GRID-BASED COORDINATED ROUTING IN WIRELESS SENSOR NETWORKS

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Wireless sensor networks are battery-powered ad-hoc networks in which sensor nodes that are scattered over a region connect to each other and form multi-hop networks. These nodes are equipped with sensors such as temperature sensors, pressure sensors, and light sensors and can be queried to get the corresponding values for analysis. However, since they are battery operated, care has to be taken so that these nodes use energy efficiently. One of the areas in sensor networks where an energy analysis can be done is routing. 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.

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CHAPTER 1

INTRODUCTION

Wireless communication and networking are becoming very predominant due to their flexibility and ease of deployment. Particularly, sensor networks that involve large numbers of small-sized sensor nodes equipped with sensors and radio for wireless operation have found applications in several commercial and industrial areas. Such ad hoc networks enable distributed information processing and sharing through wireless communication. For relatively inaccessible areas such as oil wells, turbines, natural habitats, wild fires, earthquake regions, and structures, tiny battery-powered sensor nodes uniformly placed or randomly scattered can be used to get information about the environment and transmit it to remote locations where analysts can store and analyze this information.

Energy consumption is one of the most important issues in wireless sensor networks. A good deal of research has been carried out to find ways to minimize energy consumption and thereby extend the lifetime of the network. Many existing routing protocols for ad hoc mobile wireless networks have been considered and compared to check if they are a good fit to ad hoc sensor networks [1]. One of the prominent observations is that the wireless interface which combines computation and radio used for wireless communication is shown to be the major consumer of energy [2]. Research suggests letting some nodes power down their radios which do not participate in transmitting information; thus using fewer nodes to route information can significantly extend a network's lifetime.

Energy consumption in a sensor node can be due to either “useful” or “wasteful” sources. Useful energy consumption can be due to:

- transmitting/receiving data,

- processing query requests,
- forwarding queries/data to neighboring nodes.

Wasteful energy consumption can be due to:

- idle listening to the channel,
- retransmitting due to packet collisions,
- overhearing,
- generating/handling control packets.

Several protocols have been developed to reduce useful as well as wasteful energy consumption [3].

1.1. Wireless Sensor Network Overview

Recent progress in wireless ad hoc communication networks has led to the development and use of low-power battery-operated wireless sensor networks. Tiny nodes equipped with sensors such as temperature sensors, pressure sensors, and light sensors are scattered over a sensor field. Random deployment of sensor nodes enables remote sensing of difficult to access areas. Their ability to detect neighboring nodes and form ad hoc networks is possible due to their self-organizing capability. Cooperative work is another strong feature that can be harnessed from sensor networks. The sensor nodes can be programmed to send, receive, and query specific data. The idea to query sensors for specific data has led to several concepts such as clustering sensor nodes, exploiting dense deployment, and node redundancy, thereby giving rise to efficient routing algorithms for such networks [4].

Several varieties of motes are commercially available at $50-$100 each. With the application of Moore's law and volume production, the price of sensor nodes is expected to drop to $5 over the next couple of years. Crossbow Technology Inc. [5] was the first commercial manufacturer of Intel motes. The next generation involved Intel's Stargate gateway computer network laid over sensor networks to further reduce energy consumption. Finally, to provide more processing and bandwidth requirements, Intel developed Intel $^{®}$ Mote equipped with 32-bit central processor and Bluetooth wireless standard. The Smart Dust project has brought Spec motes that have reduced large motes into single chips excluding batteries. A freely-available open source operating system called TinyOS [6] was developed for MICA2 sensor nodes. EmStar [7] is another programming environment for sensor nodes. Sensor nodes communicate with each other using NesC, an extension of the C programming language. Extracting data from heterogeneous sensor networks is difficult. To transform heterogeneous networks into user-friendly virtual databases, TinyDB database system was developed for sensor networks [8].

1.2. Motivation

Energy consumption is one of the important issues in sensor networks. For sensor nodes that are battery-operated and left unattended or cannot be recharged after deployment, using energy efficiently is crucial for longer network lifetime. In [9], authors recognized that network partition is an issue in densely populated sensor networks. For our work, we define network partition as a simulation event when the source and sink nodes are last connected. Network partition affects network connectivity. The motivation of our work is to study energy consumption and detect when network partition occurs.

1.3. Objectives

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.

1.4. Contributions

The primary contributions of our design are:

- The development, implementation, and simulation of grid-based coordinated routing protocol with a graphical user interface for network topology and protocol parameters.
- A load balancing approach based on remaining node energy is incorporated in the protocol to distribute load over all the nodes.

1.5. Organization

Chapter 2 gives an overview of existing routing protocols for mobile wireless ad hoc networks. We look at different routing protocols and discuss their advantages and disadvantages with respect to sensor networks.

Chapter 3 discusses two routing protocols Geographical Adaptive Fidelity and Span which motivated our work. It gives a brief introduction and discusses the issues of each protocol.

Chapter 4 introduces our grid-based coordinated flooding protocol. We discuss how the coordinators are elected among the nodes and explore possibilities of different coordinator election algorithms. We also calculate the relationship between grid size and radio range and analyze how it affects network lifetime. We employ load balancing in our protocol to equally distribute routing load over all the nodes.

Chapter 5 discusses the effects of tuning the parameters for routing. More detailed analysis and simulation results are presented in this chapter.

Conclusions are presented in Chapter 6. We also discuss future directions for our work.

CHAPTER 2

WIRELESS NETWORKS AND MULTI-HOP ROUTING

2.1. Introduction

There are two types of mobile wireless networks, namely infrastructure networks and ad hoc networks. Infrastructure networks involve fixed and wired gateways. Typically these networks have a number of fixed base stations and mobile units that move within the network from one base station to another. Wireless local area networks are a classic example. In ad hoc networks the nodes are all mobile and maintain routes to neighboring nodes as the network changes. Sensor networks are a type of ad hoc networks. This chapter discusses the routing protocols for ad hoc networks.

Several ad hoc routing protocols have been developed since the Defense Advanced Research Projects Agency introduced packet radio networks. They are conveniently categorized into table-driven and source-initiated (on-demand). Table-driven routing protocols require each node to maintain routing information in one or more tables and update it as the network changes. Source-initiated on-demand routing protocols require forming a route when the source node demands it. The route is maintained till either the source needs it or till the sink can no longer be reached with the existing route.

The following are some of the table-driven routing protocols [1]:

- **Destination-sequenced distance-vector routing:** Each node maintains a table consisting of all possible destinations and the number of hops to each destination. This table is continuously updated when new routes are computed.
- **Clusterhead gateway switch routing:** A node is selected as a clusterhead for a group of mobile nodes in the network. Nodes that connect two clusters are called

gateways. A source node will send information first to its clusterhead, which will forward it to the next clusterhead via the gateway node. In addition to the routing tables, each node maintains a cluster member table where it stores the destination clusterhead for each mobile node.

- **Wireless routing protocol:** In this protocol, each node maintains four tables. They are the distance table, the routing table, the link-cost table and the message retransmission list (MRL) table. Each entry in the MRL contains a sequence number of the update message, a retransmission counter, an acknowledgment-required flag indicator and a list of updates sent in the update message. Using the MRL, the protocol records the updates to be retransmitted and the neighboring nodes to acknowledge the retransmission.

We will focus on on-demand protocols since they are fitting for sensor networks. The following are some of the on-demand routing protocols [1]:

- **Ad hoc on-demand distance vector routing (AODV):** Routes are built on demand. Nodes not on the selected path do not participate in routing. A source requests a route by sending route request (RREQ) messages. The destination replies by unicasting route reply messages to the source.
- **Dynamic source routing (DSR):** Mobile nodes maintain route caches so that if they want to send data to a destination node and if the route to that destination node is stored in the cache, then the mobile node uses this route information; otherwise it broadcasts RREQ messages.
- **Temporally ordered routing algorithm:** This protocol is a highly adaptive loop-free distributed routing algorithm based on the concept of link reversal. It is designed to work in dynamic environments and provides multiple routes for any desired source-destination pair. This is due to the localization of control messages at the point of topological change.

- **Associativity-based routing:** This protocol uses a routing metric called degree of association stability. For each beacon received by the neighboring nodes, they update their associativity tables. High association stability indicates low node mobility with respect to its neighboring nodes and vice versa.
- **Signal stability routing:** This protocol selects routes based on the signal strength between the nodes and the node's location stability. This leads to selecting the nodes that show strong connectivity.

On-demand protocols are better for mobile ad hoc networks than table-driven protocols. Routing information is available only when it is demanded in on-demand protocols as opposed to table-driven protocols where routing information is always available. Though the former takes time to find a route when needed, table-driven protocols incur more signal power and traffic since routes are pre-computed and whenever the nodes change locations, the routes have to be updated throughout the network.

2.2. Related Work

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 [10] 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 [11] is a cluster-based routing protocol for wireless microsensor [12] 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 [10]. For time-critical applications in sensor networks, routing protocols such as threshold sensitive energy efficient sensor network (TEEN) and adaptive threshold sensitive energy efficient sensor network (APTEEN) are developed [10].

In [13], 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 [10]. The energy aware routing protocol developed in [14] 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 [15], 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 [16], 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) [10] sets up routes by determining the position of the sensor nodes using low-power global positioning system (GPS). The small minimum energy communication network (SMECN) protocol is an improvement of MECN by constructing a smaller backbone of sensor nodes for routing [10]. The geographic adaptive fidelity (GAF) algorithm [17] classifies nodes into equivalent groups based on their locations which are determined using GPS. Cluster-based energy conservation [18] is an improvement over GAF since it eliminates location dependence.

Adaptive fidelity energy-conserving algorithm (AFECA) [19] 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 [20] 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 [9], 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 [10].

In [21], 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 [22] 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) [10] 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 [23] 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.

Rumor routing [10] is a variant of directed diffusion. Instead of flooding the query to the entire network as in directed diffusion, the query is flooded to the nodes that have observed events of interest. Other protocols that are derived from directed diffusion are gradient-based routing, constrained anisotropic diffusion routing, cougar, and active query forwarding in sensor networks [10]. A recent survey [24] discusses emerging techniques to reduce energy consumption such as hierarchical sensor-node architectures, energy harvesting using solar cells, ultra-low-power medium access control protocols, and energy-aware sensing.

