NON-UNIFORM GRID-BASED COORDINATED ROUTING IN WIRELESS SENSOR NETWORKS

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Wireless sensor networks are ad hoc networks of tiny battery powered sensor nodes that can organize themselves to form self-organized networks and collect information regarding temperature, light, and pressure in an area. Though the applications of sensor networks are very promising, sensor nodes are limited in their capability due to many factors. The main limitation of these battery powered nodes is energy. Sensor networks are expected to work for long periods of time once deployed and it becomes important to conserve the battery life of the nodes to extend network lifetime.

This work examines non-uniform grid-based routing protocol as an effort to minimize energy consumption in the network and extend network lifetime. The entire test area is divided into non-uniformly shaped grids. Fixed source and sink nodes with unlimited energy are placed in the network. Sensor nodes with full battery life are deployed uniformly and randomly in the field. The source node floods the network with only the coordinator node active in each grid and the other nodes sleeping. The sink node traces the same route back to the source node through the same coordinators. This process continues till a coordinator node runs out of energy, when new coordinator nodes are elected to participate in routing. Thus the network stays alive till the link between the source and sink nodes is lost, i.e., the network is partitioned.

This work explores the efficiency of the non-uniform grid-based routing protocol for different node densities and the non-uniform grid structure that best extends network lifetime.

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CHAPTER 1

INTRODUCTION

Wireless sensor networks are a result of the combination of advances made in the field of analog and digital circuitry, wireless communications and sensor technology. A wireless sensor network typically consists of small devices called sensor nodes that are capable of sensing the environment around them. The sensor nodes are devices that are capable of sensing, gathering, storing and transmitting information. The main advantage of these nodes is their self-organizing capability. Large networks of such small nodes are therefore growing in use. The sensor nodes can be deployed anywhere without actually having to install or deploy them manually. In remotely inaccessible areas, these sensor nodes are just strewn across the desired sensor field. The self-organizing capability of the sensor nodes enables the nodes to form a cooperative network and gather information. This information can then be retrieved. Thus, sensor networks enable intelligent monitoring of inaccessible areas with ease and accuracy. Wireless sensor network (WSN) is a term used to describe an emerging class of embedded communication products that provide redundant, fault-tolerant wireless connections between sensors, actuators and controllers [25]. Figure 1.1 shows a wireless sensor network with sensor nodes, a source node and a sink node.

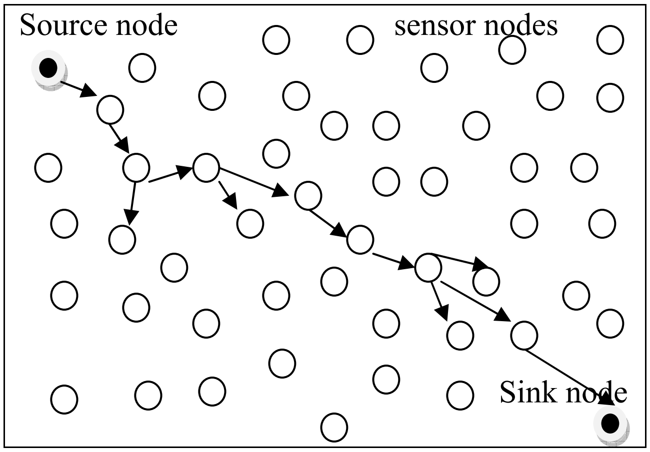


Figure 1.1 Wireless sensor network.

1.1 The Sensor Node

Like all other technologies, wireless sensor networks are also subject to constraints. One of the major challenges is the energy constraint of the sensors nodes. Sensor nodes are driven by a battery and have very low energy resources, which in turn affects the network lifetime [26]. Figure 1.2 shows the architecture of a sensor node.

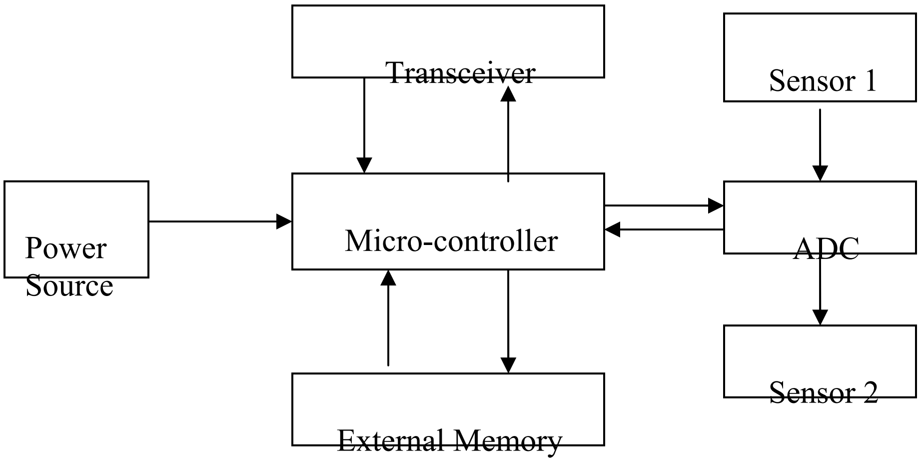


Figure 1.2 Architecture of a sensor node.

1.1.1 Components of a Sensor Node

From the Figure 1.2 [27], the components of a sensor node are a microcontroller, a transceiver, external memory, a power source and sensors.

Microcontroller: The microcontroller performs tasks, processes information and controls the functionality of the other components in the node. Microcontrollers are best suited for sensor nodes due to their flexibility to connect to other devices, less power consumption and the fact that the microcontroller can enter a sleep state wherein only a part of the controller is active, thus saving energy.

Transceiver: Sensor nodes operate in the Industrial, Scientific and Medical (ISM) band, which provides free radio, huge spectrum allocation and global availability. Radio frequency communication is best suited for sensor networks. Sensor networks use the communication frequencies between 433 MHz and 2.4 GHz. The transceiver provides the functionality of both the transmitter and the receiver in the sensor node.

External memory: Mostly, the on-chip memory of the microcontroller and flash memory are used, and off-chip random access memory (RAM) is barely used. Depending on the type of storage, two kinds of memory are used: user memory for storing application related or personal data, and program memory for programming the device.

Power source: The sensor node consumes power for sensing the environment, gathering information, storing and processing the information gathered. Most of the energy is spent for communication with other nodes in the network and staying active. Batteries are the main source of power for sensor nodes.

Sensors: A sensor is a device that responds to a change in its surroundings in a measurable manner. The continuous analog signal that is sensed by the sensors is digitized by analog-to-digital converters and sent to the controllers for further processing. Sensors should be small, adaptive to the environment, operate and configure on their own, and consume low power. There are two types of sensors, active and passive. Active sensors gather data by probing into the environment, while passive sensors gather data without actually disturbing the environment.

1.2 Hardware and Software

The hardware related to wireless sensor networks is a result of advances in technologies such as system-on-chip technology that is capable of integrating systems on a single chip, commercial Radio-frequency (RF) circuits that enable short distance wireless communication with low power consumption, and the micro-electro-mechanical systems (MEMS) technology that integrate sensors onto a single CMOS chip [28]. The first commercial manufacturer of Intel motes was Crossbow Technology Inc. [5]. This was followed by Intel's Stargate gateway computer network and the Intel r Mote, equipped with 32-bit central processor and Bluetooth wireless standard [5, 31]. The Smart Dust project lead to Spec motes that have reduced large motes into single chips excluding batteries. TinyOS [5, 29], a freely-available open source operating system was developed for MICA2 sensor nodes, and also another programming environment for sensor nodes called EmStar [5, 30] came into existence. NesC is an extension of the C programming language and is used by sensor nodes to communicate between themselves.

1.3 Problem Description and Motivation

Sensor networks are easy to deploy and enable us to remotely monitor practically inaccessible areas. One major challenge posed by sensor networks is wasteful usage of resources. Once deployed, sensor nodes are solely battery operated and left to self organize and process information. It therefore becomes very important to keep the nodes up and running for as long as possible. Energy consumption is hence a very serious issue of sensor networks. In [20], network partition is recognized as a major problem in densely populated sensor networks. In [5], network partition is defined as an event when the source node and the sink node are last connected. We therefore define the network as partitioned when no communication link can be established between the source node and the sink node. This loss of communication between the source and the sink nodes is a result of exhausted battery life of the sensor nodes in the network. Hence network partition is directly affected by the energy consumption of the nodes in the network. The motivation of our work is to study network partition and the energy consumption of the wireless sensor network.

1.4 Objectives

This work studies the conditions leading to network partition, and analyzes energy consumption to prolong the network lifetime. We focus on implementing routing in densely populated sensor networks. By maintaining constant values for parameters such as path loss exponent, receiver sensitivity and transmit power, and varying between uniform and types of non-uniform grids, we observe energy consumption patterns for each of the grid structures, and infer from the network lifetime the best suited grids for uniformly and randomly deployed sensor nodes.

I tried to achieve the following objectives:

1. Design non-uniform grid-based coordinated routing.
2. Observe network lifetime for different types of non-uniform grids under different node densities.
3. Extend network lifetime by routing only through grid coordinators.
4. Infer the best suited non-uniform grid structure for prolonged network lifetime.

5. Verify the results of the algorithm through simulations, and compare between different simulations.

1.5 Contributions

The main contributions of this work are:

- Design and implement non-uniform grid-based routing with different types of non-uniform grids.
- To maintain load balancing among the sensor nodes.
- Determine the best type of grid suitable for uniform and random deployment of nodes, and for different node densities.

1.6 Organization

Chapter 2 deals with the different routing protocols used for wireless sensor networks. It discusses the traditional routing protocols, ad-hoc routing protocols and routing protocols developed for wireless sensor networks.

Chapter 3 describes the traditional flooding algorithm, and also deals in detail about two routing protocols, namely the geographic adaptive fidelity and span protocols which are the main idea behind grid-based routing.

Chapter 4 presents the grid-based routing protocol, and also explains in detail the non-uniform grid-based routing protocol, including electing coordinators, determining the grid size for the network, and load balancing in our protocol. It also presents the different types of non-uniform grid structures.

Chapter 5 presents simulations and results for various non-uniform grid structures, the uniform grid structure and the traditional flooding algorithm.

Chapter 6 presents conclusions and future directions for this work.

Finally, the source code for all simulations, in Matlab, is provided in the appendix.

CHAPTER 2

ROUTING PROTOCOLS FOR WIRELESS SENSOR NETWORKS

2.1 Introduction

Wireless sensor networks are wireless networks consisting of autonomous sensor nodes, communicating with each other over wireless links. There are basically two modes in wireless networking: infrastructure mode and ad hoc mode. Wireless sensor networks are a form of ad hoc networks. Infrastructure mode requires the use of connecting points, such as access points, to connect a wireless network to a wired network. The additional cost of the equipment is a major drawback of infrastructure networks. Unlike the infrastructure mode, the ad hoc mode supports networking applications when a fixed infrastructure is unavailable. Communication in ad hoc networks does not rely on a central access point or connecting points, but allows wireless devices or nodes to communicate directly to each other. Mobile ad hoc networks are thus self-organized networks where the nodes discover each other and act as routers, maintaining information about their neighbors and themselves. Each node in the ad-hoc network may be the final destination for packets, or may act as a forwarding node or station for transmitting packets to their final destination. Each node in a sensor network consists of a central processing unit, memory, a radio frequency (RF) transceiver, and a power source which is usually a battery. The lifetime of the node plays a vital role in supporting network connectivity in ad-hoc networks. Several energy conserving mechanisms have been proposed to extend the lifetime of the network. I examine some of these schemes in this chapter.

2.2 Traditional Routing Protocols

An efficient routing protocol will help minimize the load on each individual node, and also minimize the traffic overhead over the network. Traditional routing protocols are aimed at finding optimal routes to every host in the network, and are not suitable for ad-hoc networks. A mobile ad hoc networking (MANET) working group has been formed within the Internet Engineering Task Force (IETF) to develop a routing framework for IP-based protocols in the ad hoc networks [1]. These ad-hoc routing protocols are divided into table-driven and on-demand protocols. Table-driven routing is also called proactive or precomputed routing, while on-demand routing is called reactive routing. Table-driven protocols require the use of routing tables at each node to keep track of routes to different nodes and make use of periodic broadcasts for periodic updates. On-demand algorithms do not maintain such routing tables, but use a procedure to identify a route as and when a source requires to transmit information to a destination. Table-driven algorithms can be classified into [1, 2]:

- Destination-sequenced distance vector routing (DSDVR): The DSDVR is a table-driven algorithm based on the classical Bellman-Ford routing mechanism. Each node in the network maintains a routing table, consisting of all the destinations in the network and the number of hops to each destination. Each entry is marked with a sequence number, to distinguish old routes from new routes. Routing table updates can employ two types of packets: full dump, carrying all available routing information, and incremental packets carrying information that has changed since the last full dump. The route with the most recent sequence number is used mostly.

- Clusterhead gateway switch routing (CGSR): The CGSR protocol uses a cluster head algorithm to determine a node as the clusterhead within a cluster. This protocol uses the DSDVR protocol as its underlying routing scheme, but uses a hierarchical cluster-head-to-gateway routing approach to route packets. On receiving a packet, a node consults its cluster member table and its routing table to determine the next cluster head in the route to the destination.
- Wireless routing protocol (WRP): In WRP, each node maintains four tables, namely distance table, routing table, link-cost table, and message retransmission list (MRL) table. The MRL table consists of the sequence number of the update message, a retransmission counter, an acknowledgement-required flag vector and a list of updates sent in the update message. Changes in the links are known between nodes through the use of update messages. Neighbors are recognized by the receipt of acknowledgements and other messages. If a node is not sending any messages, to ensure connectivity, it must send a hello message within a specified time. If the node fails to do so, the link fails. New nodes are also required to send hello messages so that they can be added to the node's routing table.

These protocols are advantageous in the fact that a route is available as and when required, and there is no delay experienced until the route can be determined. However, table-driven algorithms are not suitable for self-configuring mobile ad hoc networks as most of the network capacity is used up in maintaining current routing information.

2.3 Ad-hoc Routing Protocols

Though conventional protocols are well tested and are quite familiar to use, they pose a major drawback as they are designed for a static topology and hence, are not suitable for constantly changing networks. Conventional protocols like link state and distance vector rely highly on periodic control messages [13]. As the density of ad-hoc networks increases, it becomes difficult to maintain large and frequent exchange of such control messages. Because all such information relies on transmission over the air, maintaining such information for a wireless network implies high cost, usage of bandwidth and battery power. Thus, using traditional protocols for ad-hoc networks would only lead to wastage of resources.

Wireless sensor networks, which are a form of wireless ad hoc networks, would therefore require reactive or on-demand protocols. Most of the ad-hoc routing protocols have an underlying traditional protocol algorithm. Ad-hoc routing protocols or reactive protocols can be classified into [1]:

- Ad-hoc on-demand distance vector routing – This protocol has been classified as a pure on-demand route acquisition system. In this mechanism, if a node requires to transmit a packet to a node that does not already have a route to it, the node initiates a path discover process to locate the destination node, by broadcasting a route request packet to its neighbors. The neighbors in turn, broadcast the packet to their neighbors, and this continues till the route to the destination is discovered. Each node maintains its own sequence number, and a broadcast identity (ID), which is incremented for every route request packet the node initiates. Intermediary nodes that receive the request packet record the address of the neighbor the packet arrives from, and discard any additional requests received from these neighbors. When the request reaches the destination, the node responds by unicasting a route reply packet back to the neighbor it receives the request from.

