is elected as the grid coordinator. When this coordinator runs out of energy, the node with the second highest ID becomes the new grid coordinator. This election takes place when the flood encounters a depleted grid coordinator. For every depleted node in the grid, the algorithm elects a new coordinator before reflooding the network.

B. Grid Size Estimation

For reliable connectivity, we have to ensure that the coordinators in adjacent grids are within transmission range. This depends on the grid size, transmission power, and sensitivity of the sensor nodes.

Coordinators in adjacent grids must communicate with each other provided they are within their transmission range. Simulations show that some coordinators in adjacent grids may be out of transmission range if the grid size is too large. This must be avoided so as not to experience early network partition. The upper bound for a square grid with width r (Fig. 2) is calculated as follows:

$$r^2 + (2r)^2 <= R_n^2, \tag{1}$$

$$r <= R_n/\sqrt{5}. \tag{2}$$

This shows that if the grid size is less than or equal to r, where R_n is the maximum transmit distance, the coordinators in adjacent grids are within their transmission ranges [8].

C. Load Balancing

The grid-based coordinated routing protocol employs load balancing to keep all the nodes up and running for as long as possible. It uses node rank to determine which nodes should sleep and when. Once the node energy drops below 25% of battery life, it is ranked higher than the remaining nodes in its grid. Before the source refloods the network, the nodes with the lowest rank in their respective grids are elected as coordinators. The higher ranked nodes are put to sleep and hence do not participate in routing.

Initially, all the nodes are assigned the same rank. Our protocol elects one node per grid as a coordinator. After going through several transmissions, the node energy decreases. If the node energy is greater than 25% of battery life, its rank is raised by 1. If the node energy becomes less than or equal to 25% of battery life, its rank is raised by 2, and it becomes a candidate to be put to sleep. When a node along the route back to the source runs out of energy, the connectivity between the source and sink is lost and the source starts to reflood the network. At this time, new coordinators are elected to replace the depleted ones with the nodes whose energies are less than or equal to 25% of battery life. The depleted nodes are no longer a part of the network, and their ranking becomes insignificant. The coordinator with energy less than or equal to 25% of battery life are replaced by lower rank nodes in their respective grids. The lower rank nodes have more energy available than the former and therefore they can handle routing for longer periods of time, thereby extending network lifetime and conserving nodes with less energy.

The coordinator role is rotated among nodes in the same grid to ensure equitable distribution of routing load over all the nodes in the network. This also helps to achieve a gradual reduction in the overall network energy. This process is repeated until there are not enough nodes with energy between the source and the sink and the network is partitioned.

IV. NUMERICAL RESULTS

A. Assumptions

Our energy consumption model is as follows. We assume that a node spends 1 unit of battery energy for transmission of a packet and 0.5 unit of battery energy for reception when the transmit power is set to 1 dBm. We assume that the source and sink nodes have infinite energy. Our simulations consist of 1000 nodes that route information, 1 source, and 1 sink node.

We assume that the node location information is known in order to determine the grid in which the node is placed.

We analyze energy consumption and network partition time in our simulations. Normalized energy is calculated as the ratio of the total current energy of all nodes to the total energy of all nodes at the start of the simulation. Results are plotted as the normalized energy versus simulation time. We define network partition time as the time at which the source and sink nodes are no longer connected.

The field is 1000 m in length and 1000 m in width. A total of 1000 nodes are randomly placed in the field. The battery life per node is initialized to 100 units. Simulations were carried out by setting the grid widths to 50 m, 100 m, 150 m, 200 m, and 250 m.

We ran extensive simulations that included all combinations of 3 receiver sensitivity levels, 3 transmit power levels, and 5 grid sizes.

B. Varying the Receiver Sensitivity

The sensitivity of the receiver plays an important role in successful communication. The sensitivity of the receiver affects the radio range [17]. For all these simulations, we set the transmit power to 1 dBm.

Fig. 3 shows the network partition time for receiver sensitivity equal to -93 dBm. Table I shows our simulation results for receiver sensitivity equal to -87 dBm, -90 dBm and -93 dBm. We observe the interaction of grid size and receiver sensitivity. The lower the sensitivity, the longer the reception range. Thus, a bigger grid size is preferable up to a threshold where the coordinator nodes in adjacent grids can no longer communicate. If the grid size is relatively small, too many nodes are awake and communicating which leads to faster power depletion and shorter network partition time.

TABLE I
NETWORK PARTITION TIME FOR RECEIVER SENSITIVTY OF -87 DBM, -90 DBM, AND -93 DBM.