2.3. Conclusions

We reviewed several routing protocols for wireless mobile ad hoc networks. On-demand routing protocols are suitable for wireless sensor networks. Most of the related work on routing protocols focuses on controlling the number of active nodes, thereby allowing fewer nodes to stay awake, thus saving energy and extending the overall network lifetime.

CHAPTER 3

GAF AND SPAN

3.1. GAF Protocol

The geographical adaptive fidelity (GAF) protocol [17] belongs to the class of adaptive fidelity algorithms. An adaptive fidelity algorithm is one where the quality (fidelity) of the answer can be traded against battery lifetime, network bandwidth or number of active sensors [25]. In other words, maintaining fidelity of sensor data is relaxed to increase overall network lifetime. This is usually done by putting off redundant nodes and routing only via a small number of active nodes. GAF discusses overlaying a virtual grid over a sensor field. It uses location information to associate every node with a grid square. Node location can be determined either by GPS or other location systems. All the nodes within each grid square are said to be equivalent so that only one of these nodes stays awake. The virtual grid size is calculated based on the nominal radio range of the sensor nodes. Using the location information and the grid size, each node determines its corresponding grid identification number. All the nodes in one grid are assumed to be reachable from nodes in adjacent grids. By tuning parameters such as grid size, nominal radio range, and timer values, GAF consumes 40 - 60% less energy than an unmodified ad hoc routing protocol [17].

Nodes running GAF go through three states: discovery, sleeping, and active. They transition between the states to perform load balancing. A node starts in the discovery state. It sends discovery messages to find other nodes within the same grid. When the node enters the discovery state, it starts a timer for T_d seconds. When the timer expires, the node enters the active state. The active node participates in routing. When the node enters the active state, it sets a timer for T_a seconds. The node will remain in the active state for the duration of the timer. When the timer expires, the node goes back to the discovery state. If a node in the discovery or active state receives discovery messages from a higher rank node, it will enter the sleeping state. The higher rank node will become active and participate in routing. GAF employs load balancing by letting active node switch to the discovery state and nodes in the sleeping state to become active. This prevents the same active nodes from using energy all the time. Since node ranking is based on the remaining energy, the active node switching to the discovery state will be ranked lower than before.

Ideally, GAF maintains one active node per grid square. However, due to mobility, an active node may move out of its grid and affect routing fidelity. To cater to this situation, GAF uses another parameter, expected node grid time or $engt$. This value is sent to neighboring nodes in the discovery messages. This will enable the neighboring nodes to determine how long they should be in the sleeping state.

3.2. GAF Issues

GAF was evaluated for a total number of nodes ranging from 50 to 200 [17]. It needs to be tested for a larger number of nodes, thus exploiting high-density node deployment effectively. Node redundancy was determined using location information. Improvements are required to eliminate location dependency of GAF. More insight is needed for determining the network partition time. Implementation on actual motes is required to validate the results presented.

3.3. Span Protocol

Span [20] elects coordinators that form a network backbone to route packets within the network. Each node running Span decides whether or not to join the network depending on the connectivity of its neighboring nodes. It elects just enough coordinators so that every coordinator is in radio range of at least one coordinator. A Span node switches its role between coordinator and non-coordinator to share the load equally with all the other nodes. When a Span coordinator detects that its neighboring nodes can communicate with each other, it withdraws itself from being the coordinator. Span is implemented to run on top of 802.11 medium access control (MAC) and physical layers with ad hoc power saving mode. This ensures routing throughput and improves packet delivery latency.

3.4. Span Issues

One of the key features of Span is to ensure that the total number of coordinators is minimal. However, it is shown that Span elects more coordinators than are necessary [20]. This results in higher energy consumption and overhead for maintaining the extra coordinators. Span performance was compared with 802.11 power saving mode [20]. To verify its performance, Span on top of 802.11 needs to be compared with other ad hoc protocols such as GAF and adaptive fidelity energy-conserving algorithm (AFECA).