- Dynamic source routing (DSR): The DSR protocol consists of two main phases: route discovery and route maintenance. When no route exists to a destination, the route discovery process is initiated by broadcasting a route request packet. Each node that receives the packet checks to see if it can locate a route to the destination, and if not, adds its address to the route record of the packet, and then forwards it. A route reply arrives when the request reaches the destination. Route maintenance makes use of route error packets and acknowledgements.
- Temporally ordered routing algorithm (TORA): This algorithm is a highly adaptive loop-free distributed routing algorithm, based on link reversal. The key concept of this algorithm is the localization of control messages to a small set of nodes. This protocol performs three basic functions – route creation, route maintenance, and route erasure.
- Associativity-based routing – The associativity-based routing protocol defines a new routing metric, known as the degree of association stability, based on which a route is selected. Each node signifies its existence by generating a beacon periodically and upon its reception by the neighboring nodes, their associativity tables are updated. The three phases of this algorithm are: route discovery, route reconstruction and route deletion.

- Signal stability routing: This protocol selects routes based on the signal strength between the nodes and a node's location stability. This can be further classified into two protocols: the dynamic routing protocol (DRP) and the static routing protocol (SRP). The DRP maintains the signal stability table and the routing table while the SRP processes packets.

Table-driven routing protocols rely on the information contained in the routing table, continuously updating the routing table. This is not the case with on-demand routing protocols, where a node has to wait to discover a route to a destination. Though table-driven protocols have a route available even before it is needed by a node, they are not suitable for reconfigurable ad hoc networks. On-demand routing protocols are better for self configuring mobile wireless sensor networks.

2.4 Related Work

In response to the needs of wireless sensor networks, new protocols have been proposed to meet the requirements of wireless sensor networks. A few of these are listed below:

- Flooding: Flooding is a technique where each node receives a packet which it broadcasts to its neighbors, which in turn broadcast to their neighbors. This process continues till the maximum number of hops has been reached for the packet, or the destination has been reached [3].
- Gossiping: Gossiping is different from flooding in the way that the nodes do not broadcast to all their neighbors, but randomly pick a neighbor and then forward the packet to it. Each node then again picks a random neighbor and transmits the packet to it.

- Sensor protocols for information via negotiation (SPIN) [4, 16]: SPIN uses a data-centric routing mechanism, and names the data using meta-data that describes the characteristics of that data. There are three types of messages in SPIN, namely ADV, REQ and DATA. ADV is used for advertizing that a node has data to send, REQ is when a node is ready to receive data and DATA contains the actual data. SPIN solves the problems of flooding and is very energy efficient, but is not scalable, and due to its data advertisement mechanism, the life time of a node is affected.
- Directed diffusion [4, 14]: This algorithm uses a naming scheme for the data to transmit data through the nodes. The sink node sends out task descriptors to all the nodes, called the interest. The interest and data propagation and aggregation are determined locally. The main advantage of this scheme is that it saves energy, but results in overhead and synchronization problems in the network.
- Low energy adaptive clustering hierarchy (LEACH) [4, 15]: LEACH is a clustering based protocol, wherein clusters are formed based on the received signal strength, and clusterheads are used to route packets between these clusters. These clusterheads are changed randomly to distribute the load equally on all the nodes. LEACH adopts direct hop transmission instead of multi-hop transmission, but the main drawback is the fact that this algorithm was designed taking into consideration assumptions that do not actually refer to the wireless sensor network architecture.
- Power-efficient gathering in sensor information systems (PEGASIS): PEGASIS relies on LEACH, and is a chain-based power efficient protocol. The chain can be

constructed using a greedy algorithm, since all nodes have global network information. This algorithm suffers from the problem of scalability and keeping global information about the network.

- Geographic and energy aware routing (GEAR): As the name suggests, GEAR uses energy aware and geographically informed neighbor selection to transmit the packets to their destination.

Energy efficiency is a key challenge in wireless sensor networks, and energy consumption is dominated by the energy required to keep the nodes active and running. Many topology management schemes have been proposed so as to cleverly choose nodes to be put to sleep without affecting the capacity of the network. We will focus more on these schemes here:

- Geographic adaptive fidelity (GAF) [18]: GAF uses the fact that neighboring nodes can replace each other in the routing topology. The sensor network is divided into small grids, and nodes in the same grid are equivalent in routing. At a point of time, only one node is active in each grid, while the other nodes in the grid can stay in the energy saving mode. This algorithm is very helpful in the case of dense networks.
- Span [17]: In span, the capacity of the ad hoc network is conserved by a set of nodes that forms a multi-hop forwarding backbone. Nodes other than the nodes in this set transition to sleep states frequently. The functionality in the backbone network is rotated through the set of nodes to distribute load equally.
- Sparse topology and energy management (STEM) [19]: STEM is a topology management technique that emulates a paging channel by having a separate radio

operating at a lower duty cycle. When a wakeup message arrives, the primary radio is turned on, and this takes care of the data transmissions. STEM can integrate with the above two schemes to produce energy savings beyond GAF or Span alone.

- Adaptive self-configuring sensor networks topologies (ASCENT) [20]: Each node in the network assesses its connectivity and adapts its participation in routing. Initially, a few nodes are active while other nodes are only listening and not transmitting. Help messages are sent to listening nodes to join in the network, and become active neighbors. This continues till the number of active nodes reaches a certain value. When this is done, the data delivery is more reliable since there are more active nodes participating in the routing process. The process of inviting more neighbors to join in the network starts again when a network event or change triggers the need for more active nodes in the routing path.
- Cluster-based energy conservation (CEC) [21]: CEC creates clusters, selecting clusterheads based on the highest remaining energy that is advertised.
- Adaptive fidelity energy-conserving algorithm (AFECA) [21]: AFECA allows each node to sleep for the number of neighbors it has. Therefore if a node has a large number of neighboring nodes, it can sleep longer without affecting network connectivity.

Several topologies have been proposed for conserving energy in sensor networks including cluster, link, grid, and diffusion, which were adopted to route packets across the sensor network. Amongst these, the grid-based approach, as put forward in the GAF algorithm is more suited for sensor networks, since the grid topology can dynamically be configured with the configuration of the nodes.

In [5], the authors explore grid-based coordinated routing in wireless sensor networks. The underlying routing protocol is based on flooding, but unlike flooding, grid-based coordinated routing reaches only selected nodes in the field. Sensor nodes are randomly deployed over a sensor field, and the entire field is divided into square shaped grids, of sizes defined by the user. Of the nodes in each grid, one node is elected as the coordinator node, which actually takes part in the routing process while the remnant nodes power down their radios to save energy. The source floods the network with a query message to each coordinator. When the message reaches the sink node, the sink node sends information by tracing a route back to the source node. This process continues till a coordinator node in the route runs out of energy. Nodes in the network are assigned ID's. Coordinator nodes are elected based on the ID's. The node with the highest ID in the grid is elected to be the coordinator. If this node runs out of energy, the next highest node is elected as coordinator. New coordinators are elected to replace nodes that run out of energy. The process continues till the network is partitioned and the connection between the source and sink is lost. This scheme employs load balancing to keep the nodes running for a long time.

In [6], a directed grid topology is proposed from the source node to the sink node. This grid is constructed with respect to the diagonal line between the source and sink nodes. Here, the sink node can move around in the network and hence the topology of the grid varies according to the positions of the source and sink nodes. The parameter determining the distance between the grids is the average transmission cost, unlike in the previous scheme. There are two criteria for selecting a grid node: the distance to the location of the ideal grid node and the residual power. A cost parameter has been defined as the metric to select a grid node. The next hop is determined by the node with the smallest value for the cost parameter. There are two contributions of this scheme, namely the optimal grid distance is derived from the from the transmission cost point of view. Also, the routing scheme can be used for one sink and single or multiple sources.

In [7], the concept of grid-based routing is proposed wherein variants of grid-based routing are proposed for different environments. The authors maintain that grid-based routing requires as few grids as possible to participate while ensuring network connectivity. The notion that to keep the network connected one node per grid is required to stay active is contradicted with the argument that a largely reduced subset of grids can still preserve the same degree of coverage. This paper therefore puts forward variants of grid-based routing schemes which reduce the number of grids that are required to support routing while supporting network connectivity. Also, the authors demonstrate that diagonal routing with a different side length of grids outperforms rectilinear routing.

The above mentioned grid-based schemes are common with the fact that they propose routing schemes for a uniform grid structure. In [8], a non-uniform grid structure is proposed for the GAF protocol, by deducing the relationship between the optimal radio range and traffic in the network. The minimum energy consumption characteristic range is not a constant but varies with the amount of traffic. Optimal range increases as the loaded traffic decreases. To save energy by radio range adjustment, the network is divided into sections of different sizes, according to a derived range-traffic relationship. The number of grid sections is not a free parameter as in the case of the GAF protocol.

The authors demonstrate that a lower energy consumption is achieved by the non-uniform virtual grid routing, as compared to the values for the uniform grid.

2.5 Conclusions

Presented in this chapter are the different routing protocols for wireless sensor networks and different topology management schemes in use. Amongst all the topology schemes proposed, grid-based topology management is more affective in terms of energy efficiency and extending network lifetime. Grid-based schemes can be of a uniform grid structure and a non-uniform grid structure. Uniform grid-based routing can be modified to fit in different environments. Between the two of them, non-uniform grid-based routing is more energy efficient than uniform grid-based routing.

CHAPTER 3

FLOODING, GAF AND SPAN

3.1 The Flooding Algorithm

The flooding algorithm is one of the most simple and widely used algorithms in a point-to-point communication network. In the flooding algorithm, the source first broadcasts information to all its neighboring nodes. Each receiving node, in turn broadcasts the information it receives to all its neighboring nodes, other than the source node. The information thus traverses from the source node to the destination node and through all the nodes in the network.

The basic algorithm for flooding is as shown below:

Algorithm 1:

```
For the source $r_0$, do:
    Send the message on all outgoing links.
For vertex $v \neq r_0$ do:
    If the message is received for the first time:
        1. Store the information in an output buffer.
        2. Forward the message to every other node in its own vicinity.
    If the message is received again, discard the message.
End
```

Though flooding algorithm is easy to implement, it is still complex and poses its own challenges. Flooding is inefficient in terms of network bandwidth utilization, because each node transmits and receives multiple packets of data, thus wasting network bandwidth. Real world flooding is considerably complex as care has to be taken to avoid duplication of data packets, infinite loops and clearing the output buffers of multiple entries of data.

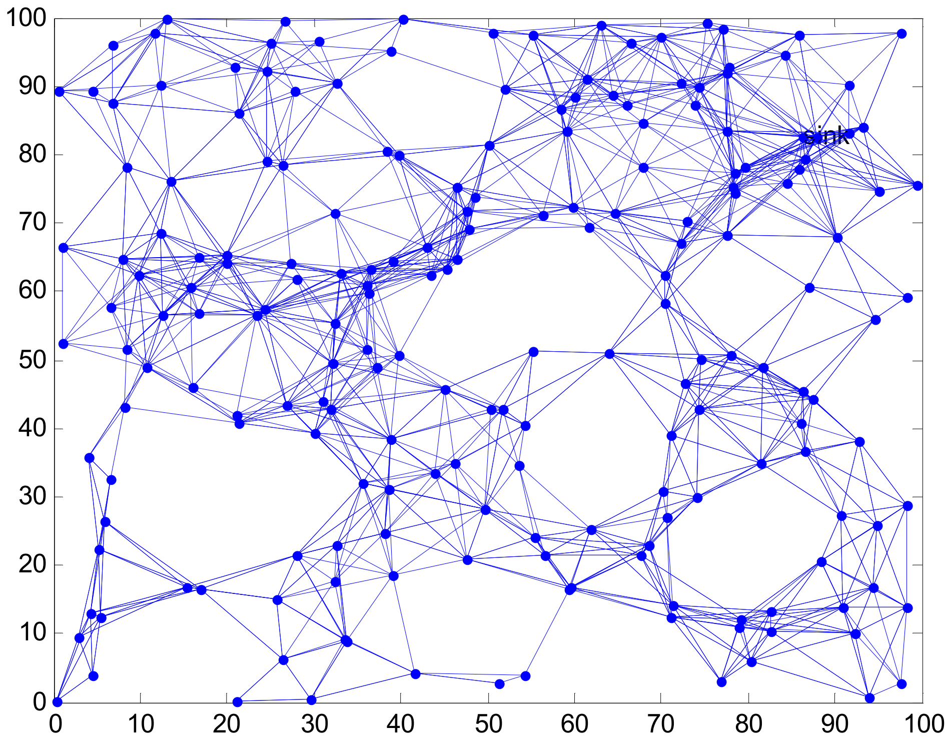


Figure 3.1 Simulation topology showing the traditional flooding algorithm.