Receiver Sensitivity (dBm)	Grid Width (meters)	Network Partition Time (unit time)	Normalized Energy
-87	250	1.48	0.99
	200	44.42	0.69
	150	95.28	0.32
	100	70.09	0.43
	50	11.92	0.34
	Trad. flood	10.02	0.32
-90	250	19.12	0.82
	200	47.73	0.52
	150	50.89	0.28
	100	34.42	0.39
	50	7.12	0.30
	Trad. flood	6.02	0.25
-93	250	55.26	0.42
	200	66.22	0.19
	150	46.82	0.25
	100	29.64	0.34
	50	28.51	0.28
	Trad. flood	19.67	0.37

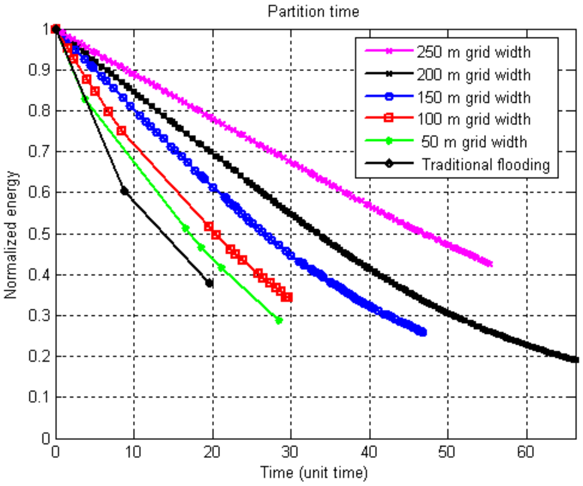

Fig. 3. Network partition time for receiver sensitivity equal to -93 dBm.

C. Varying the Transmit Power

By changing the transmit power, we adjust the transmission coverage region and control the number of nodes that participate in routing. For all these simulations, we set the receiver sensitivity to -90 dBm. We assume that the node spends 0.5, 1.0 and 2.0 units of battery energy when the transmit power is set to -2 dBm, 1 dBm, and 4 dBm, respectively.

Table II summarizes our simulation results. We observe that for lower transmit power, the energy in the nodes is conserved longer and thus yields in general longer network lifetime. As the transmit power level increases, the network partition time is prolonged in some cases for specific grid sizes. As the grid size increases the network partition time increases also up to the point where the coordinator nodes in adjacent grids can

TABLE II

ENERGY CONSUMPTION FOR TRANSMIT POWER OF -2 DBM, 1 DBM, AND 4 DBM.

Transmit Power (dBm)	Grid Width (meters)	Network Partition Time (unit time)	Normalized Energy
-2	250	3.39	0.98
	200	39.34	0.76
	150	113.14	0.31
	100	80.00	0.43
	50	11.98	0.32
	Trad. flood	10.01	0.20
1	250	19.12	0.82
	200	47.73	0.52
	150	50.89	0.28
	100	34.42	0.39
	50	7.12	0.30
	Trad. flood	5.05	0.28
4	250	57.57	0.32
	200	57.48	0.22
	150	58.67	0.30
	100	41.92	0.42
	50	42.98	0.36
	Trad. flood	31.43	0.38

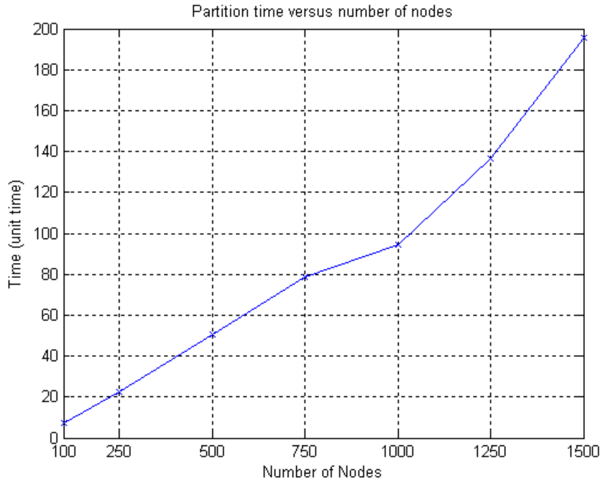

Fig. 4. Network partition time versus number of nodes.

no longer communicate.

D. Scalability

In this section, we analyze the scalability and robustness of our protocol. We simulate with 100, 250, 500, 750, 1000, 1250, and 1500 nodes. For every simulation, we have the following. The transmit power and sensitivity are 1 dBm and -90 dBm, respectively. The field is fixed at 1000 m in length and 1000 m in width. The grid width is set to 200 m.

As expected, as the number of nodes increases, the node redundancy increases. Consequently, the network partition time is prolonged. There is a linear increase in network partition time as the number of nodes is increased.

V. CONCLUSIONS

We designed a grid-based coordinated routing protocol for sensor networks. We described how the coordinators are elected from the given set of nodes. We determined the upper bound on the grid size to ensure connectivity between the coordinators. Finally, we incorporated load balancing in our protocol to distribute routing load over all the nodes. We analyzed the effects of varying transmit power, receiver sensitivity, and grid size on the network lifetime. We found that decreasing the transmit power, extends the network lifetime and prolongs network partition. We also observed that networks with grid sizes around 150 m show consistently better performance than the other grid size networks.

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