CHAPTER 4

GRID-BASED COORDINATED ROUTING

4.1. Introduction to 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 [26].

Algorithm 1 FLOOD(Node S)

```
if Node $n$ receives packet for the first time then
    Mark Node $n$ as received
    $Parent \Leftarrow S$
    $Source \Leftarrow n$
    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.

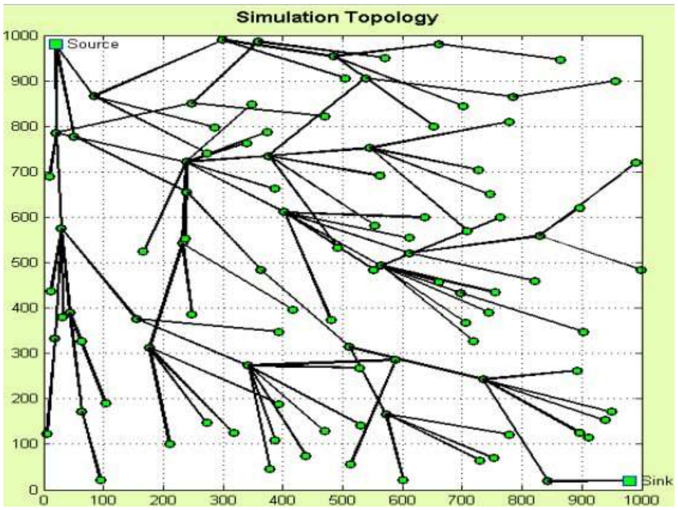


Figure 4.1. Simulation topology showing source flooding the network.

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. Fig. 4.1 shows the tree structure formed from flooding.

4.2. Grid-based Coordinated Routing Protocol

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, it sends information by finding a route back to the source. This process

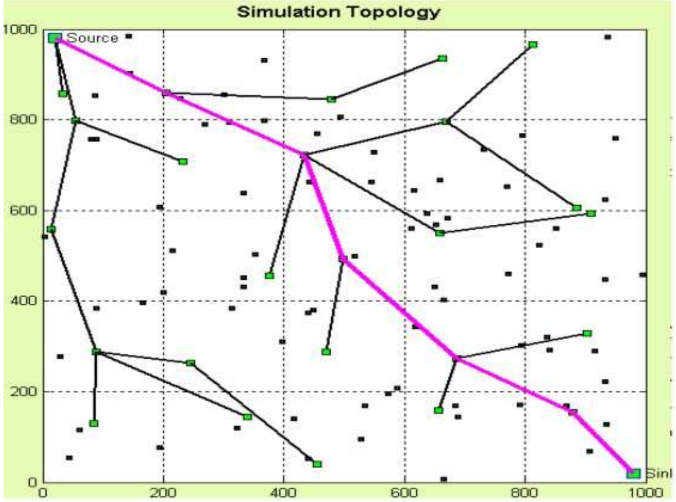


Figure 4.2. Simulation topology showing sink sending information to the source through a back route.

repeats until a node (coordinator) along that route runs out of energy. Fig. 4.2 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 protocol.

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. Figures 4.3 and 4.4 show the nodes in different states according to their available energy. Figures 4.5 to 4.8 show the working of the protocol at each levels.

4.3. Link Model

The dynamic and lossy nature of wireless communication links poses major challenges to reliable, self-organizing multi-hop networks [27]. This unreliable behavior of wireless links

Algorithm 2 GRID-BASED COORDINATED ROUTING PROTOCOL

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

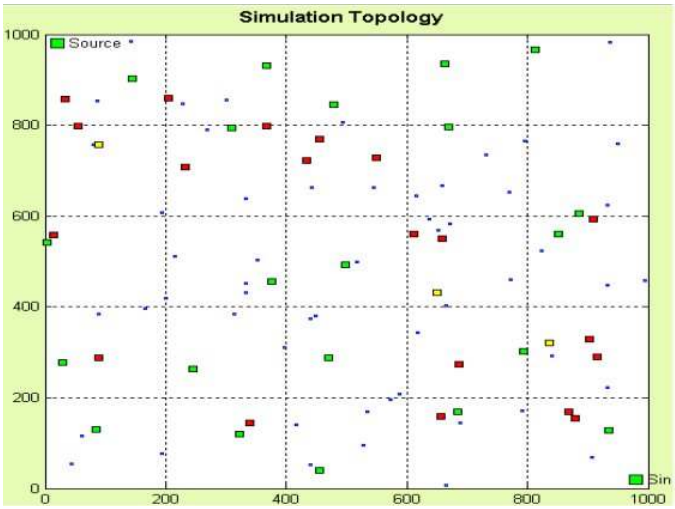


Figure 4.3. Simulation topology showing different states of the nodes depending on available energy. Green: node energy is greater than 25% of battery life. Yellow: node energy is less than or equal to 25% of battery life. Red: node energy is equal to zero. Small Blue: nodes that haven't yet been elected in place of coordinator nodes.

should be taken into account by the routing protocols designed for sensor networks. There are several link models that exhibit this behavior. We will discuss three types of link models.

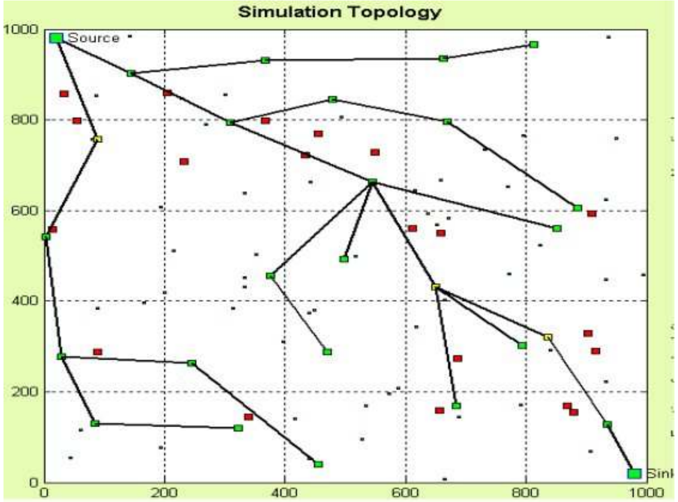


Figure 4.4. Simulation topology showing flooding through nodes in different states depending on available energy. Green: node in routing state. Yellow: node in warning state. Red: node in depleted state.

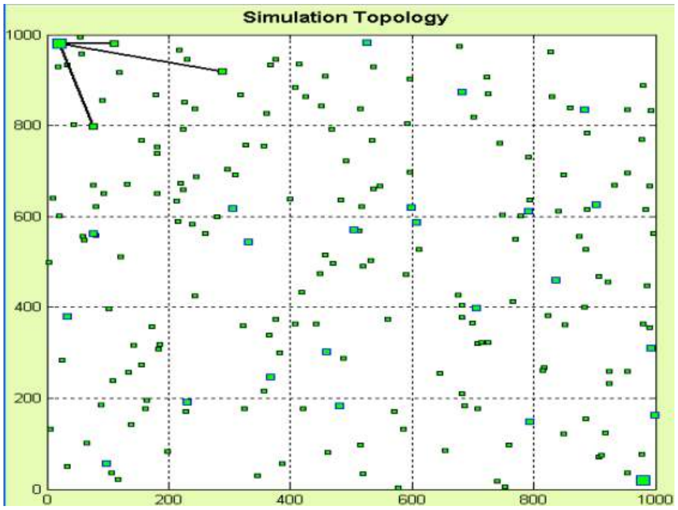


Figure 4.5. Level 1 flooding.

4.3.1. Deterministic Link Model

The first link model we used for simulation considered the path loss exponent n, distance between nodes d, transmit power P_t, and receiver sensitivity S. The value of n depends on the environment. It is typically between 2 to 4. Using these variables, the power P_r of the

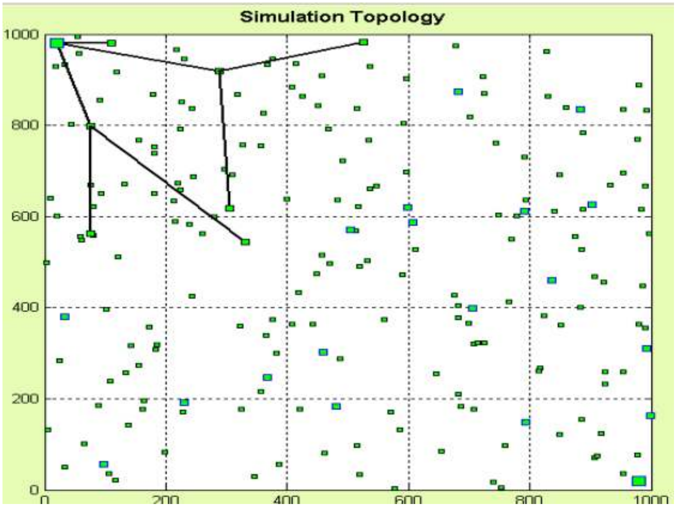


Figure 4.6. Level 2 flooding.

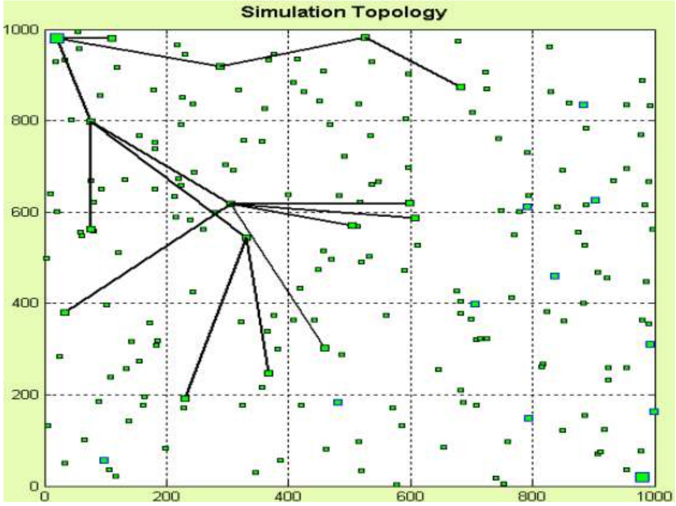


Figure 4.7. Level 3 flooding.

received signal is computed as follows:

$$P_r = P_t/d^n. \tag{1}$$

If P_r is greater than S, then the transmission was considered to be successful and the two nodes were connected by a communication link.

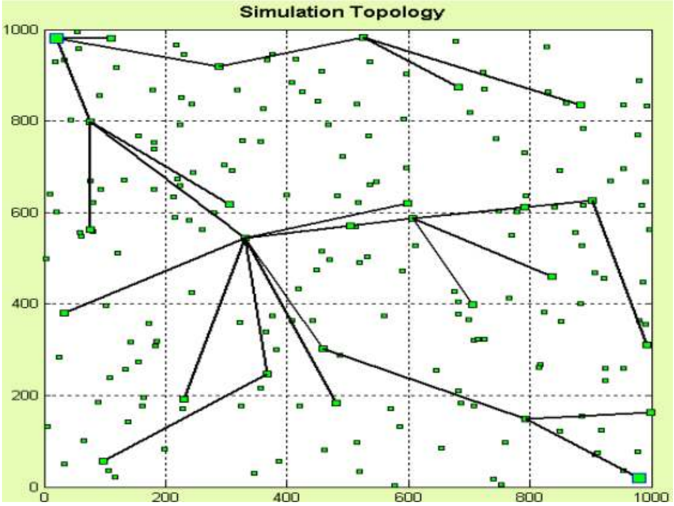


Figure 4.8. Level 4 flooding.

4.3.2. Probabilistic Link Model

In [27], experiments were carried out to characterize the empirical link quality on the Mica sensor platform. They measured the loss rates between different pairs of nodes at different distances. Results show that for a given power setting there is a distance within which all the nodes have good connectivity. The size of this *effective region* increases with transmit power. There is also a point beyond which the nodes show poor connectivity. In the *transitional region* between these points, the average link quality drops off smoothly [27]. Our current link model uses the same premise by including multi-path variation in (1). Multi-path can either increase or decrease the likelihood for reception to occur. This is represented in the current model by a random number R as shown below:

$$P_r = (P_t/d^n) * R. \tag{2}$$

The likelihood of a successful transmission falls into one of three categories: guaranteed success, guaranteed failure, and uncertain. Nodes at distances less than a certain point A are guaranteed to successfully receive a transmission, nodes beyond a certain point B are guaranteed not to receive the transmission, and nodes in between A and B are the ones truly

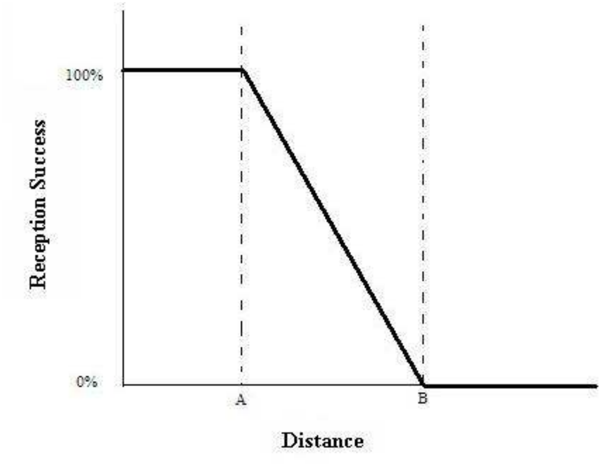


Figure 4.9. Probabilistic Link model.

affected by multi-path variation. For these nodes, the probability is calculated and is used to determine the power of the received signal.

The probability of transmission between points A and B is determined by the following equation:

$$R = R_A + (1 - R_A) * rand(1), \tag{3}$$

where R_A is calculated in (4), and $rand(1)$ is a random number uniformly distributed between 0 and 1.

$$R_A = (A^n * S)/P_t. \tag{4}$$