Another flooding algorithm that shows a flooding-based tree construction protocol for avoiding duplicate deliveries [5] is as shown below:

```
Algorithm 2:  FLOOD (Node $S$)

if Node $n$ receives the 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 which sends the packet to a node for the first time is the parent of the node. The *Level* field is incremented by one, and then the packet is rebroadcast. The *Level* field is to denote the number of hops the node is away from the source node.

The main advantage of this flooding is that a node can receive a packet only if it has not yet received a packet. Therefore, the duplication of data packets is reduced and hence the network bandwidth is efficiently utilized to a certain extent. Every node in this algorithm has a unique parent and as many children as the nodes it can reach. This flooding algorithm is an improvisation of the traditional flooding algorithm.

3.2 Motivation

A wireless sensor network is a wireless network of spatially distributed sensors, which respond to any change in the physical or environmental conditions. The sensor node gathers information by responding to changes in its surroundings, processes the information so gathered and communicates the same with its neighbors. Power consumption is a very important issue for deploying wireless sensor networks as each node operates with limited power and the lifetime of the nodes effects the lifetime of the wireless sensor network. If each node was to transmit directly to its destination, the amount of power it consumes for each transmission would deprive the node of its energy completely. Hence direct transmission is beneficial when the destination is within a limited coverage area.

Transmitting packets in a multi-hop manner, wherein the consumption of power can be shared by all the nodes in the network increases the network lifetime. Each node controls its transmission power and self organizes a network topology by controlling its coverage area. The network topology can therefore be dynamically changed, in accordance with the neighboring nodes. In multi-hop transmission, selection of the intermediate node is done considering not only the shortest path possible but also by taking into account the residual power of the potential intermediary nodes. This is important because selecting the same intermediate nodes often will result in depleting the intermediate nodes of their energy, and causing the nodes to die. This will in turn decrease the network lifetime. Therefore, focusing on network longevity, many topologies have been developed to route packets from the source node to the destination node.

The various topologies adopted for routing packets in sensor networks are grid, cluster, link, and diffusion topologies. Amongst them, the grid approach is most beneficial, since the topology of the grid can be configured dynamically with respect to the source and the sink nodes, and also there are multiple paths between the source and the destination, making the selection of the forwarding path and the intermediate nodes flexible. The grid approach was designed to achieve node equivalence in a network, and was implemented initially in the GAF and span protocols [6].

3.3 Geographic Adaptive Fidelity

The GAF [9] protocol belongs to the class of protocols that concentrate on energy consumption to increase network lifetime. The energy consumed by sensor nodes for transmitting, receiving and idle listening is significant and is wasted. When significant node redundancy exists in the ad hoc network, it is observed that intermediary nodes can actually be put to sleep, or turned off to conserve energy while still maintaining the connectivity of the network. Routing fidelity, defined as the uninterrupted connectivity between communicating nodes, can be maintained as long as any intermediate node is awake. In GAF, routing fidelity is maintained to be constant while node behavior is adapted to extend network lifetime.

GAF uses a virtual grid over the entire sensor field, and each node associates itself with this virtual grid. Node location in GAF is determined by using global positioning system (GPS) or other location systems. All nodes in a particular grid are equivalent with respect to forwarding packets. In each grid, nodes determine which of them will sleep and for how long, and which node will remain active for a certain period of time. To balance the load in the network, sleeping nodes turn on their radios periodically and trade places with the active nodes, which then turn off their radios. The distance between any two nodes is within the nominal radio range of the nodes, to maintain connectivity in the network.

Each node in GAF has three states: sleeping, discovery and active states respectively. Nodes are initially in the discovery state, when they send and receive discovery messages to find other nodes in the grid. In the discovery state, the node sets a timer, after which it broadcasts its discovery message and enters the active state. In the active state, the node again sets a timer for how long it will stay active. Once this timer expires, the node enters into sleeping state and lets other active nodes handle routing for that grid. Nodes in each grid are ranked according to their remaining energy level. GAF employs load balancing using node ranking to maintain the nodes running for as long as possible, thereby increasing network lifetime.

3.4 Span

Span [10] is a technique that is similar to GAF algorithm with regard to power conservation in sensor nodes. Unlike GAF, span does not divide the entire network into grids, but instead it elects coordinator nodes from all the nodes in the network to participate in routing. Span thus forms a backbone network of active nodes that participate in the actual routing while the other nodes in the network, that are not part of this backbone network turn off their radios to conserve energy. Load balancing is achieved by rotating the role of the coordinator node amongst all the nodes in the network. Span does not require knowledge about the location of the nodes to elect coordinates, but uses local information to know about neighboring nodes and elect coordinators. Coordinators are elected such that every node is in the radio range of a coordinator node. These coordinators actively participate in routing while the other nodes in power saving mode periodically check to see if they should wake up to act as coordinators and participate in routing.

The span protocol operates under the routing layer, and above the medium access layer. Each node in span broadcasts HELLO messages that contain the node’s status, its current coordinators and its neighbors. At a time, only those entries in the routing table that correspond to current coordinators are used for routing packets to and from the destination node. Unlike GAF, a node in span can only be in two states: coordinator and a non-coordinator. A node volunteers to be the coordinator if two of its neighbors fail to communicate with each other, either directly or through another coordinator. In other words, a node offers itself to participate in routing if it can detect loss of connectivity among the neighbor nodes. A node determines whether to participate in routing by considering two factors: the energy remaining in the node and the number of neighbors it can connect by using up its battery life. This ensures that maximum connectivity is achieved with the least possible number of active nodes, thus maintaining network longevity.

CHAPTER 4

UNIFORM AND NON UNIFORM GRID BASED ROUTING

4.1 Grid-Based Coordinated Routing

The main focus of grid-based coordinated routing (GBCR) is on partitioning the network into square shaped grids to extend network lifetime. The entire network is divided into equally shaped grids, and in each grid an active node, the coordinator is elected, like in the span algorithm. The underlying routing algorithm used in GBCR is similar to level flooding.

The following algorithm is used by grid-based coordinated routing protocol [5]:

Algorithm 3 Grid-based coordinated routing protocol