The value of R is substituted in (2) to calculate the power of the received signal. In this way, the transmission success of a packet is determined probabilistically when the distance between the points A and B is known. Fig. 4.9 shows an example of the link model of the probabilistic reception of packets versus distance.

4.3.3. Log-Normal Shadowing Model

The Log-Normal Shadowing Model accounts for variations in the environmental clutter. To include these variations, (1) is modified as follows:

$$P_r = (P_t/d^n) * 10^{X_\sigma/10}, \tag{5}$$

where X_σ is a zero-mean Gaussian distributed random variable with standard deviation σ. The distance d, the path loss exponent n, and the standard deviation σ, statistically describe the link model with log-normal distribution [28].

4.4. 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.

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. Figure 4.10 shows the simulation topology in which nodes with maximum ID in a grid square were elected as coordinators.

4.5. 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

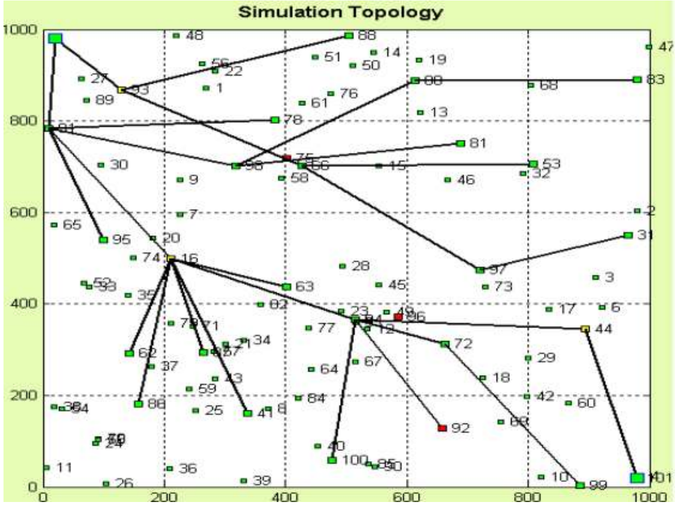


Figure 4.10. Simulation topology showing coordinator election by maximum node ID.

out of transmission range if the grid size is too large. This must be avoided so as not to experience early network partition.

When P_r is set to sensitivity S in (1), d is the maximum distance at which transmission can be received successfully. Let this maximum value of d be $dmax$. Therefore, $dmax$ is the nominal radio range R_n.

For example, if P_r=-90 dBm(sensitivity), P_t=-2 dBm, and n=3.5, the value of R_n equals to 326.80 m.

The upper bound for a square grid with width r (Fig. 4.11) is calculated as follows:

(6) $$r^2 + (2r)^2 <= R_n^2,$$

(7) $$r <= R_n/\sqrt{5}.$$

Substituting R_n=326.80 m in (7), we get

(8) $$r <= 146.15\text{m}.$$

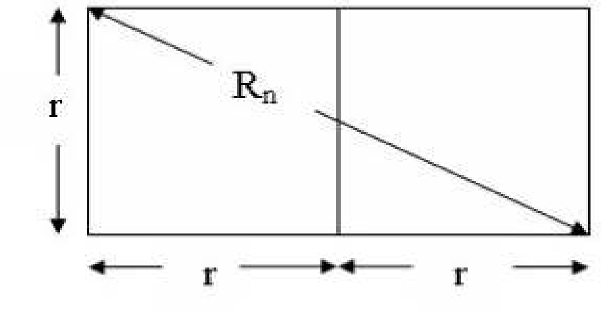


Figure 4.11. Calculation of grid width.

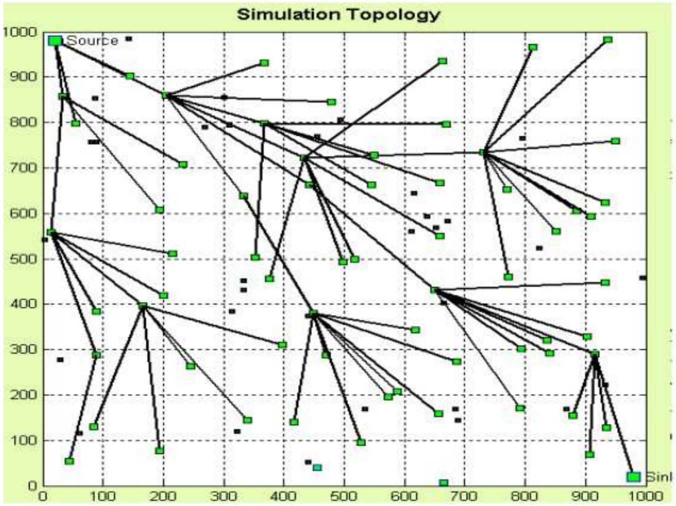


Figure 4.12. Simulation topology showing network with 100 m grids.

This shows that if the grid size is less than or equal to 146.15 m for the above example, the coordinators in adjacent grids are within their transmission ranges [17]. To ensure connectivity between the coordinators for grid sizes greater than 146.15 m, one has to change either P_t or S.

4.6. 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 (Sec. 4.2). 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.

Figure 4.13 shows the simulation topology with coordinator election by node rank to achieve load balancing.

4.7. Conclusions

We designed a grid-based coordinated routing protocol for sensor networks. We analyzed the link model of the network that incorporated deterministic, probabilistic, and log-normal shadowing. We described how the coordinators are elected from the given set of nodes. We

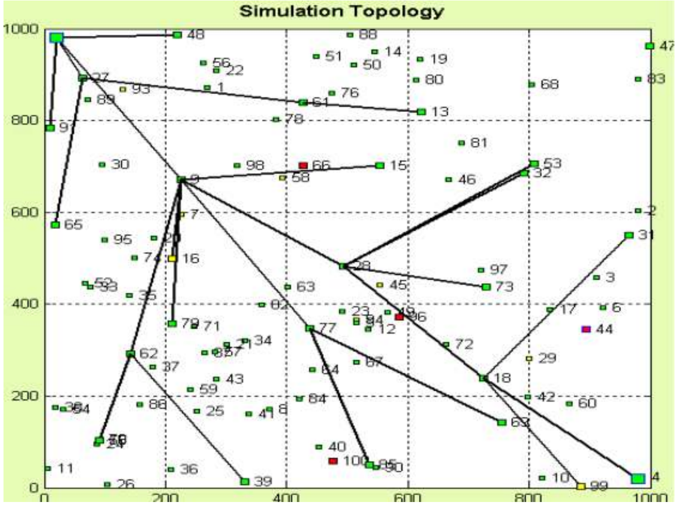


Figure 4.13. Simulation topology showing coordinator election by node rank. The topology shows nodes whose remaining energy is below 25% of battery life are in standby mode. In their place, nodes with energy greater than 25% of battery life are elected as coordinators. Unlike previous coordinator election rule, load balancing conserves energy by putting off nodes whose energy is less than 25% of battery life.

determined the upper bound on the grid size to ensure connectivity between the coordinators. Finally, we incorporated load balancing in our protocol to equally distribute routing load over all the nodes.

CHAPTER 5

NUMERICAL ANALYSIS AND RESULTS

5.1. Assumptions

We discuss in detail, the numerical analysis carried out for our grid-based coordinated routing protocol and present simulation results to support our analysis. Using this protocol, we asses the energy consumption of wireless sensor networks.

Actual radios consume energy not only while transmitting and receiving packets, but also while listening. Stemm and Katz show the idle:receive:transmit ratios to be 1:1.05:1.4 by measurement [29], whereas more recent studies show the ratios to be 1:2:2.5 [30] and 1:1.2:1.7 [20]. The RangeLAN2 7401/02 PC Card draws a current of 300 mA for transmission, 150 mA for reception, and a negligible 5 mA in doze mode [30]. Our energy consumption model is as follows. We assume that a node spends 1.0 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. When the transmit power is halved which is -2 dBm, the node uses 0.5 unit of battery energy for transmission and 0.5 unit of battery energy for reception. When the transmit power is doubled which is 4 dBm, the node uses 2.0 units of battery energy for transmission and 0.5 unit of battery energy for reception. We assume that the energy costs due to idle listening are negligible. For every active coordinator located within the radio range of a transmitting coordinator, we assume that the active coordinator uses 0.5 unit of battery energy for receiving the broadcast packets.