```
$C \Leftarrow$ set of coordinator nodes
  while network is not partitioned do
  while $C \neq \emptyset$ or sink node not yet reached do
   Pick a node $C_i$ randomly from $C$
   FLOOD($C_i$)
  end while
  send information from the sink node back to the source node
  elect new coordinator nodes $C'$
$C \Leftarrow C'$
```

In grid-based coordinated routing, information reaches only selected nodes in the field instead of to all the nodes in the network. The main idea of dividing the network into grids is to make only one node alive for each grid, while the rest of the nodes in that grid are sleeping so as to conserve their battery life. In each grid, the coordinator participates in routing as long as the amount of energy in that coordinator is above a certain threshold value. When the energy drops below the threshold, a new coordinator is elected for that grid. The source transmits information to the sink through the active coordinators, and the sink traces a route back to the source. The process of flooding continues till the nodes participating in the routing run out of energy, when new coordinators are elected and a new route back to the source from the sink is calculated. The source starts flooding by sending a query message to all the neighbor coordinators, which flood other coordinators in the network till the message reaches the sink node.

Each coordinator node in grid-based routing has three states, namely, routing, warning and depleted states. When coordinator nodes in a particular route die, or run out of energy, new coordinators are elected to replace the old nodes. All nodes in the network are randomly assigned IDs. In each grid, the node with the highest ID becomes the coordinator. When the node with the highest ID runs out of energy, the node with the next highest ID becomes the coordinator for that grid. Each time the coordinator node changes the sink node traces back a route to the source node.

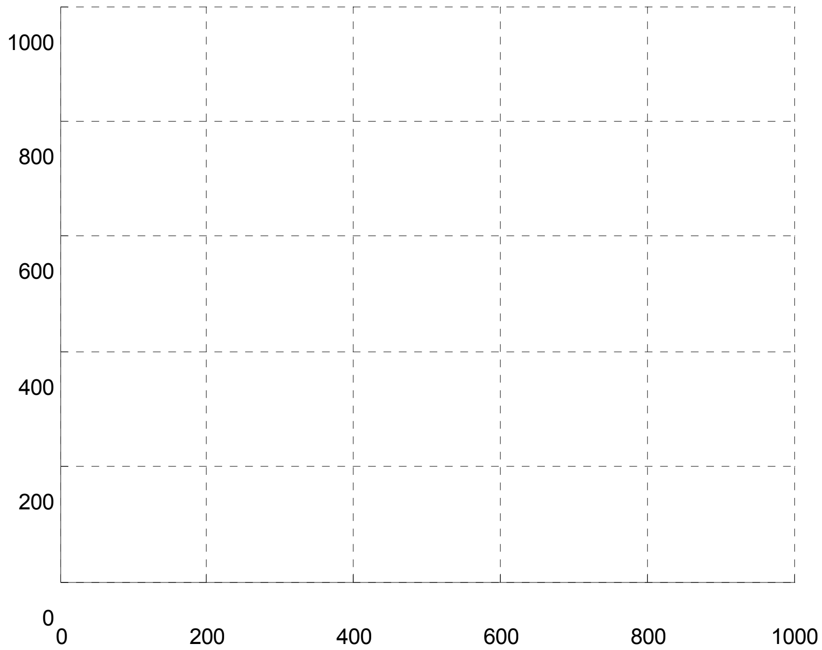


Figure 4.1The uniform grid structure of grid-based coordinated routing protocol.

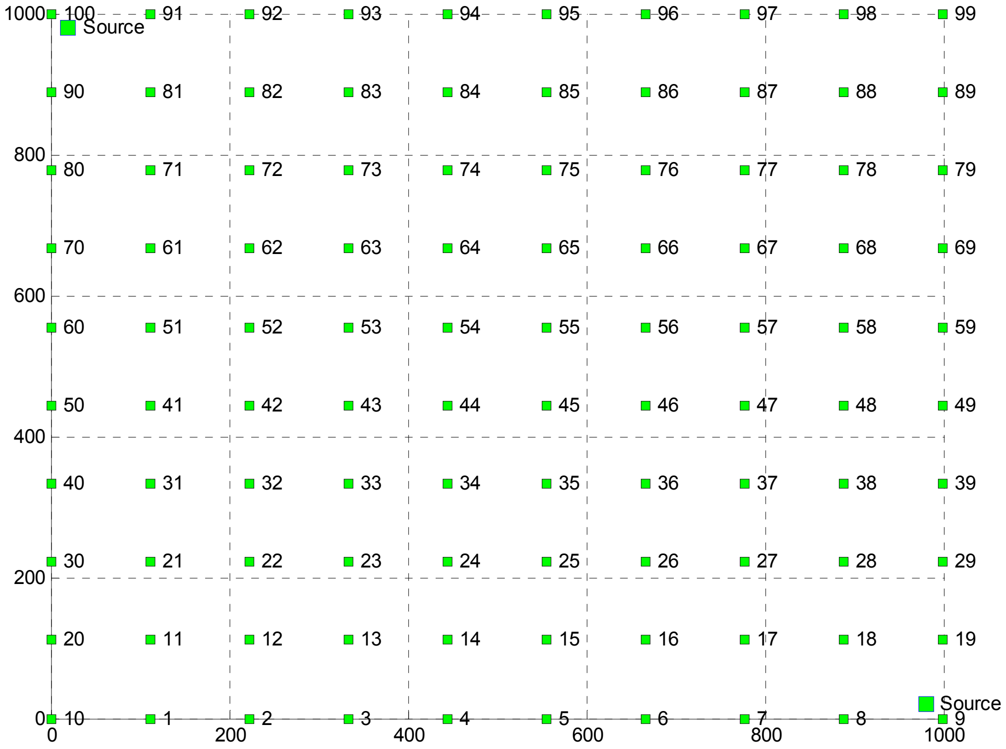


Figure 4.2 The uniform grid structure with 100 sensor nodes deployed uniformly in the field.

Grid-based coordinated routing adopts a grid structure as shown in Figure 4.1. Each grid is a square of side of a fixed length, 200 m for example. Different results have been observed by varying the grid size from 50 m to 200 m. Connectivity in the network depends on the grid size, transmission range and the sensitivity of the nodes. When grid coordinators are elected, care should be taken such that the coordinators must still be able to connect to neighboring grid coordinators. Therefore, grid size is very important to maintain connectivity throughout the network as too large a grid size will result in loss of connectivity of the nodes in the network. Grid-based coordinated routing places an upper bound on the grid size and determines the conditions to maintain connectivity throughout the network depending on the grid side and the transmission range of the nodes.

Grid-based coordinated routing maintains load balancing as does Geographic Adaptive Fidelity. The function of the coordinator node is distributed amongst the nodes in the network based on the ranking of the nodes in each grid. GBCR observes the effects of transmit power, receiver sensitivity and grid size on network lifetime, and determines that decreasing the transmit power increases network lifetime.

4.2 Non-Uniform Grid-based Coordinated Routing

Excluding some of the nodes in the network to participate in routing to conserve battery life and increase network lifetime was proposed in SPAN. The idea of a virtual grid over the network field was proposed in the geographic adaptive fidelity algorithm. Dividing the entire network into equal sized grids, and electing nodes in each grid to participate in routing while other nodes were put to sleep was introduced in grid-based coordinated routing. Uniform grid-based routing is efficient when the distribution of the nodes in the sensor field is uniform.

Varying the grid sizes in the network extends the lifetime of the network. In [8], the relation between optimal radio range and traffic is used to define a non-uniform grid for the GAF protocol. In this work, I apply the non-uniform grid size for the grid-based coordinated routing protocol and analyze the results of the same.

4.3 Non-Uniform Grid-Based Routing Protocol

The underlying routing algorithm of non-uniform grid-based routing protocol is the same as the grid-based coordinated routing protocol. The entire sensor field is divided into non-uniform sized grids. In this work, I consider three different non-uniform grids. Figures 4.3 to 4.5 show the different types of grid structures considered for simulation.

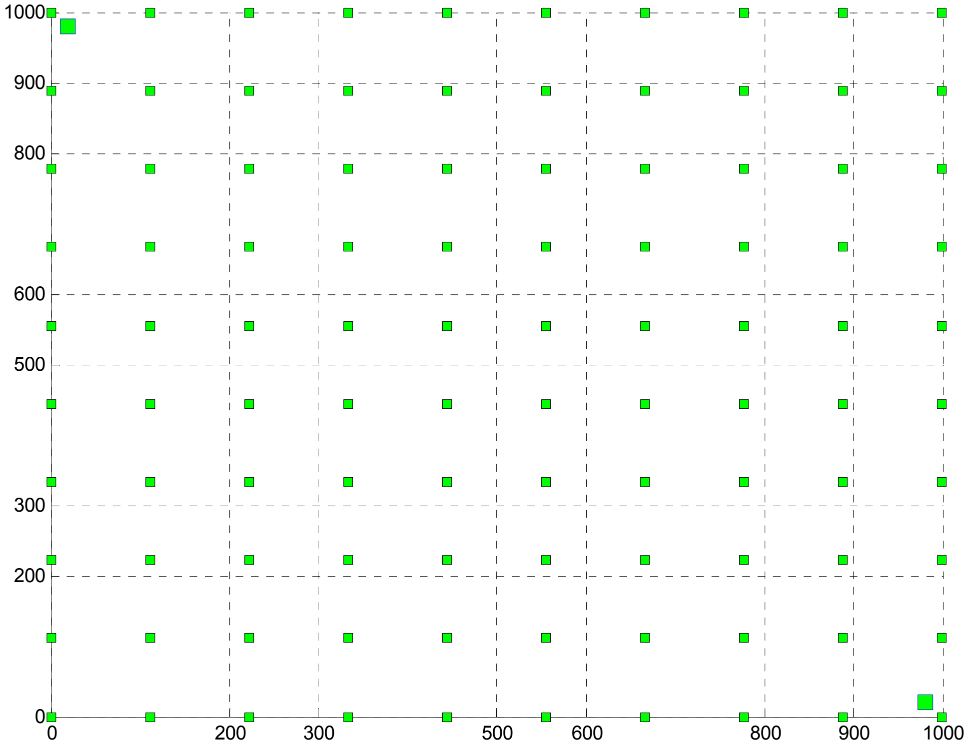


Figure 4.3 Topology showing the alternating non-uniform grid structure called the alternate structure with 100 nodes uniformly deployed across the field and alternate small grids of 100 m each side, and large grids of 200 m each side.

In each grid, as in the uniform grid-based routing, from all the nodes of the grid, a coordinator node is elected that involves in the routing process, while the other nodes in the grid save their battery by putting themselves to sleep. New coordinators are elected when the node runs out of energy or falls below a threshold value.

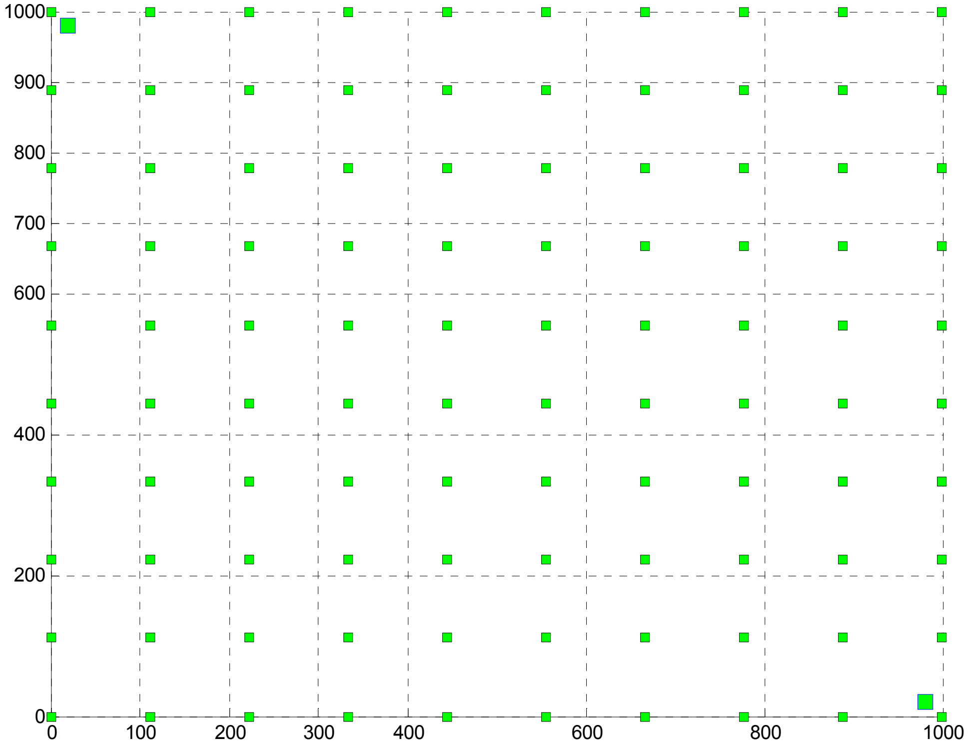


Figure 4.4 Simulation topology showing the source non-uniform structure with 100 sensor nodes deployed uniformly in the field wherein the area containing the source node is divided into small grid sizes of 100 m each, while at the sink node the area is divided into grids of size 200 m each.

Though the grid sizes can be varied, we fix the lower bound on the grid size to be 100 m and the upper bound as 200 m. Also, we do not take into consideration the other possible non-uniform grid structures, as the results show no significant improvement for the same.

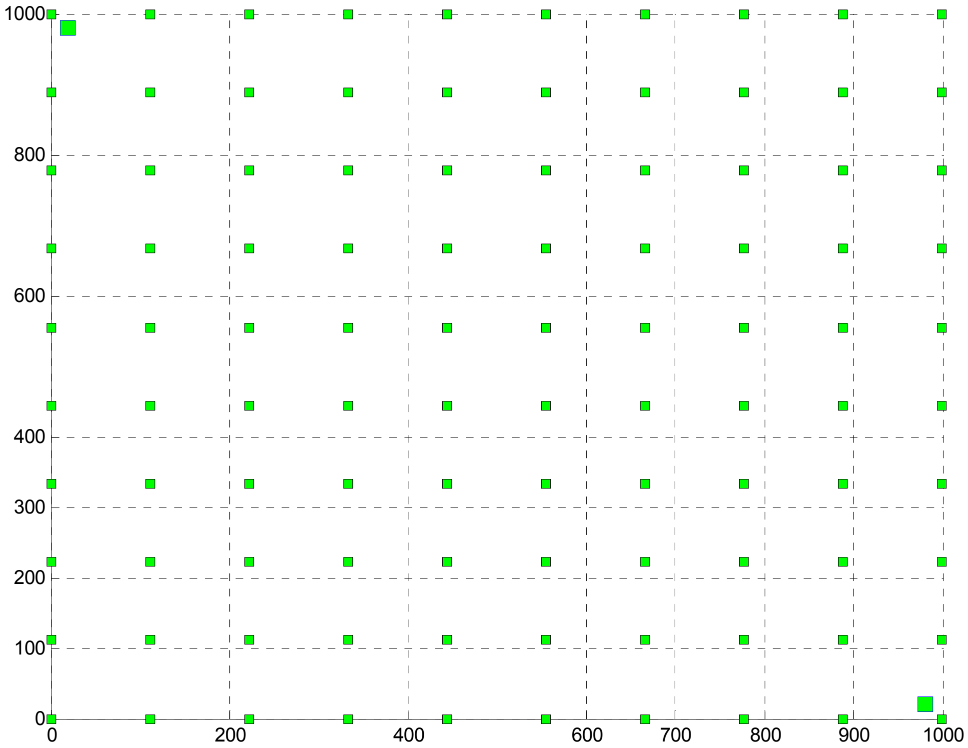