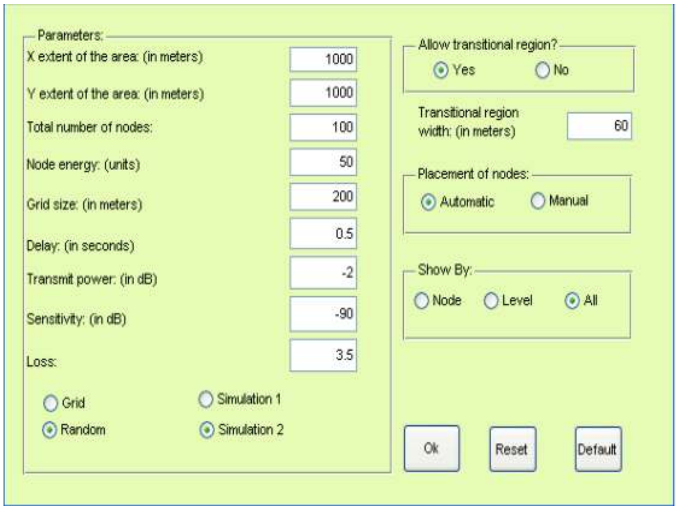
We assume that the source and sink nodes have infinite energy. Since we treat the source and sink nodes differently, we do not count them when reporting the number of nodes in the simulation. For example, our 1000-node simulation consists of 1000 nodes that route information, 1 source, and 1 sink node. The nodes that do the actual routing have limited energy. 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 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. We define an event as a point when the sink node is connected to the source node. Results are plotted as the normalized energy versus number of events. We define network partition as the simulation event at which the source and sink nodes are last connected.

We run extensive simulations that include all combinations of 3 transmit power levels, 3 receiver sensitivity values, 3 node energy values, and 5 grid widths with load balancing.

5.2. Protocol Parameters

Our grid-based coordinated routing protocol uses a number of parameters that affect the routing in the network. They include transmit power, receiver sensitivity, path loss exponent, node battery life, grid width, number of nodes, transition region width, and dimensions of the sensor field. Fig. 5.1 shows the interface that we designed to specify the parameters. We analyze the effects of these parameters on the network lifetime and determine the values that yield better network connectivity and longer network lifetime. We also compare our results to the traditional flooding algorithm (Alg. 1) presented in Section 4.1. We assume the following for the analysis. 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 250 units. The transmit power, sensitivity, and path loss exponent are -2 dBm, -90 dBm, and 3.5 respectively. The transition region width is set to 60 m. Simulations were carried out by setting the grid widths to 50 m, 100 m, 150 m, 200 m, and 250 m.



Parameters:

X extent of the area: (in meters) 1000

Y extent of the area: (in meters) 1000

Total number of nodes: 100

Node energy: (units) 50

Grid size: (in meters) 200

Delay: (in seconds) 0.5

Transmit power: (in dB) -2

Sensitivity: (in dB) -90

Loss: 3.5

○ Grid
● Random

○ Simulation 1
● Simulation 2

Allow transitional region?
● Yes ○ No

Transitional region width: (in meters) 60

Placement of nodes:
● Automatic ○ Manual

Show By:
○ Node ○ Level ● All

Figure 5.1. Different parameters that affect the routing behavior in the network.

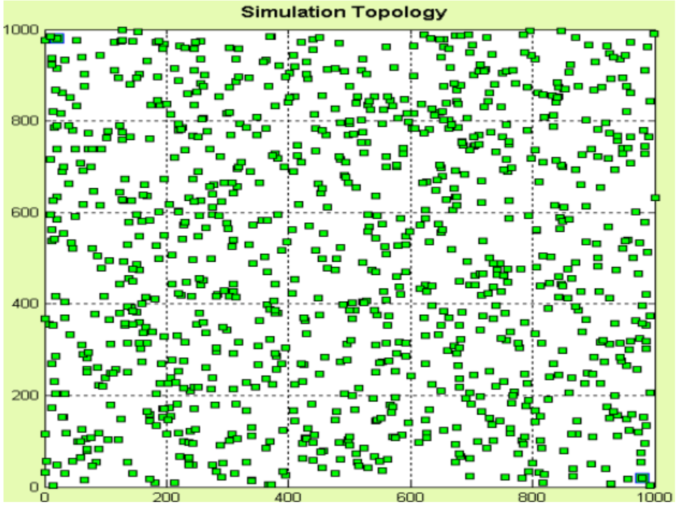


Figure 5.2. Simulation topology.

5.3. Analysis of Simulation Results

First, we vary the transmit power of the sensor nodes. We analyze how the change in transmit power affects the network partition. Next, we analyze the effect of changing the receiver sensitivity of the nodes on the network partition time and energy consumption. We also analyze the scalability and robustness of our algorithm.

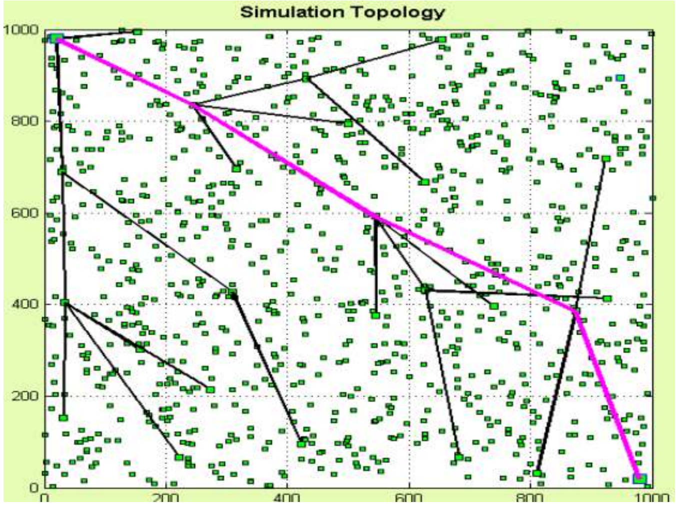


Figure 5.3. Simulation topology showing a path from sink to source.

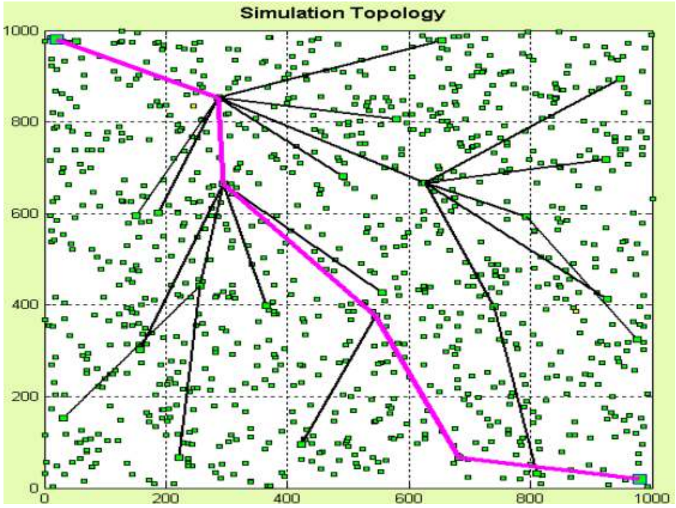


Figure 5.4. Simulation topology showing another path from sink to source.

5.3.1. Varying the Transmit Power

The topology of the network depends on uncontrollable factors such as interference and noise as well as controllable factors such as transmit power and antenna direction [16]. By changing the transmit power, we adjust the transmission coverage region and control the number of nodes that participate in routing. For the following simulations, we set the receiver sensitivity to -90 dBm and battery life to 250 units. We assume that a node spends 0.5, 1.0,

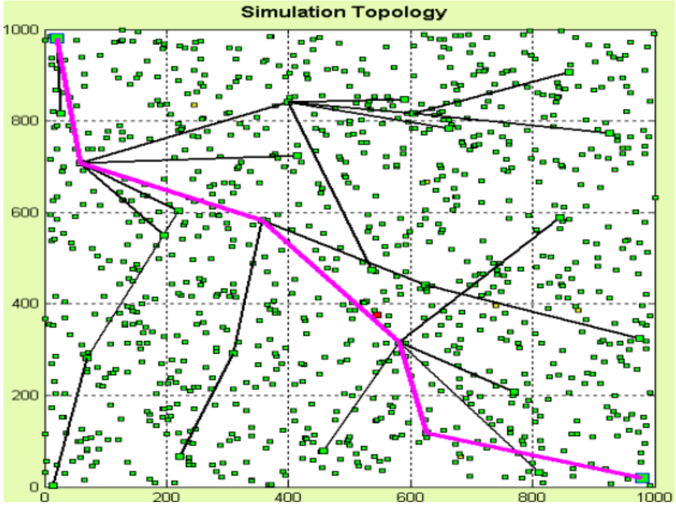


Figure 5.5. Simulation topology showing another path from sink to source.

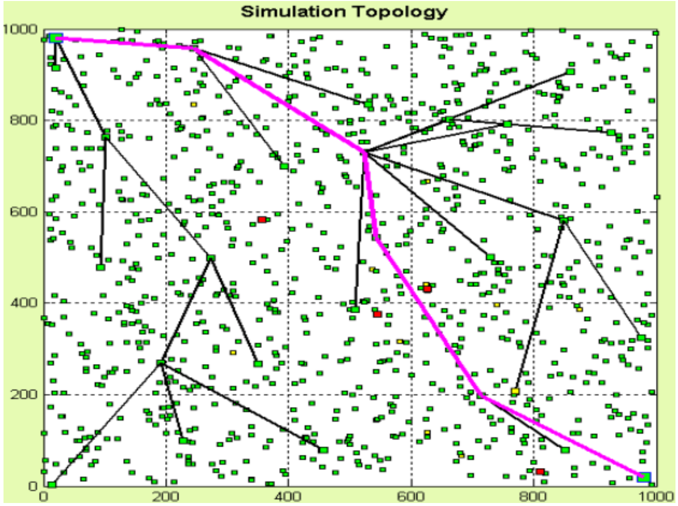


Figure 5.6. Simulation topology showing another path from sink to source.

and 2.0 units of energy for transmission when the transmit power is set to -2 dBm, 1 dBm, and 4 dBm, respectively.

Figures 5.7, 5.8, and 5.9 show the normalized energy when the transmit power is -2 dBm, 1 dBm, and 4 dBm, respectively. Table 5.1 summarizes the results from Figures 5.7 to 5.9. From the simulation results we observe the following:

- As the transmit power level increases, the network partition is prolonged.

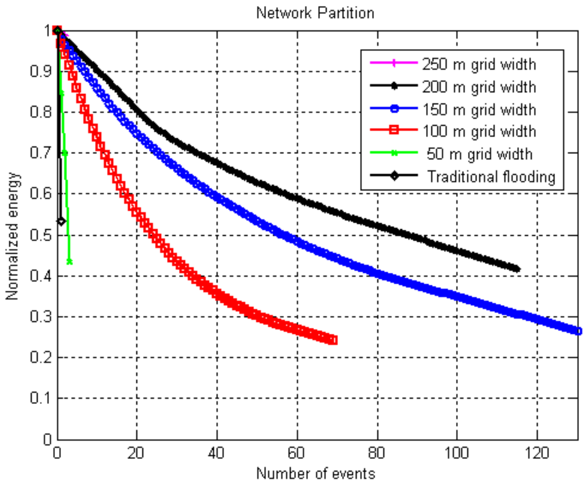


Figure 5.7. Network partition for transmit power equal to -2 dBm and node energy equal to 250 units.

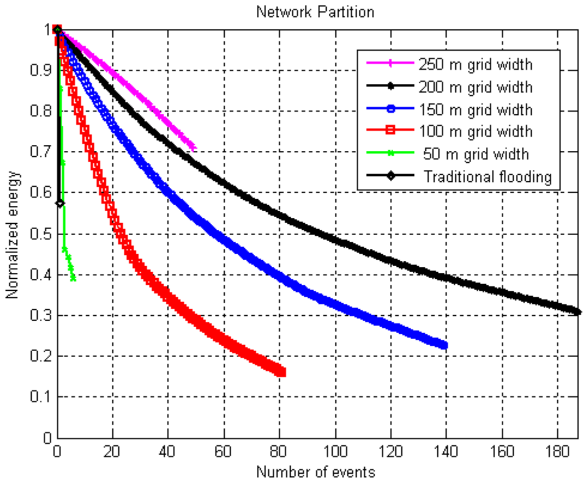


Figure 5.8. Network partition for transmit power equal to 1 dBm and node energy equal to 250 units.

- Network partition is extended by a factor of 2.20 when the transmit power is 4 dBm and is extended by a factor of 1.62 when the transmit power is set to 1 dBm compared to when the transmit power is -2 dBm for 200 m grid networks.