Figure 4.5 Simulation topology showing the sink non-uniform grid structure with 100 nodes deployed uniformly across the field, wherein the vicinity around the source node is divided into 200 m sized grids while the area in the vicinity of the sink node is divided into 100 m sized grids.

4.4 The Link Models

For successful transmission between two nodes, a successful link has to be established. A major challenge to wireless networks is the lossy nature of the wireless links. There are many link models that exhibit the lossy nature of wireless links, but for wireless sensor network, we consider the deterministic link model and the probabilistic link model.

4.4.1 Deterministic Link Model

The amount of energy that is required to establish a link between two nodes is proportional to the distance between the two nodes raised to a constant power, called the path loss exponent, *n* [11]. For the deterministic link model, the value of the path loss exponent is usually assumed to be between 2 and 4. This is represented in the following equation:

$$P_r = P_t / d^n \;; \qquad (1)$$

where P_r is the power of the received signal;
P_t is the transmit power;
d is the distance between the two nodes and
n is the path loss exponent.

If *S* is the receiver sensitivity, the communication link between the two nodes leads to a successful transmission between the nodes if P_r is greater than *S*.

4.4.2 The Probabilistic Link Model

Results from [12] show that for a given power setting, there is a region within which all the nodes have good connectivity, called the effective region and a distance beyond which the nodes show poor connectivity. The size of the effective region is observed to increase with transmit power. Between the two extreme points lies the transitional region, where the average link quality drops off smoothly.

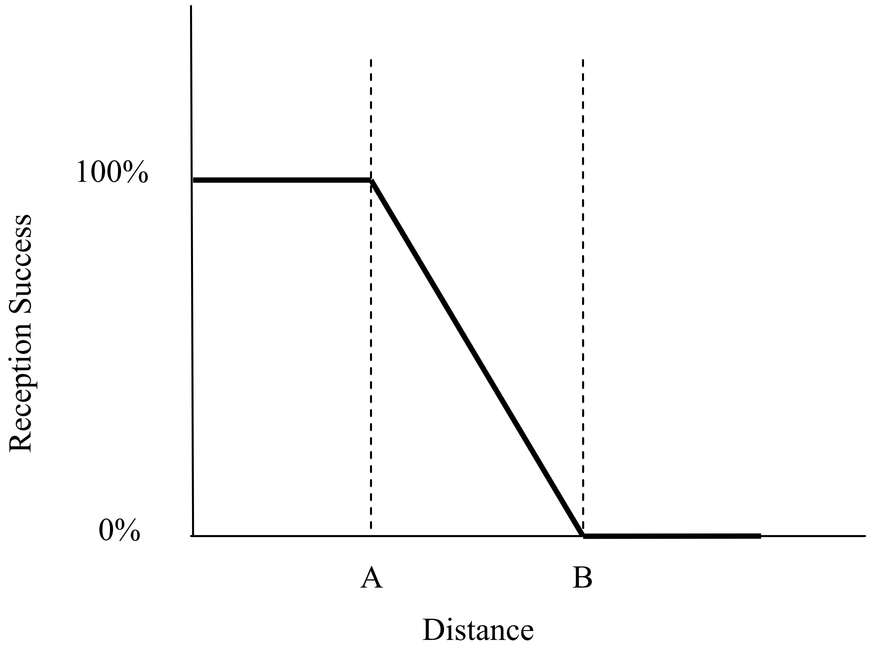


Figure 4.6 Probabilistic link model.

The deterministic link model does not take into account multi-path fading, which either increases or decreases the possibility of a successful communication link. This is included in the current model by a random number *R*, as shown below [5]:

$$P_r = (P_t/d^n) * R \qquad (2)$$

If nodes within the point A are guaranteed to successfully receive a transmission, and nodes beyond a point B are guaranteed not to receive a transmission, then the nodes between the points A and B are the nodes that are affected by the multi-path variation.

From [5], the probability of transmission between the points A and B is determined by the equation as shown:

$$R = R_A + (1 - R_A) * rand(1) \qquad (3)$$

where $R_A = (A^n * S)/ P_t$, and (4)

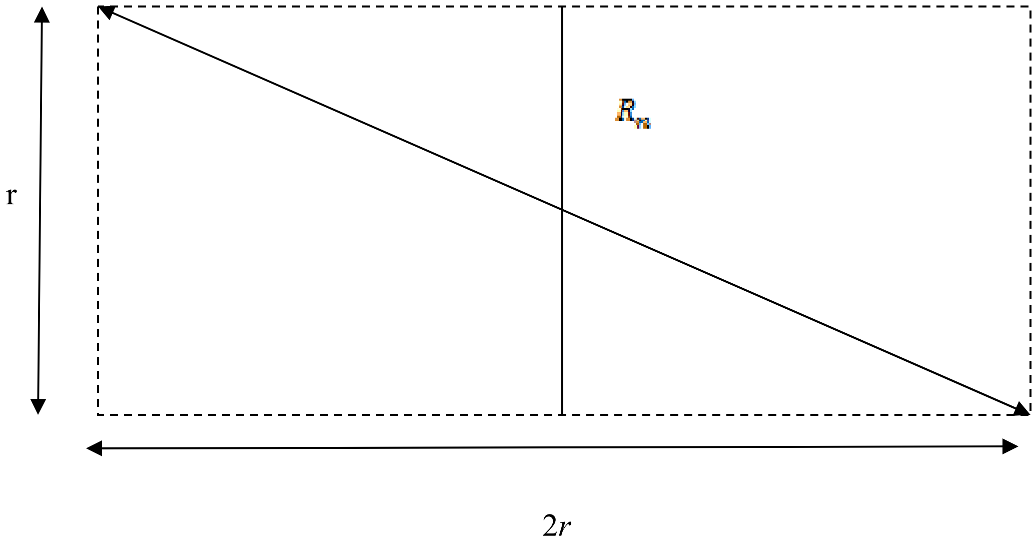
rand(1) is a random number uniformly distributed between 0 and 1.

To calculate the power of the received signal, the value of R is substituted in (2). Thus when the distance between the two points A and B is known, the transmission success of a packet is determined probabilistically.

4.5 Determining the Grid Size

To ensure connectivity between any two coordinator nodes in adjacent grids, proper grid size must be determined. Grid size is affected by factors such as the transmission range of the transmitter, or the transmission power and the sensitivity of the nodes. If the grid size is too large, it will lead to early partition of the network if the coordinator nodes are located too far off from each other. Thus, it cannot form a link between the nodes even if the nodes are alive in each grid.

From (1), d is the maximum distance for successful transmission, when P_r is set equal to S. If this maximum distance is d_{max}, then d_{max} is the nominal radio range, R_n. GAF defines a virtual grid as follows [9]:



The maximum limit for the side r can be estimated as follows:

$$r^2 + (2r)^2 <= R_n^2. \qquad (5)$$

Therefore, we get,

$$r <= R_n/\sqrt{5}. \qquad (6)$$

By estimating the value of R_n, by assigning values for P_t, P_r and n, we can determine the value of r and hence the grid size so that two coordinator nodes from adjacent grids can successfully communicate with each other. It is equally important not to have very small grid sizes, as the transmit power and the receiver sensitivity allow a minimum distance between the nodes to be covered. Thus having very small grid size will also lead to wasted resources.

4.6 Grid Coordinator Election

As mentioned earlier, grid-based coordinated routing requires having coordinator nodes in each grid that remain active while the other nodes in the grid are sleeping. Initially, all the nodes in the field have energy equal to 100% of battery life and are marked green in the simulation. As the nodes get elected and routing of information to and from the source takes place as a continuous process, the node energy depletes with time. If node energy equals or falls below 25% of battery life, the node is marked in yellow and finally when the node is devoid of any energy, it is called a dead node, marked in red. This is illustrated in Figure 4.7.

In grid-based routing, all the nodes in the network are assigned IDs randomly. In each grid, the node with the highest ID becomes the coordinator node. When this coordinator is out of energy, the node that has the second highest ID is chosen to take its place. Thus the node with the second highest ID becomes the coordinator node and so on. This process continues till all the nodes in the network are out of energy, or till no more communication links can be established from the source to the sink, thereby partitioning the network. Thus even when not all the nodes in the network are dead, if a successful route cannot be established from the source node to the sink node, the network is partitioned.

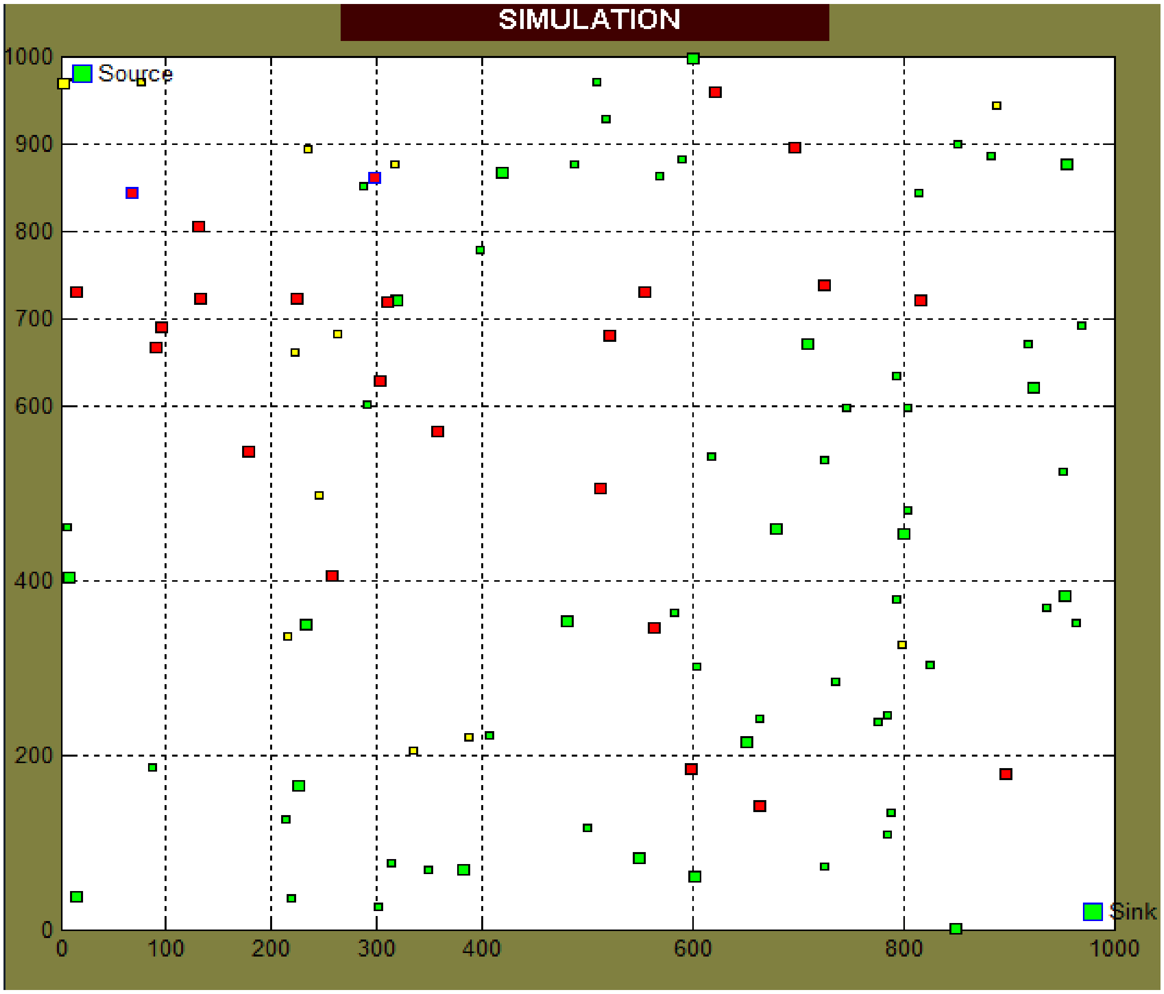


Figure 4.7 Simulation topology showing nodes having greater than 25% of battery life, marked in green ; nodes having less than or equal to 25% of battery life in yellow ; nodes with zero battery life in red.

The information traverses through the grid coordinators only, and the rest of the nodes in the network are put to sleep to conserve their battery life. Once the route from the source to the destination has been established, data travels from the source to the sink and back through that route only. The other coordinator nodes are also awake and listening while the coordinators in the route receive and transmit information. Hence the coordinators in that particular route tend to lose energy more rapidly than the coordinator nodes that are not transmitting. Thus when a node runs out of energy, another coordinator node has to be elected.

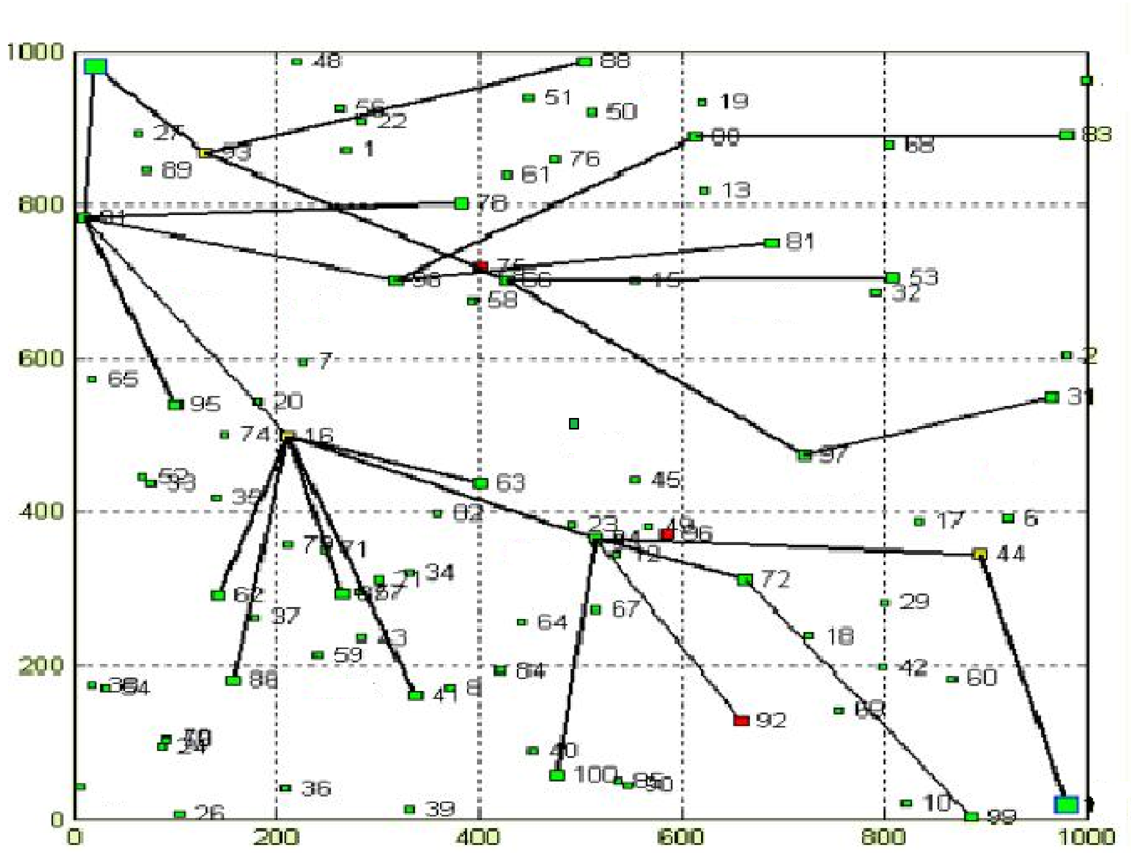


Figure 4.8 Simulation topology showing node election by maximum node ID.

4.7 Load Balancing

To utilize the nodes to their maximum lifetime, grid-based routing protocol employs the use of load balancing. The coordinator role is shared by all the nodes in the network to ensure fair usage of node resources.

Each node in the network is initially assigned a rank. The node with the lowest rank is elected the coordinator. To ensure load balancing, the node ID’s are not considered to elect coordinator nodes. Initially, since all the nodes have the same rank, one node per grid is randomly elected the coordinator node for that grid. Once transmissions to and from the source begin, the node energy gradually depletes. If the energy of the node is greater than 25% of its battery life, the rank of that node is incremented by one, and if the energy drops to or less than 25% of battery life, the rank of that node is incremented by two, and the node has to be put to sleep. When such a node is detected in the route, the link between the source and sink is disrupted as one of the coordinator nodes in now dead. Hence the source has to reflood the network once new coordinator nodes are elected in place of the nodes that have energies equal to or less than 25% battery life. The dead nodes are removed from the network and are no more ranked. The new coordinator nodes are the nodes that have a lower rank, and hence more energy and can handle routing for a longer time. Thus maintaining load balancing, grid-based routing protocol increases network lifetime. The process of node re-election continues till the network is partitioned and no link can be established between the source and the sink. Figure 4.9 illustrates load balancing in the network to increase network lifetime and equally distribute the routing load on all nodes.

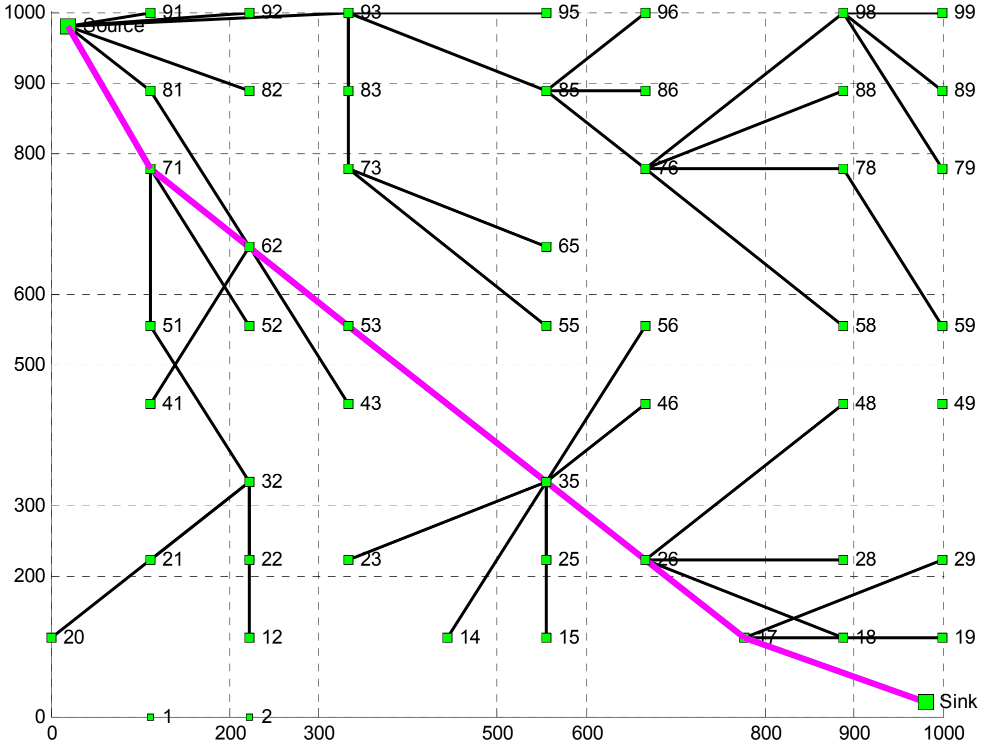


Figure 4.9 Topology showing load balancing in the network.

4.8 Conclusions

I have examined the grid-based routing protocol, and have presented the different non-uniform grid structures and defined an upper bound on the grid size to ensure a successful link between two adjacent grid coordinators. I have considered the deterministic link model and the probabilistic link model for the network, and discussed the election of the coordinator nodes for each grid. Finally, I have included load balancing for network longevity and efficiency.

CHAPTER 5

SIMULATIONS AND RESULTS

Real-time simulations of the non-uniform grid-based coordinated routing protocol, results from the simulations and the analysis of the simulations are presented in detail in this chapter. I also compare and contrast the results from of the uniform grid with three different types of non-uniform grids, as well as with the traditional flooding algorithm. Using these results, we prove the efficiency of the non-uniform grid-based coordinated routing protocol for non-uniform node placement.

5.1 Assumptions

In simulating, observing and comparing the behavior of the non-uniform grid-based coordinated routing protocol, the following assumptions have had to be made:

5.1.1 The Energy Model

The radio of the sensor node is used for transmitting and receiving information from the source to the destination as well as for idle listening. In reality, sensor nodes expend energy not only while transmitting and receiving information, but also for idle listening, or just staying awake in the network. The energy thus used is sometimes useful while at other times, it is simply unnecessary, or wastefully spent. Hence the largest constraint on ad-hoc wireless sensor networks is the increased energy consumption, which leads to decreased network lifetime. Though a node may not be part of routing information to and from the source to the destination, a node may waste its resources by just staying alive. Thus, it leads to unnecessary exchange of information between nodes, wastage of bandwidth, consumption of battery life and hence early death of the sensor node.

The energy spent by a node in transmitting, receiving and idle listening may not be the same. The idle:receive:transmit ratios of energy spent has been shown to be 1:1.05:1.4 by Stemm and Katz [22], while in [23] it is shown to be 1:2:2.5 and in [17] it is shown to be 1:1.2:1.7. For this protocol, I assume that the energy spent by a node for transmission is 1.0 unit, for reception is 0.5 units and for idle listening is again 1.0 unit of energy. A counter array keeps track of the energies left in each node. A node is initially given a value of zero in the array, denoting there is no loss of energy. If the node is elected as a coordinator node, it immediately loses 1.0 unit of energy. Then, if the same node is used for transmission of data between nodes, it loses another unit of energy, but if the node only receives the information from a node and does not transmit the same information to another coordinator, the node only loses 0.5 units of energy.

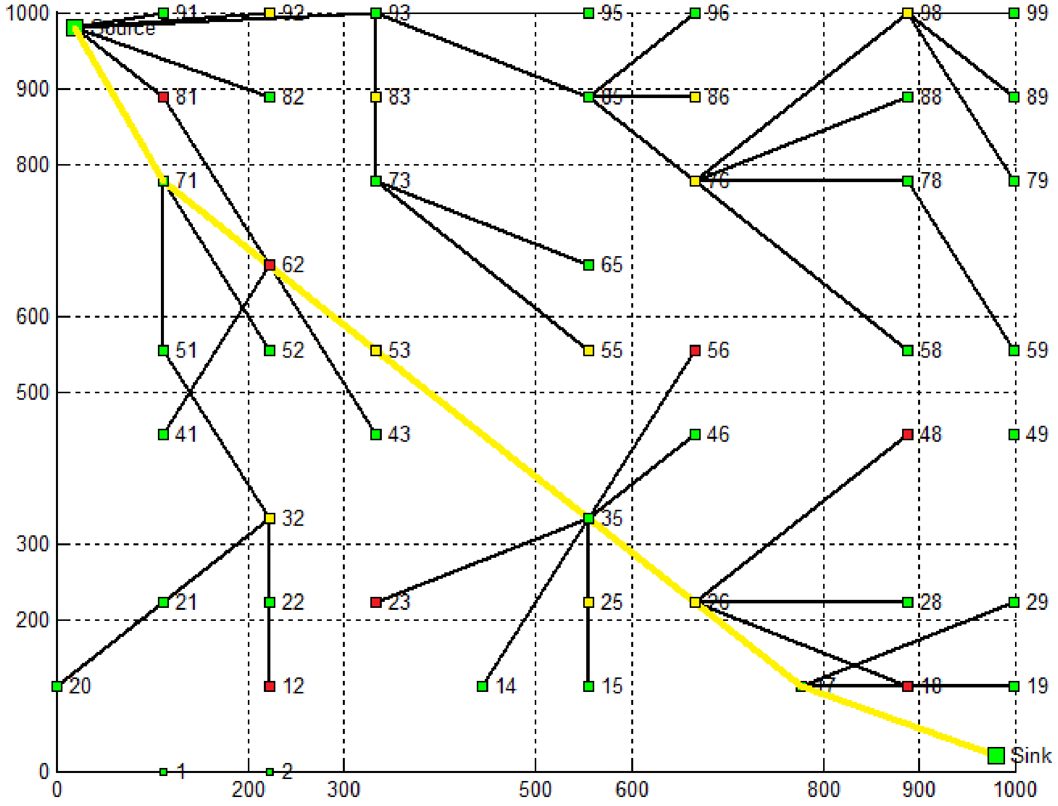


Figure 5.1 Topology showing the energy depletion of nodes.

5.1.2 Simulation of the Sensor Field and Deployment of Nodes

To examine the working of the non-uniform grid-based routing protocol, I assume a simulation of a sensor field that is close to an actual sensor field. I limit the size of the sensor field to be a two dimensional axes, 1000 m in the x-axis, and 1000 m in the y-axis. I assume the sensor nodes also to be actual sensor nodes. I developed a graphical user interface (GUI) for observing the flooding simulations and the behavior of the uniform and non-uniform routing protocols. This is as shown in Figure 5.2.