- Network with a grid width of 200 m provides the longest network partition on average.

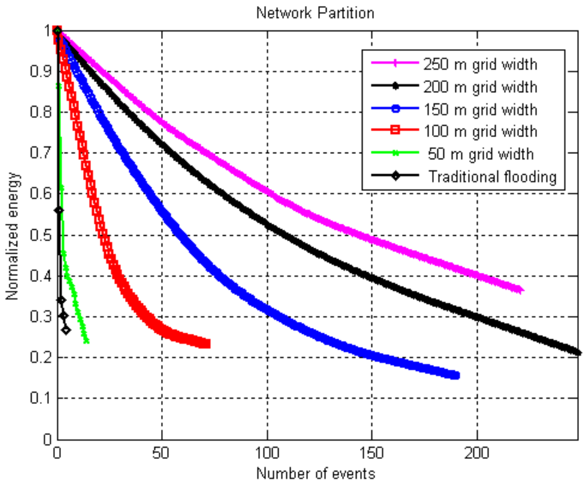


Figure 5.9. Network partition for transmit power equal to 4 dBm and node energy equal to 250 units.

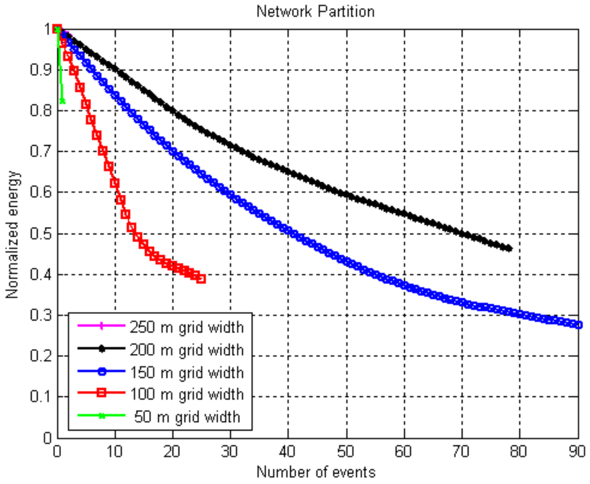


Figure 5.10. Network partition for transmit power equal to -2 dBm and node energy equal to 100 units.

Figures 5.10, 5.11, and 5.12 show the normalized energy when the transmit power is -2 dBm, 1 dBm, and 4 dBm, respectively, when the battery life per node is initialized to 100 units. Table 5.2 summarizes the results from Figures 5.10 to 5.12.

Figures 5.13, 5.14, 5.15, and 5.16 show why the 50 m grid width and the traditional flooding yield results as shown in Figures 5.10 to 5.12. The number of nodes is 200 and node

Table 5.1. Network partition for transmit power of -2 dBm, 1 dBm, and 4 dBm when node energy is initialized to 250 units.

Transmit Power (dBm)	Grid Width (meters)	Network Partition (number of events)	Normalized Energy
-2	250	2	0.98
	200	115	0.42
	150	130	0.27
	100	69	0.24
	50	3	0.43
	Trad. flood	1	0.53
1	250	49	0.71
	200	187	0.30
	150	139	0.22
	100	81	0.16
	50	6	0.38
	Trad. flood	1	0.57
4	250	221	0.36
	200	248	0.23
	150	190	0.15
	100	71	0.23
	50	14	0.24
	Trad. flood	4	0.26

energy is initialized to 100 units. The results also help us infer that node energy of 100 units is insufficient to perform network partition analysis.

Figures 5.17, 5.18, and 5.19 show the normalized energy when the transmit power is -2 dBm, 1 dBm, and 4 dBm, respectively, when the node battery is initialized to 500 units. Table 5.3 summarizes the results from Figures 5.17 to 5.19.

5.3.2. Varying the Receiver Sensitivity

The sensitivity of the receiver is important for successful communication. Once the signal has been transmitted, it will reach the receiver, which has to decode it. The sensitivity of

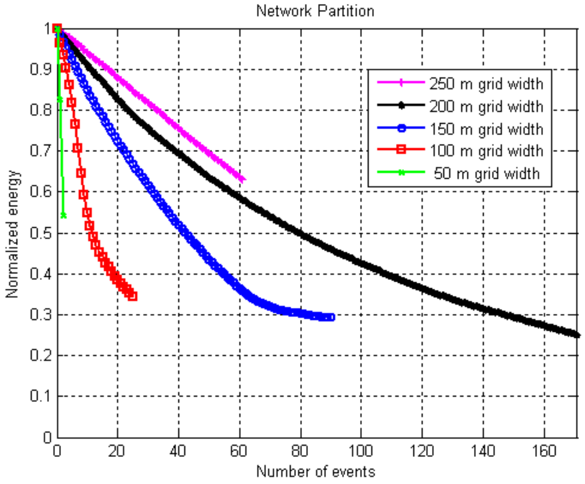


Figure 5.11. Network partition for transmit power equal to 1 dBm and node energy equal to 100 units.

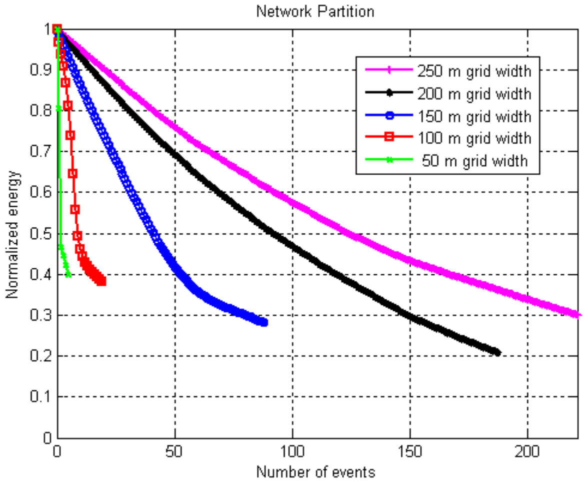


Figure 5.12. Network partition for transmit power equal to 4 dBm and node energy equal to 100 units.

the receiver plays a major role in determining the radio range [31]. For all these simulations, we set the transmit power to 1 dBm and the battery life is initialized to 250 units.

Figures 5.20, 5.21, and 5.22 show the normalized energy when the receiver sensitivity is -87 dBm, -90 dBm, and -93 dBm respectively. Table 5.4 summarizes the results from Figures 5.20 to 5.22. From the simulation results, we observe the following:

Table 5.2. Network partition for transmit power of -2 dBm, 1 dBm, and 4 dBm when node energy is initialized to 100 units.

Transmit Power (dBm)	Grid Width (meters)	Network Partition (number of events)	Normalized Energy
-2	250	2	0.98
	200	78	0.46
	150	90	0.27
	100	25	0.38
	50	1	0.82
1	250	61	0.63
	200	171	0.25
	150	90	0.29
	100	25	0.34
	50	2	0.54
4	250	221	0.30
	200	187	0.21
	150	88	0.28
	100	19	0.38
	50	5	0.39

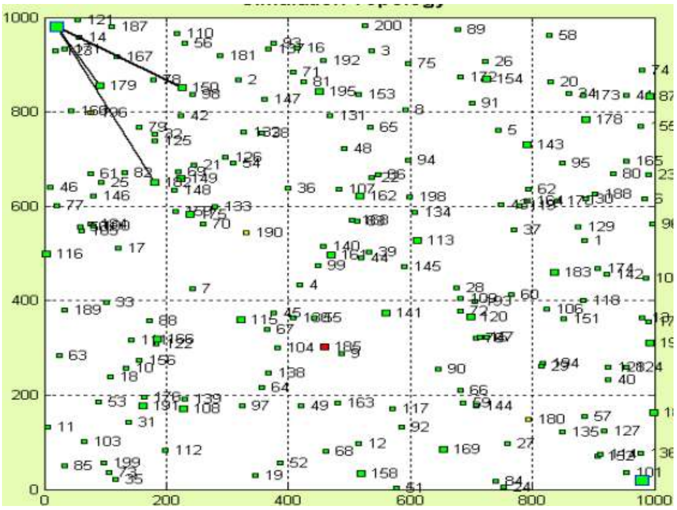


Figure 5.13. Simulation topology showing the state of the coordinators in 200 m grid network when the source node refloods for the first time. The number of nodes whose energy level is below 25 % of battery life is low.

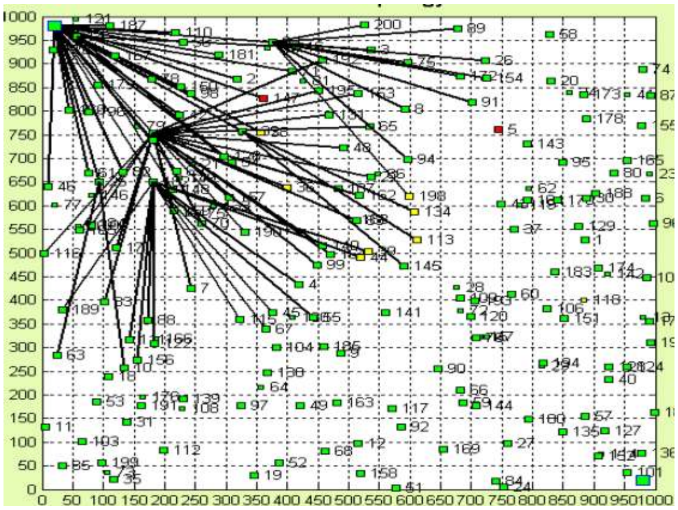


Figure 5.14. Simulation topology showing the state of the coordinators in 50 m grid network when the source node refloods for the first time. The number of nodes whose energy level is below 25 % of battery life is high, since more number of nodes are actively listening.

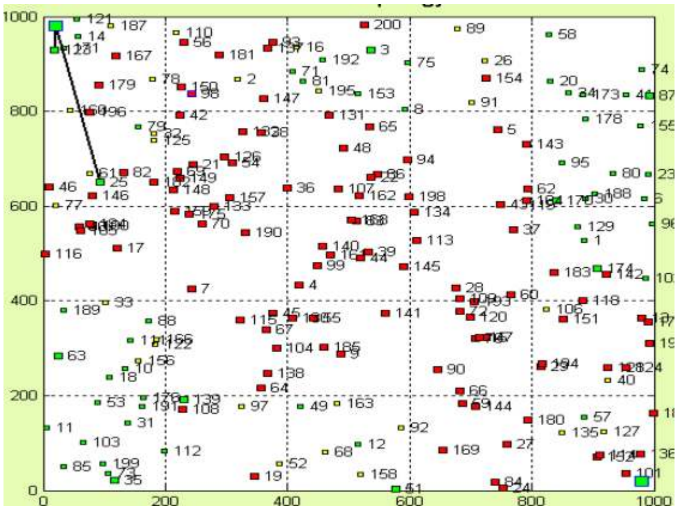


Figure 5.15. Simulation topology showing the state of the coordinators in 200 m grid network when the network is partitioned. Due to redundancy and inherent load balancing, the network lifetime is prolonged and dead nodes are evenly distributed.

- As the sensitivity is varied from -87 dBm to -93 dBm, the network partition is prolonged for 250 m and 200 m and it is reduced for 150 m and 100 m.

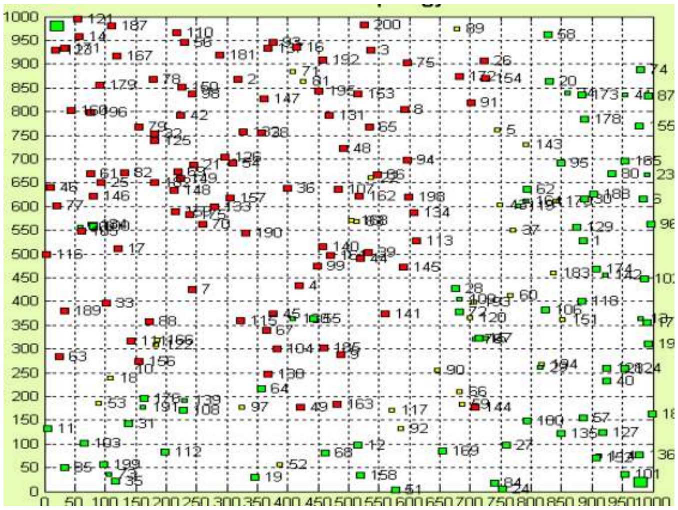


Figure 5.16. Simulation topology showing the state of the coordinators in 50 m grid network when the network is partitioned. Since almost all the nodes were active all the time, and due to source reflooding the network frequently to reach the sink, the dead nodes are concentrated near the source, leaving significant number of nodes with non-zero energy present. As a result, the network partitions earlier than 200 m grid network.

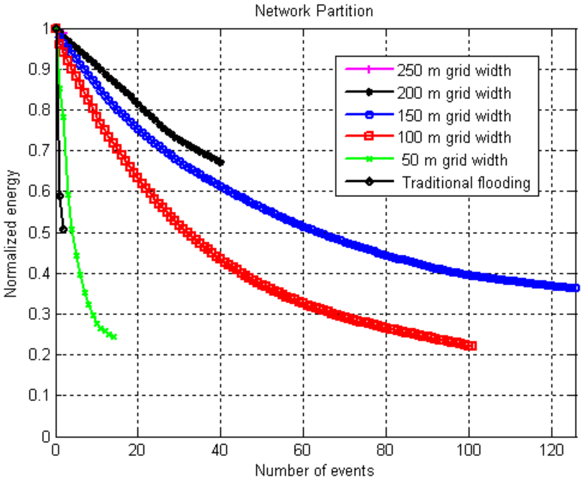


Figure 5.17. Network partition for transmit power equal to -2 dBm and node energy is equal to 500 units.

- Network partition is extended by a factor of 4.0 when the sensitivity is -93 dBm and is extended by a factor of 3.0 when the sensitivity is set to -90 dBm compared to when the sensitivity is -87 dBm for a grid width of 200 m.

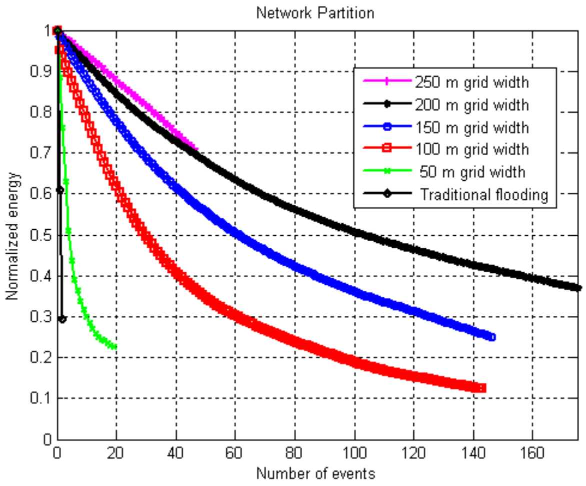


Figure 5.18. Network partition for transmit power equal to 1 dBm and node energy is equal to 500 units.

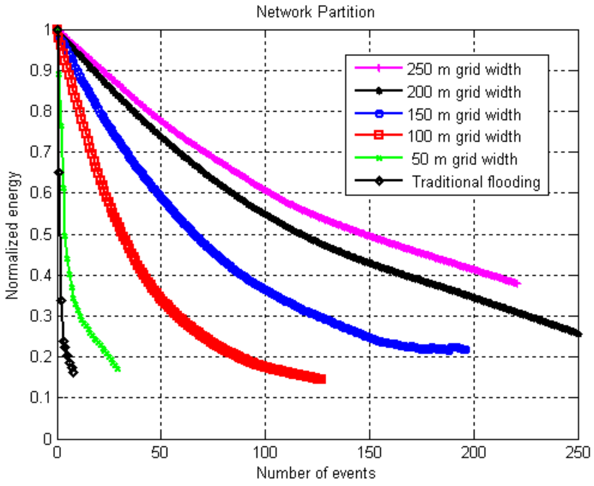


Figure 5.19. Network partition for transmit power equal to 4 dBm and node energy is equal to 500 units.

- Network with a grid width of 200 m provides the longest network partition on average.

Figures 5.23, 5.24, and 5.25 show the normalized energy when the receiver sensitivity -87 dBm, -90 dBm, and -93 dBm respectively, and the battery life is initialized to 100 units. Table 5.5 summarizes the results from Figures 5.23 to 5.25.

Table 5.3. Network partition for transmit power of -2 dBm, 1 dBm, and 4 dBm when node energy is initialized to 500 units.

Transmit Power (dBm)	Grid Width (meters)	Network Partition (number of events)	Normalized Energy
-2	250	2	0.98
	200	40	0.67
	150	126	0.36
	100	101	0.22
	50	14	0.24
	Trad. flood	2	0.51
1	250	46	0.71
	200	175	0.37
	150	146	0.25
	100	143	0.12
	50	19	0.23
	Trad. flood	2	0.30
4	250	221	0.38
	200	250	0.25
	150	196	0.21
	100	127	0.14
	50	29	0.17
	Trad. flood	8	0.16

Figures 5.26, 5.27, and 5.28 show the normalized energy when the battery life is initialized to 500 units. Table 5.6 summarizes the results from Figures 5.26 to 5.28.

5.3.3. 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 each simulation, we have the following. The field is 1000 m in length and 1000 m in width. The battery life per node is initialized to 250 units. The transmit power, sensitivity, and path loss exponent are 1 dBm, -90 dBm, and 3.5 respectively. The grid width is set to 200 m. The nodes are randomly

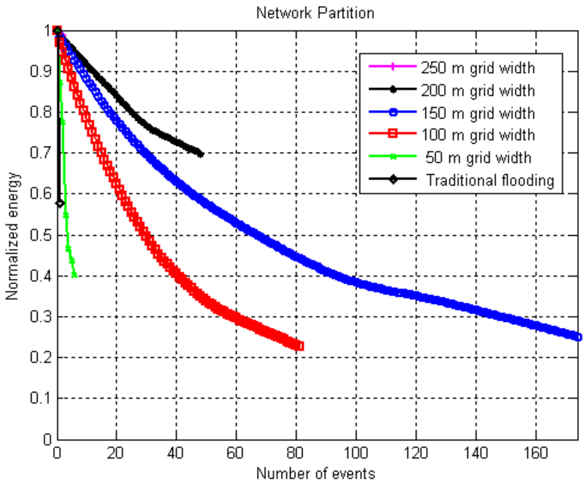


Figure 5.20. Network partition for sensitivity equal to -87 dBm and node energy is equal to 250 units.

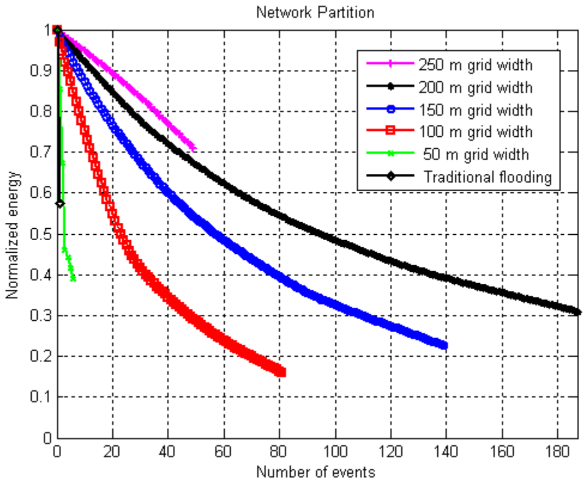


Figure 5.21. Network partition for sensitivity equal to -90 dBm and node energy is equal to 250 units.

placed in the field. Table 5.7 summarizes the results obtained from Figure 5.29. From the simulation results, we observe the following:

- As the number of nodes increases, the node redundancy increases. Consequently, the network partition is prolonged.

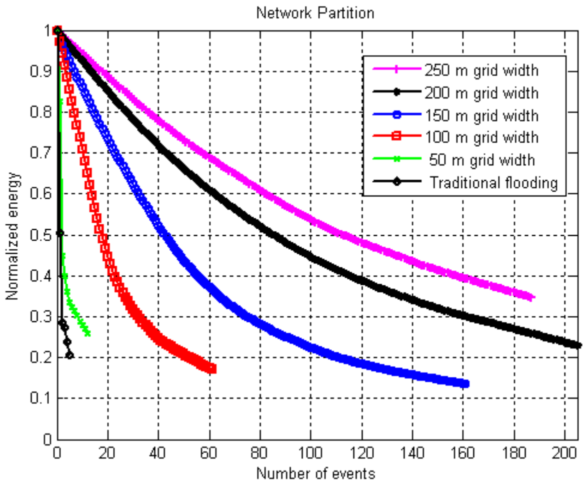


Figure 5.22. Network partition for sensitivity equal to -93 dBm and node energy is equal to 250 units.

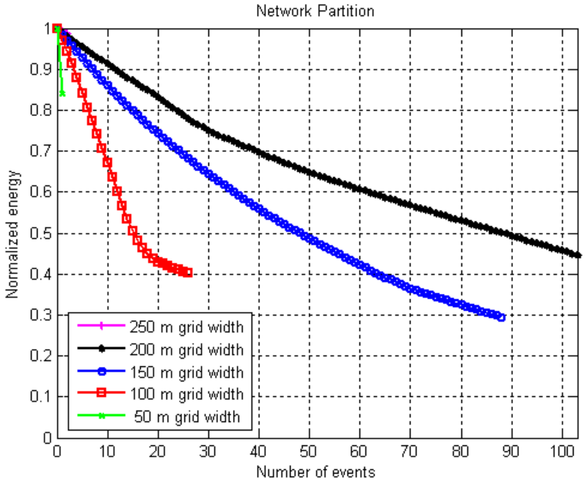


Figure 5.23. Network partition for sensitivity equal to -87 dBm and node energy is equal to 100 units.

- The network partition for the network of 1500 nodes is extended by a factor of 2 compared to the network of 1000 nodes. It is extended by a factor of 17 compared to the network of 100 nodes.
- There is a linear increase in network partition as the number of nodes increases.

Table 5.4. Network partition for receiver sensitivity of -87 dBm, -90 dBm, and -93 dBm when node energy is initialized to 250 units.

Receiver Sensitivity (dBm)	Grid Width (meters)	Network Partition (number of events)	Normalized Energy
-87	250	2	0.98
	200	48	0.69
	150	174	0.25
	100	81	0.23
	50	6	0.40
	Trad. flood	1	0.57
-90	250	49	0.71
	200	187	0.30
	150	139	0.23
	100	81	0.16
	50	6	0.38
	Trad. flood	1	0.57
-93	250	187	0.34
	200	205	0.23
	150	161	0.13
	100	61	0.17
	50	12	0.26
	Trad. flood	5	0.21

5.3.4. Comparison with Flooding

Our protocol shows better results in terms of extending network partition compared to the traditional flooding algorithm. We know that, in traditional flooding, information is disseminated through all nodes in the network. As a result, each node performs the task of receiving and transmitting the information. This leads to increased energy consumption. On the other hand, in grid-based coordinated routing protocol, fewer nodes participate in routing process. It follows that our protocol can maintain routing and connectivity for a much longer time compared to the traditional flooding algorithm. Our simulation results verify that since

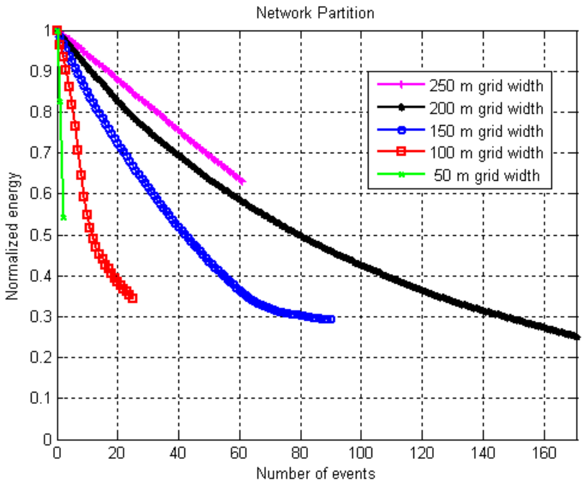


Figure 5.24. Network partition for sensitivity equal to -90 dBm and node energy is equal to 100 units.

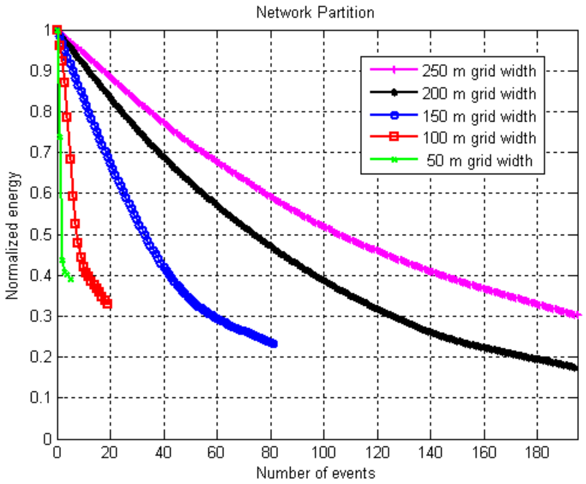


Figure 5.25. Network partition for sensitivity equal to -93 dBm and node energy is equal to 100 units.

less nodes are active at a time in the grid networks, network partition is prolonged compared to traditional flooding where more nodes have to be active all the time.

5.4. Conclusions

We analyzed the effects of varying transmit power, receiver sensitivity, grid width, and number of nodes on the network lifetime. We found that increasing transmit power, extends the network partition for larger grid widths. We also observed that networks with grid width

Table 5.5. Network partition for receiver sensitivity of -87 dBm, -90 dBm, and -93 dBm when node energy is initialized to 100 units.

Receiver Sensitivity (dBm)	Grid Width (meters)	Network Partition (number of events)	Normalized Energy