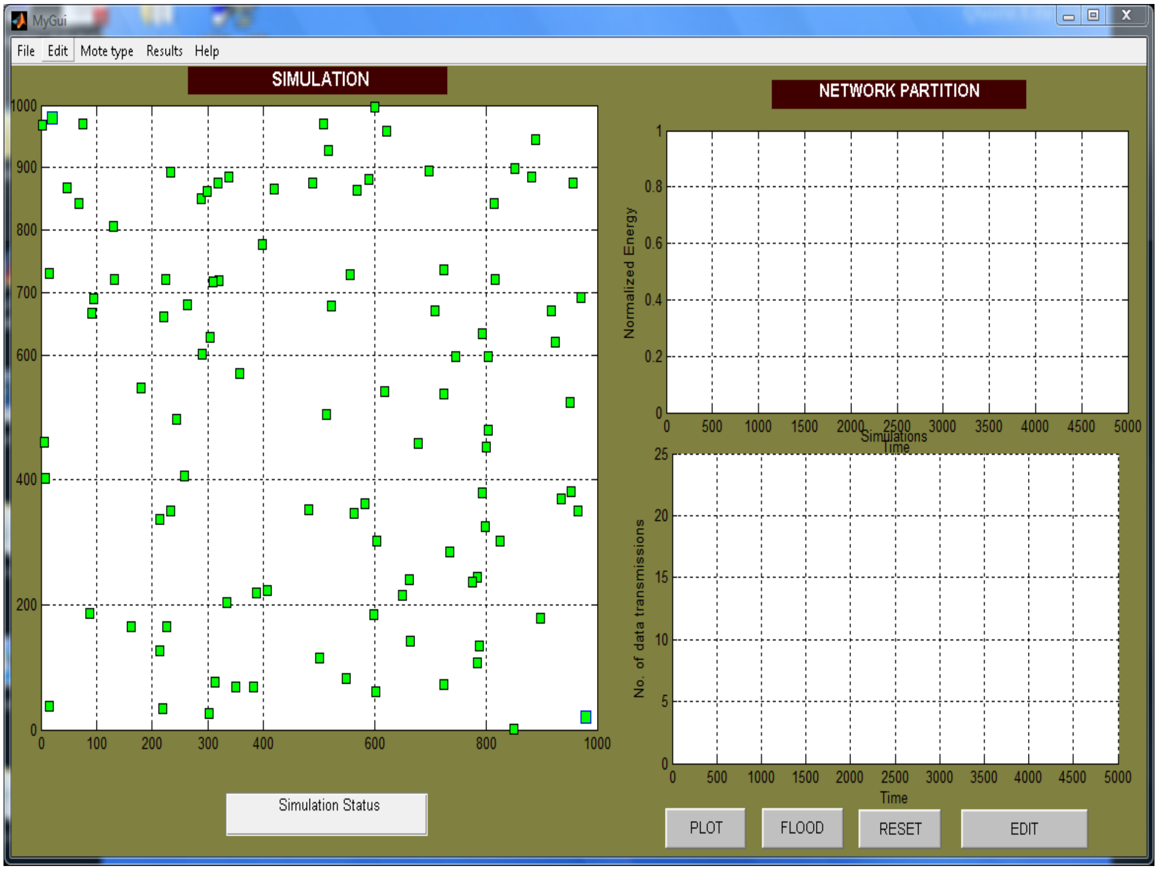


Figure 5.2 GUI developed for simulation of the test area and the routing protocol.

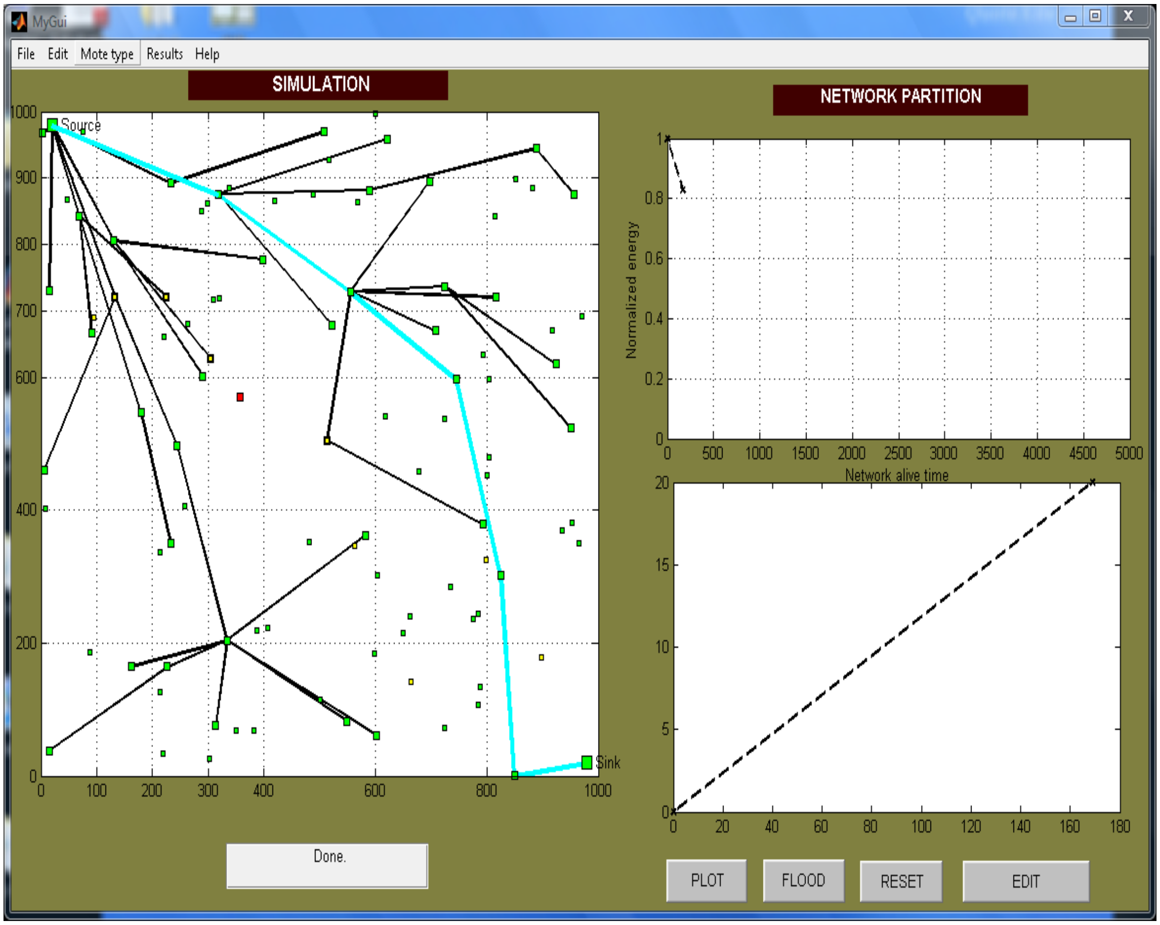


Figure 5.3 Snapshot of flooding in the GUI.

The sensor nodes in the field can be deployed either uniformly throughout the sensor field or randomly strewn across the field. The uniform deployment of nodes is as shown in Figure 5.4 and the random distribution of nodes is as shown in Figure 5.5.

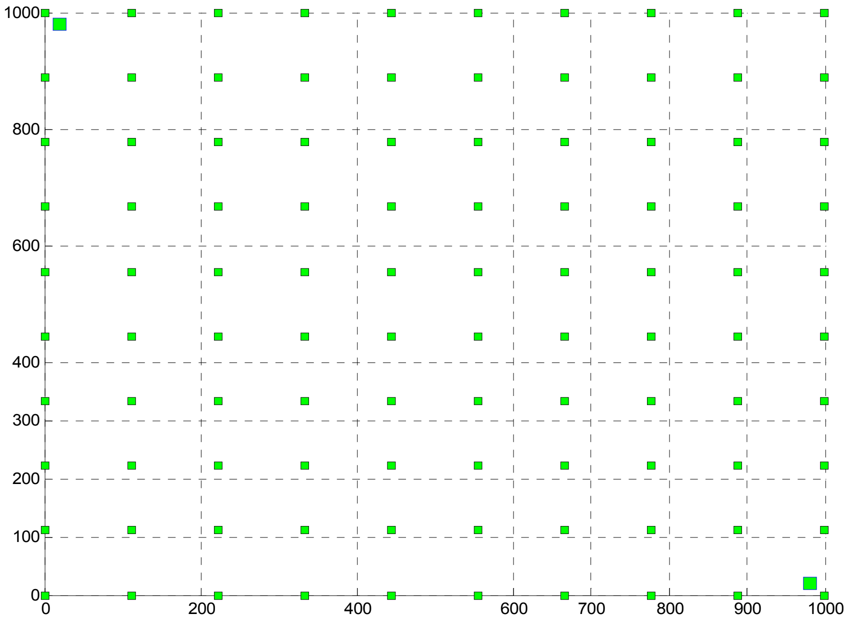
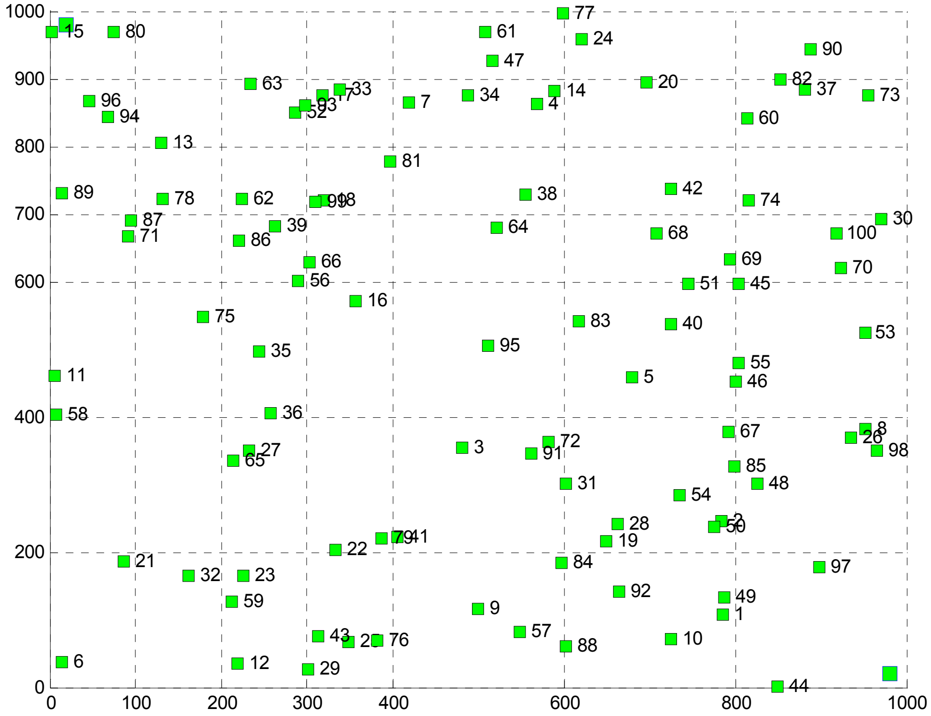


Figure 5.4 Uniform deployment of sensor nodes across the field when source node is in 200 m sized grids and sink node is in 100 m sized grids.



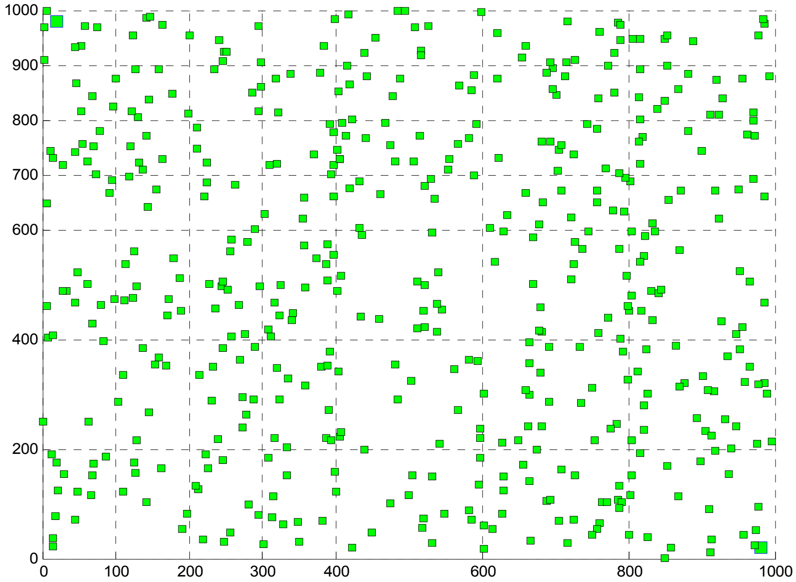


Figure 5.5 Simulation topology showing random deployment of 100 and 1000 nodes in the field when the source node is in 100 m sized grids and the sink node is in 200 m sized grids.

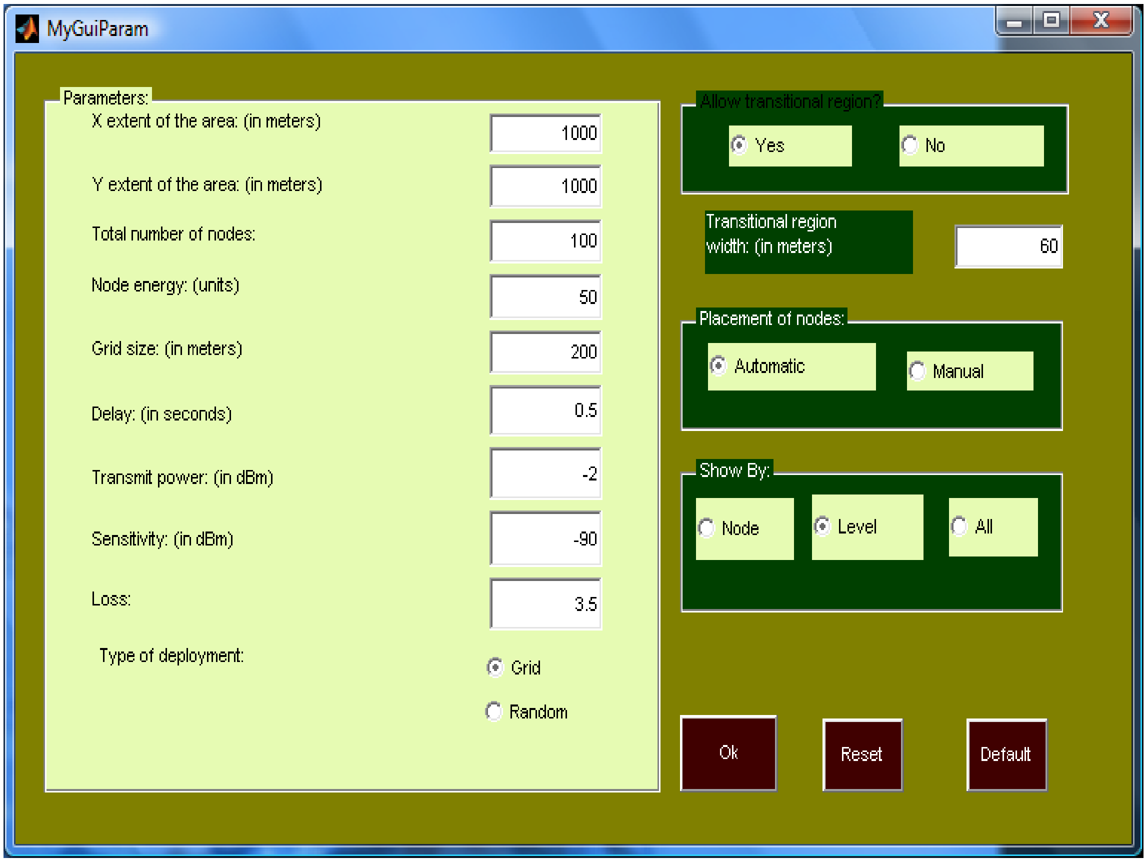
The number of nodes in the network can be varied from 100 to a 1000 nodes. The network also consists of two nodes of infinite energy, the source node and the sink node. When the node density is said to be 100 nodes, we mean that the number of nodes deployed in the sensor field other than the fixed source and sink nodes are 100. The locations of the source and the sink nodes are fixed, irrespective of the type of deployment of the nodes, uniform and random. Though each node loses energy with time, the source and sink nodes are not restricted with such limited energy. The source and the sink nodes never run out of energy. Simulations are thereby observed for different node densities to analyze the scalability of the non-uniform grid-based coordinated routing protocol.

5.2 Parameters Affecting Routing in the Network

There are innumerable parameters that affect the performance of a wireless sensor network. These include, in general, the type of node, the battery life of the node, the application of the network, and so on. As pertains to our study, I list the following parameters that affect the performance of the sensor network:

1. Node deployment
2. The node density
3. The grid size
4. Receiver sensitivity
5. Transmission range of the nodes
6. Node energy
7. Delay in the network

The parameters node deployment, node density, receiver sensitivity, transmission range, and node energy affect the lifetime in the network. The grid size parameter is used only for uniform grid sizes and the delay parameter is only to delay the routing process so as to be able to observe the routing process as the information transmits from the source to the destination. If the delay parameter is not introduced, the routing process occurs instantaneously and is difficult to observe. The delay parameter does not affect the network efficiency in any way. To start with, I pre-define values for each of the above parameters. Figure 5.6 shows the different parameters that affect routing in the network.



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 dBm) -2

Sensitivity: (in dBm) -90

Loss: 3.5

Type of deployment: ● Grid ○ Random

Allow transitional region? ● Yes ○ No

Transitional region width: (in meters) 60

Placement of nodes: ● Automatic ○ Manual

Show By: ○ Node ● Level ○ All

Figure 5.6 Different parameters affecting performance of the sensor network.

As mentioned before, I assume the simulation field to be a square field of 1000 m side. It is assumed that the field is devoid of any obstacles, and is leveled completely. The node density is initially taken to be 100, and is gradually varied from 100 to a 1000 nodes. The grid size varies with the type of grid being used, from uniform grid to the three different types of non-uniform grids. The node energy is fixed to be 50 units, and gradually decreases with the participation of the node in routing. The transmission range or the transmit power is the range within which a node can transmit its information. Beyond this range, the signal for that node is lost. The sensitivity of the receiver is fixed to be at -90 dB and the path loss exponent is set to 3.5. The flooding can be observed node by node or level by level.

5.3 Analyzing the Results

In order to analyze the efficiency of the protocol, I have to determine how long the network stays alive while allowing transmissions from the source to the destination. For this, I designed two graphs. The variables that are required are the normalized energy, total time for which the network is up and running, and the count of the total transmissions that the network allows between the source and the sink. The total transmissions allowed in the network is important so as to assure that the network actually allows a fair amount to information exchange throughout the network for as long as the network is alive, and not just keeping the network alive while not actually allowing enough transmissions in the network. The essential variables are the normalized energy and the total time for which the network stays alive.

Normalized energy is defined as the ratio of the total current energy of all nodes to the total energy of all nodes at the start of the simulation. Network time is kept track of by a timer that starts once the network starts to flood and stops when there is no communication link between the source and the sink nodes. The timer is set once the routing begins and stops only when the network partitions, thereby calculating the total time for which the network is alive. Figures 5.7 and 5.8 show the two graphs plotting the energy and the total transmissions in the network. The network longevity is determined by the X-axis in each graph which denotes the timer values.

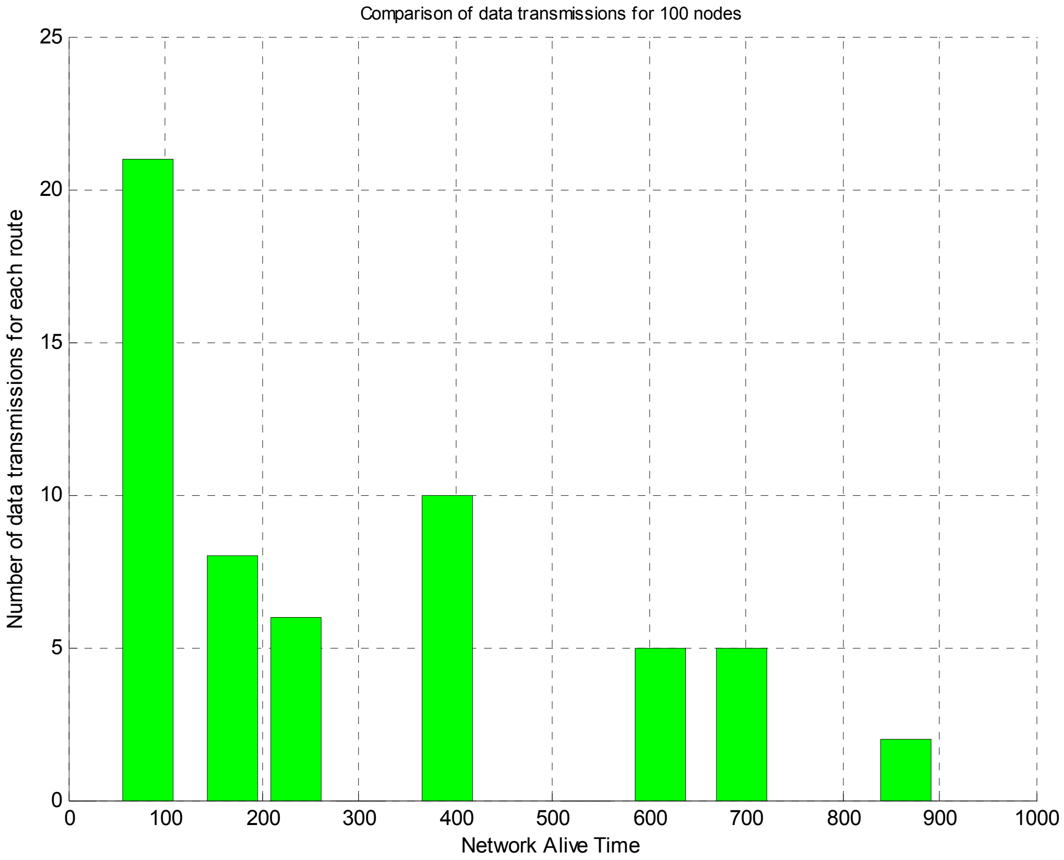


Figure 5.7 Graph showing the transmissions for each successful link established between the source and the sink nodes. The Y-axis denotes the count of the transmissions while the X-axis denotes the time for which the network is alive, in time units.