-87	250	2	0.98
	200	103	0.45
	150	88	0.29
	100	26	0.40
	50	1	0.83
-90	250	61	0.63
	200	171	0.25
	150	90	0.29
	100	25	0.34
	50	2	0.54
-93	250	195	0.30
	200	194	0.17
	150	81	0.23
	100	19	0.33
	50	5	0.39

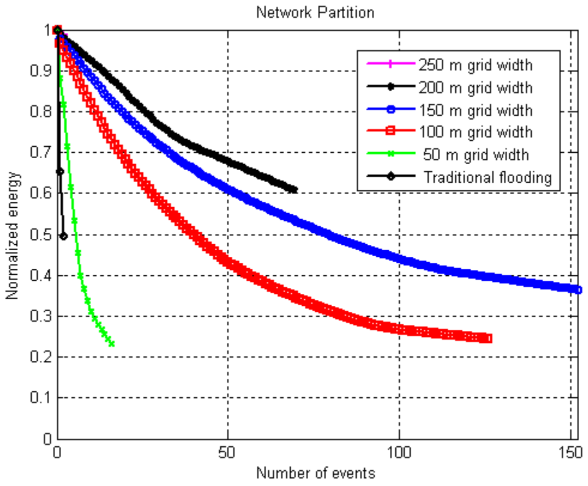


Figure 5.26. Network partition for sensitivity equal to -87 dBm and node energy is equal to 500 units.

Table 5.6. Network partition for receiver sensitivity of -87 dBm, -90 dBm, and -93 dBm when node energy is initialized to 500 units.

Receiver Sensitivity (dBm)	Grid Width (meters)	Network Partition (number of events)	Normalized Energy
-87	250	2	0.98
	200	69	0.61
	150	152	0.36
	100	126	0.24
	50	16	0.23
	Trad. flood	2	0.49
-90	250	46	0.71
	200	175	0.37
	150	146	0.25
	100	143	0.12
	50	19	0.23
	Trad. flood	2	0.30
-93	250	184	0.38
	200	202	0.27
	150	141	0.20
	100	121	0.12
	50	29	0.13
	Trad. flood	8	0.12

Table 5.7. Network partition (number of events) versus number of nodes.

Number of Nodes	Number of Events
100	16
250	55
500	111
750	186
1000	209
1250	262
1500	273

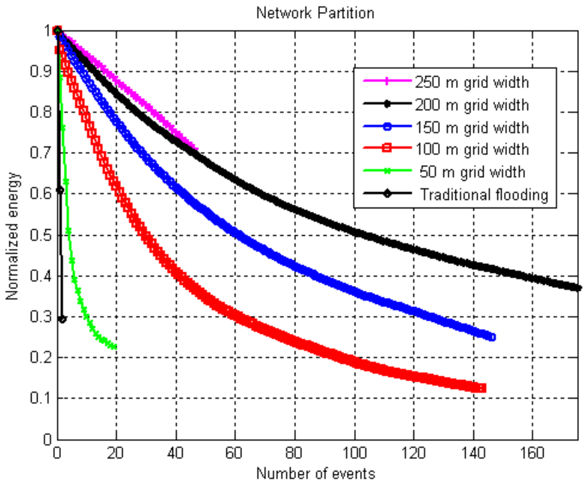


Figure 5.27. Network partition for sensitivity equal to -90 dBm and node energy is equal to 500 units.

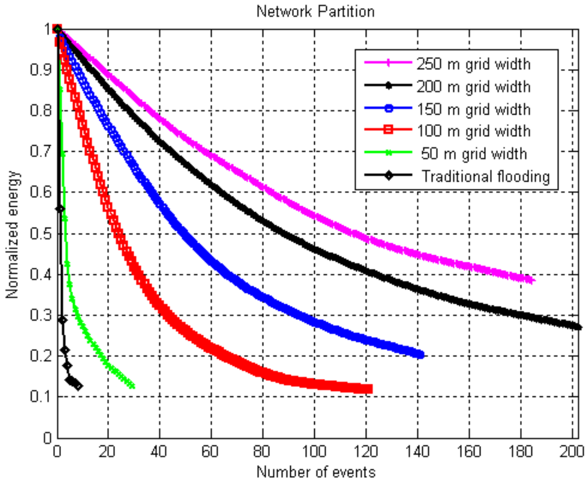


Figure 5.28. Network partition for sensitivity equal to -93 dBm and node energy is equal to 500 units.

equal to 200 m show consistently better performance. Also, by decreasing sensitivity, we experience longer network lifetimes. We observed that network partition is increased by a factor of 17 when the total number of nodes is increased from 100 to 1500 nodes. Finally, all the simulation results show that our grid based coordinated routing outperforms the traditional flooding by extending network connectivity significantly.

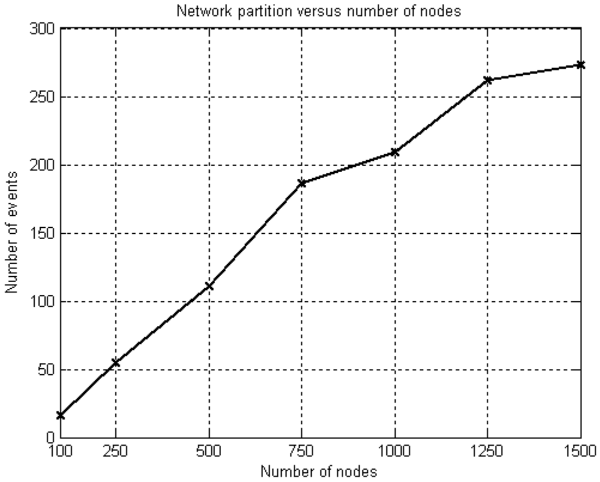


Figure 5.29. Network partition versus number of nodes.

CHAPTER 6

CONCLUSIONS

6.1. Summary

Efficient routing in wireless sensor networks is an active area of research. Routing algorithms need to consume less power, scale well with number of sensor nodes, prolong network partition, and maintain network connectivity. We introduced the grid based coordinated routing algorithm that meets the above needs by exploiting node redundancy and load balancing.

In Chapter 2, we reviewed several routing protocols for mobile ad hoc networks. On-demand routing protocols were found to be fitting for sensor networks. We also presented existing routing protocols for sensor networks and noted that all of them focus on conserving energy.

In Chapter 3, we discussed two routing protocols GAF and Span which are closely related to our work. GAF was designed to exploit node redundancy by overlaying a grid over the network of sensor nodes. However, it was studied for fewer number of nodes. Span was designed to ensure connectivity between neighboring coordinator nodes. But, in some cases, it resulted in having more coordinators active than necessary.

In Chapter 4, we designed a grid-based coordinated routing protocol for sensor networks. We analyzed the link model of the network that incorporated deterministic, probabilistic, and log-normal shadowing. 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 equally distribute routing load over all the nodes.

In Chapter 5, we implemented and simulated our protocol for sensor networks. We analyzed our algorithm for different values of transmit power, sensitivity, and grid widths. Networks with grid width of 200 m show consistently better performance. We also studied the scalability of our protocol. For this, we examined the network partition by increasing the number of nodes from 100 to 1500. The network partition increases linearly with respect to number of nodes. Our results verify that our protocol extends network lifetime and maintains connectivity compared to the traditional flooding algorithm.

6.2. Future Research

We conclude by outlining the possible future extensions to our work:

- **Physical implementation:** The grid based coordinated routing protocol has been simulated in Matlab. Actual implementation on motes can be done to match the simulation results.
- **Localized reflooding:** To further extend network partition, one could implement localized reflooding. Our protocol is designed for the source node to reflood whenever a coordinator node is out of energy. A possible improvement could be to let the immediate parent node of the depleted coordinator reflood locally. This could save energy significantly, but it would also result in protocol overhead.
- **Node mobility:** Our work is focused on routing issues in immobile sensor nodes. A further extension of our work would be to check how the protocol can accommodate node mobility by considering high and low mobility patterns. Mobile nodes can change network topology frequently. This will need improved coordinator election algorithms.

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