The graph has been plotted for a node density of 100 nodes deployed randomly over the sensor field and is for the alternating non-uniform grid structure. The total transmissions for each successful route varies with the energy of the nodes that participate in routing, but is always maximum for the first link established between the source and the sink nodes since no amount of energy is spent by then. The x-axis denotes that the network is alive for nearly 900 time units.

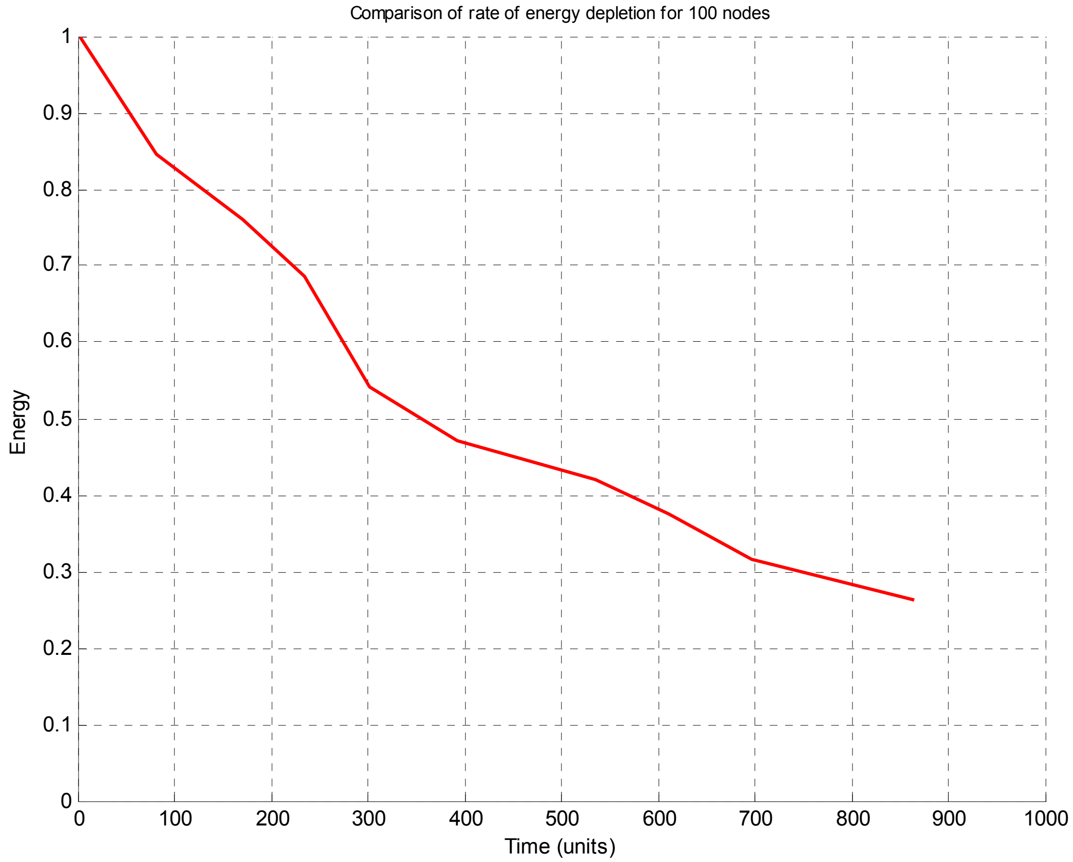


Figure 5.8 Graph showing the gradual decrease of normalized energy of the network with time. The Y-axis denotes the normalized energy of the network while the X-axis denotes the time for which the network is not partitioned, in time units.

The graph is plotted for a density of 100 nodes deployed randomly across the sensor field, and is for the alternating non-uniform grid structure. The energy falls gradually from 1.0 units to 0.28 units and the network stays alive for nearly 900 time units.

5.4 Uniform Node Deployment

With nodes distributed uniformly over the sensor field, simulations are run for the uniform and the non-uniform grids respectively. Figures 5.9, 5.10, 5.11, 5.12 show the uniform and the non-uniform grid simulations.

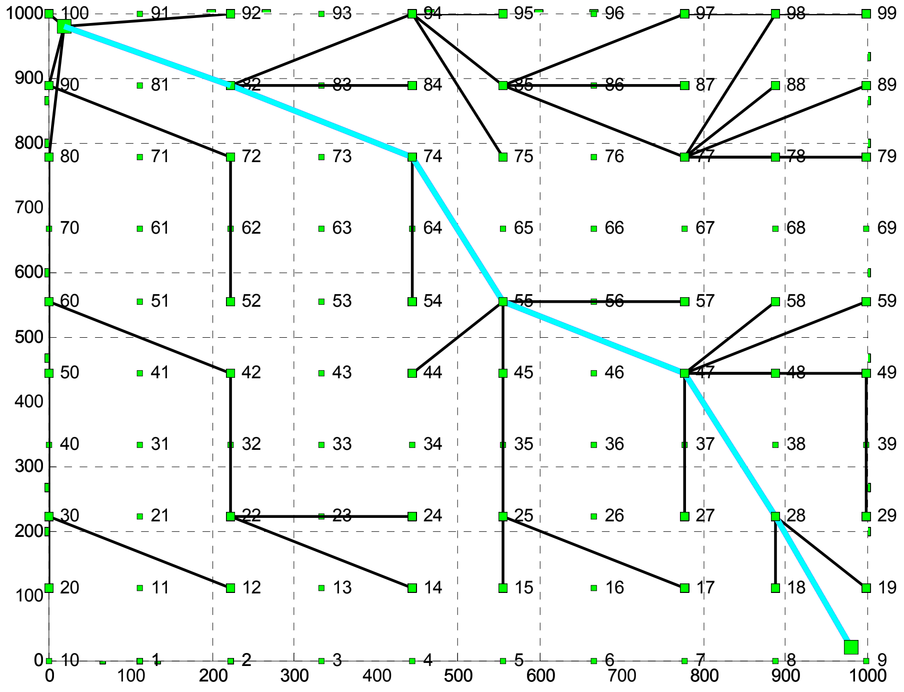


Figure 5.9 Simulation topology showing flooding for 100 nodes uniformly distributed in the field for the alternating non-uniform grid structure.

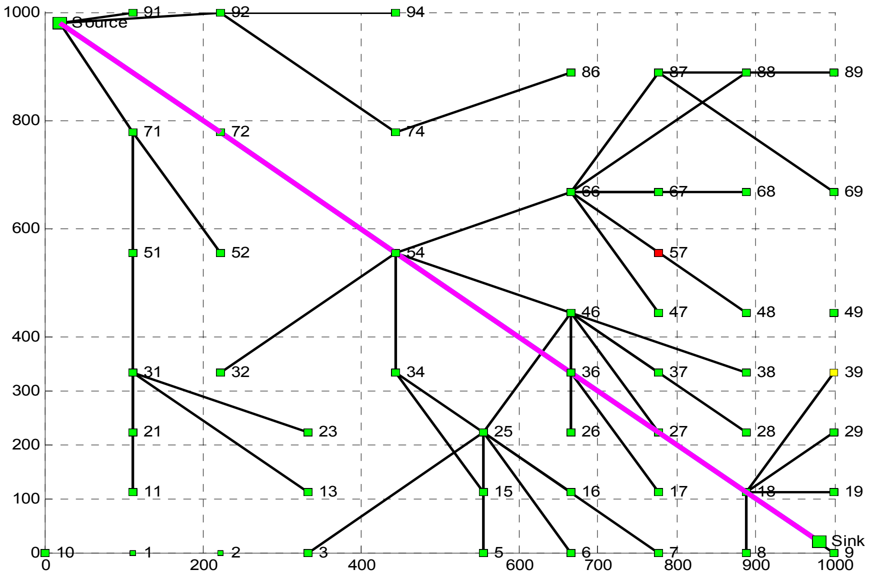


Figure 5.10 Simulation topology showing flooding between the coordinator nodes in the network for a grid structure with the source node in nodes of size 200m and sink node in grids of size 100m each.

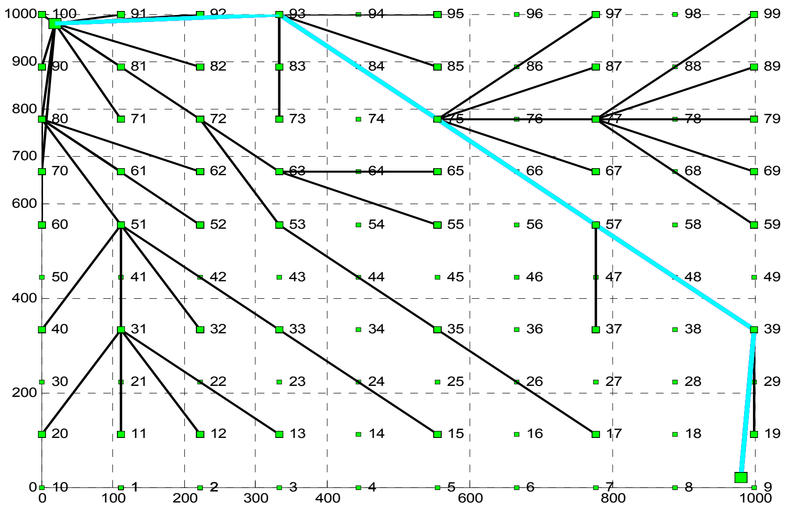


Figure 5.11 Simulation topology showing flooding between the coordinator nodes in the network for a grid structure with the source node in nodes of size 100 m and sink node in grids of size 200 m each.

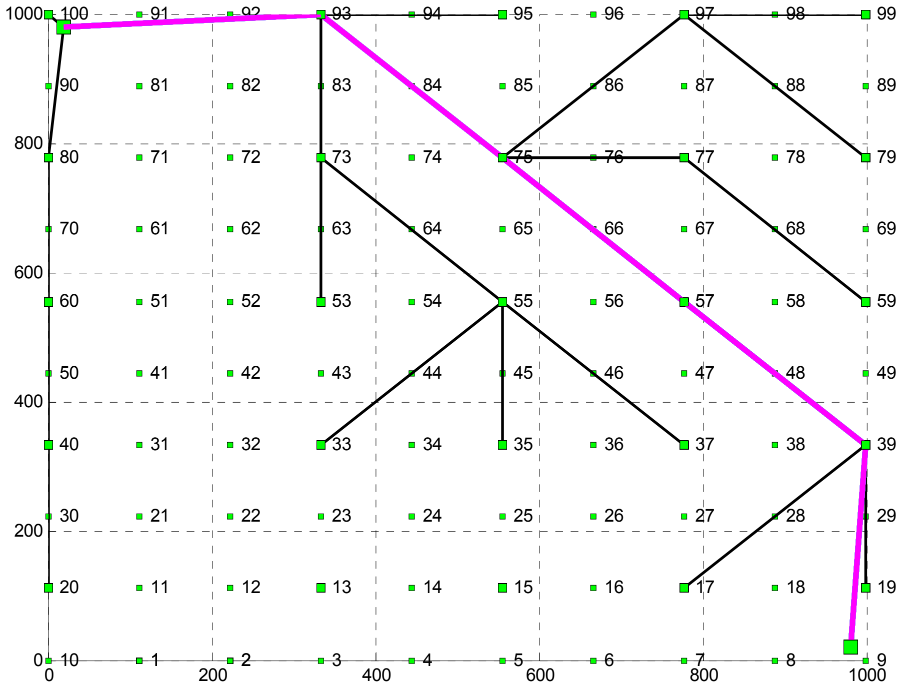


Figure 5.12 Simulation topology showing flooding in the network for 100 nodes deployed uniformly in the sensor field for a uniform grid structure.

From these simulations, it has been observed that the uniform grid-based coordinated routing protocol is best suited for uniform node deployment.

5.5 Random Node Deployment

Because I assign a random number to plot sensor nodes randomly across the field, each simulation results in different random locations of sensor nodes. This makes it difficult to compare the performance of the different grid structures for the same node density. Therefore, I assigned fixed node positions to each node that fix the nodes to their random positions for each simulation. This means that the deployment of nodes is non-uniform across the field, but the positions of the nodes remain the same anyway. This is also applicable for varying node density. Figure 5.13 shows the node placement for 250 nodes. It remains the same for all grid structures.

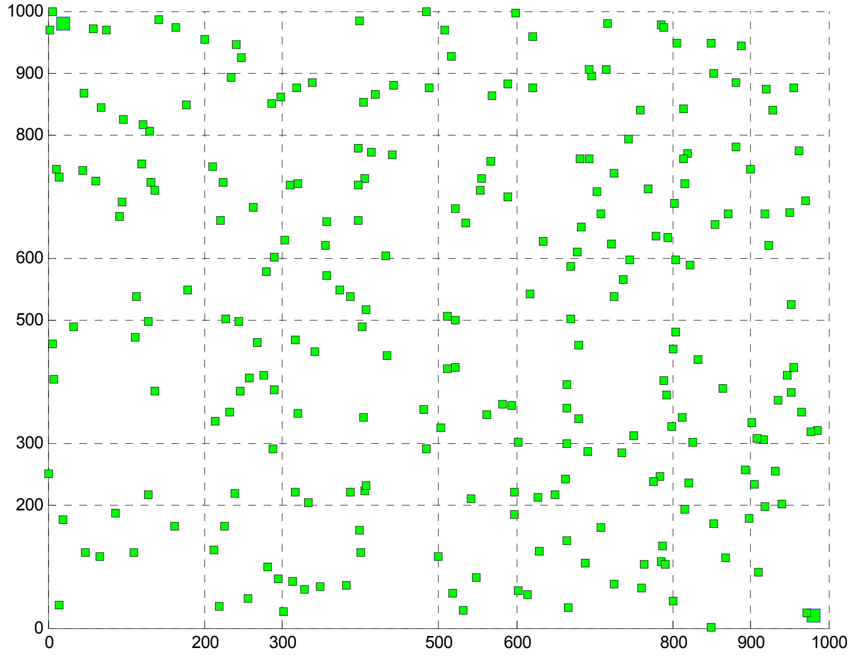


Figure 5.13 Simulation topology showing random node deployment for 250 nodes. The position of the nodes remains the same for all the grid structures.

For example, if we are dealing with a node density of 100 nodes, the nodes are randomly distributed at certain positions. The topology remains constant for all the grid structures, thus enabling fair comparison between them. If the node density is increased from 100 to 500, the nodes from 1 to 100 retain their old positions and the nodes from 100 to 500 are randomly placed in the field. In all, the placement of the nodes from 1 through 50 remains the same for all simulations. This holds true for node densities 600 through 1000. Figure 5.14 shows the random node placement for 1000 nodes.

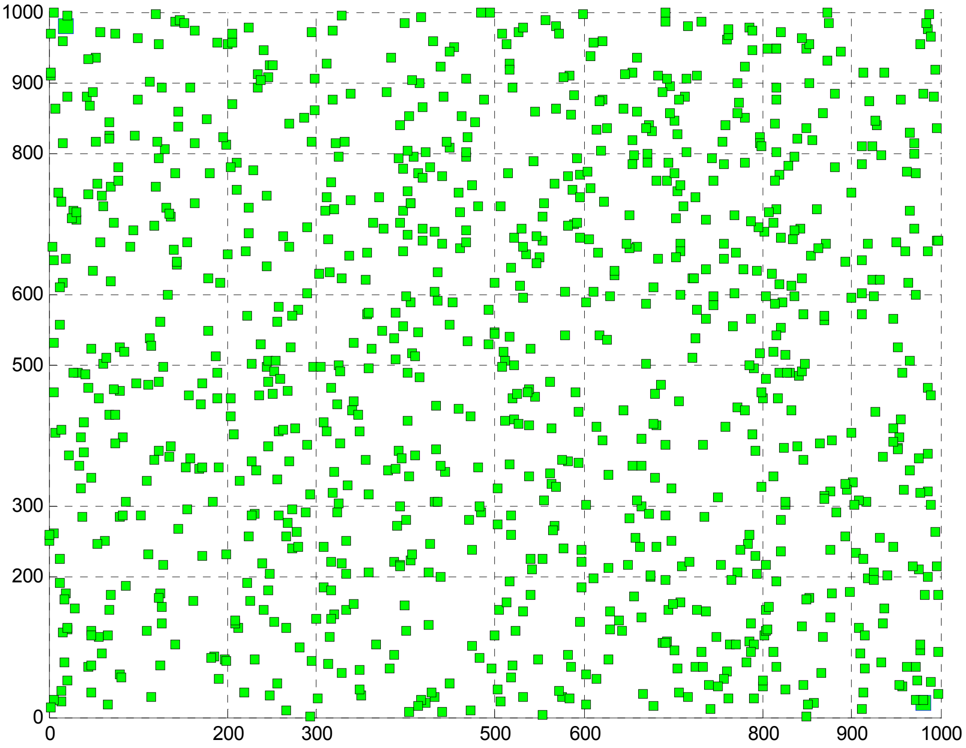


Figure 5.14 Simulation topology showing random node deployment of 1000 nodes for alternating non-uniform grid structure.

5.6 Results

For a given node density, I analyzed the efficiency of the different grid structures by comparing the network alive times of each structure. Also, I compared the total transmissions for each structure. The longest network structure does not necessarily have to possess the maximum transmissions, but it should still support a fair amount of transmissions between the source and the sink. Thus, we have three cumulative graphs:

1. The network lifetime of the network for each grid structure.
2. The total transmissions for each grid structure.
3. The energy depletion graph.

Figure 5.15 shows total transmissions allowed in the network for a node density of 100 nodes for all the grid structures.

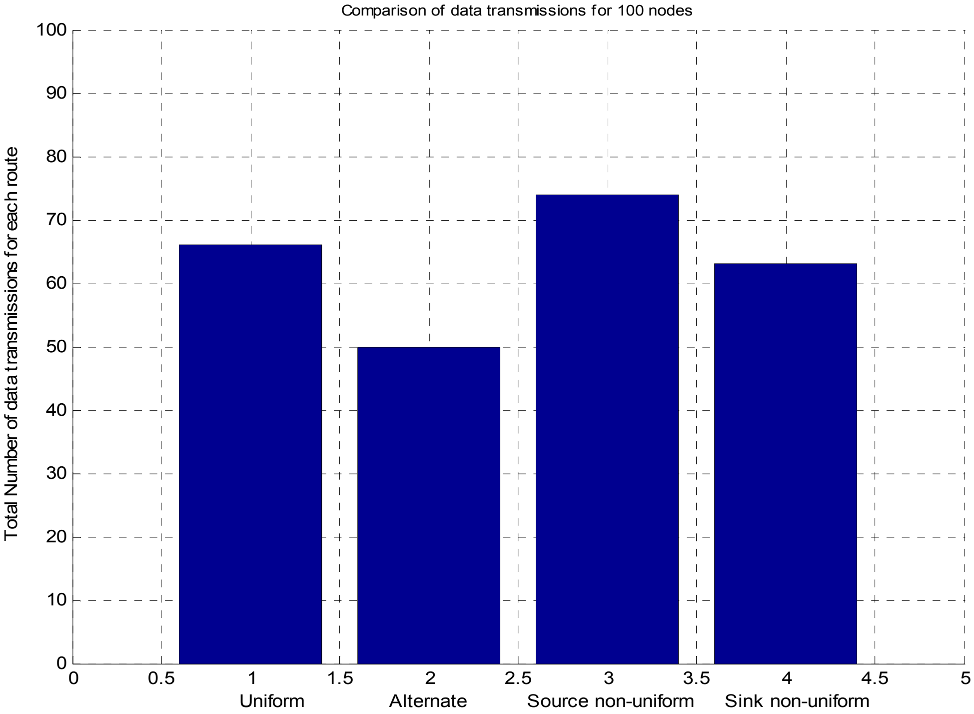


Figure 5.15 Graph showing the total transmissions the network allows for the same node density of 100 nodes, for different grid structures.

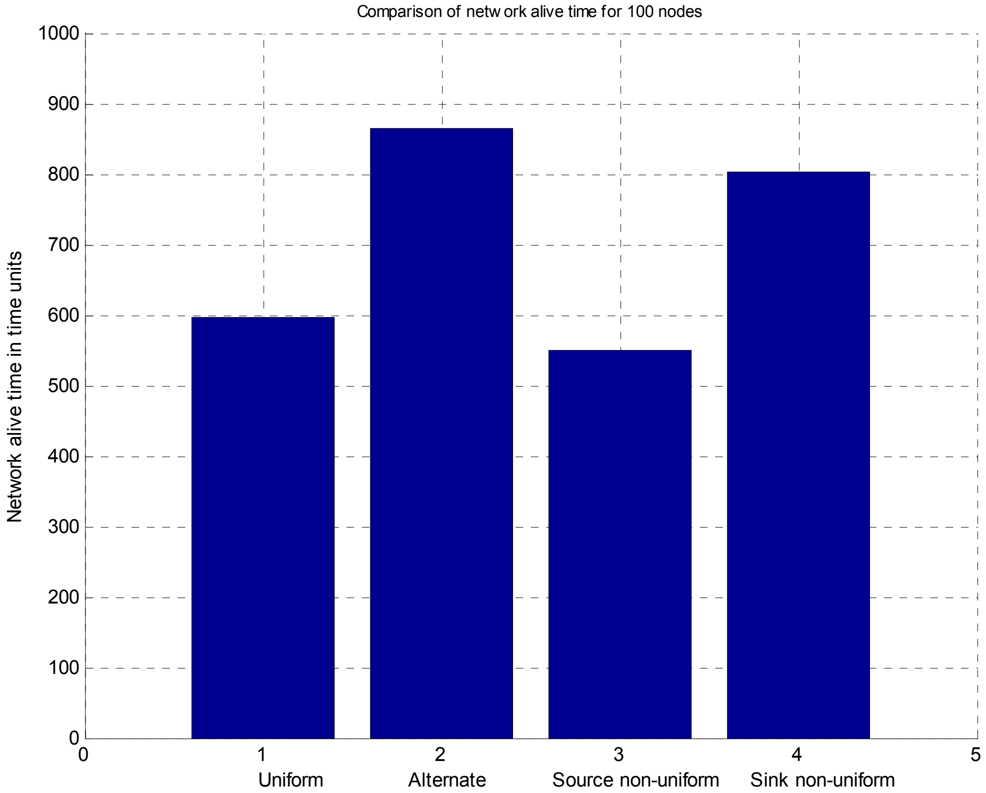


Figure 5.16 Graph representing the network lifetime for different grid structures for 100 nodes deployed randomly across the sensor field.

The y-axis is a cumulative count of the total number of time units the network is alive. The x-axis represents the different types of grid structures. It is observed that the lifetime of a non-uniform grid structure exceeds the total transmissions allowed by the uniform grid structure.

Figure 5.17 shows the energy plot of different grid structures for 100 nodes.

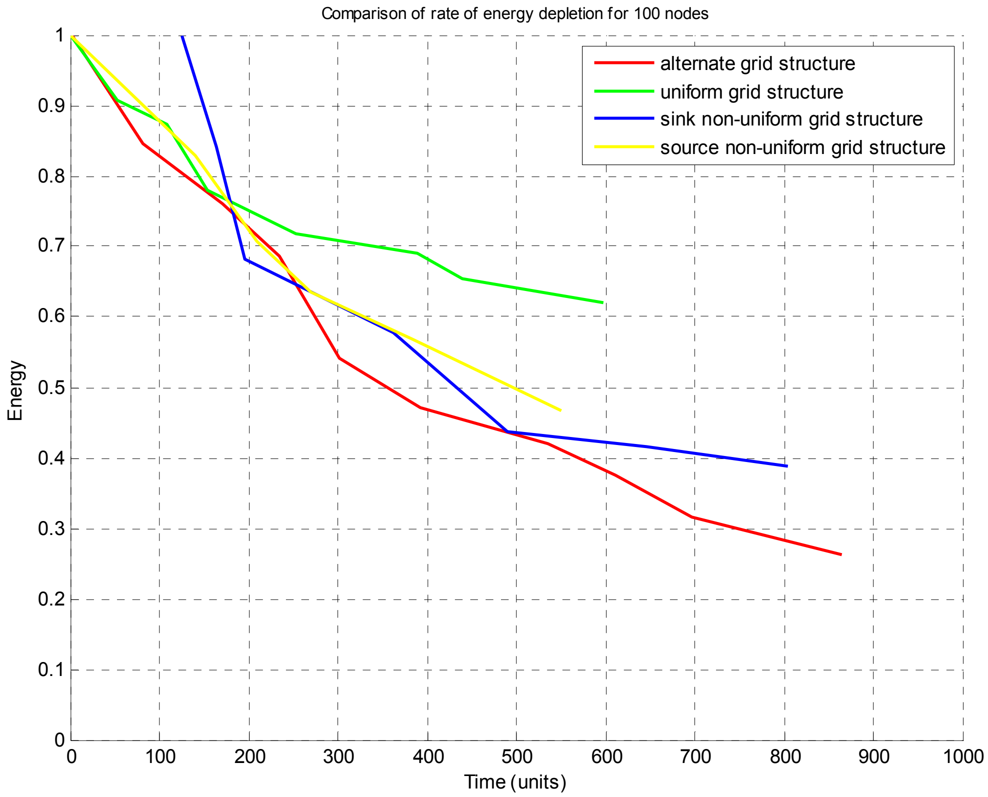


Figure 5.17 Graph showing the gradual decline of energy in the network with time.

The maximum network lifetime is nearly 900 time units for the alternating non-uniform grid structure, and this structure best utilizes the entire energy in the network since the energy gradually decreases from 1.0 unit to nearly 0.28 units.

To analyze the simulations, we take into consideration two graphs: the graph that plots the total transmissions supported by the network, as in Figure 5.15 and the graph that plots the energy depletion, as in Figure 5.17.

Figure 5.18 through Figure 5.21 show graphs representing network lifetime and energy depletion for node densities 200 and 1000.

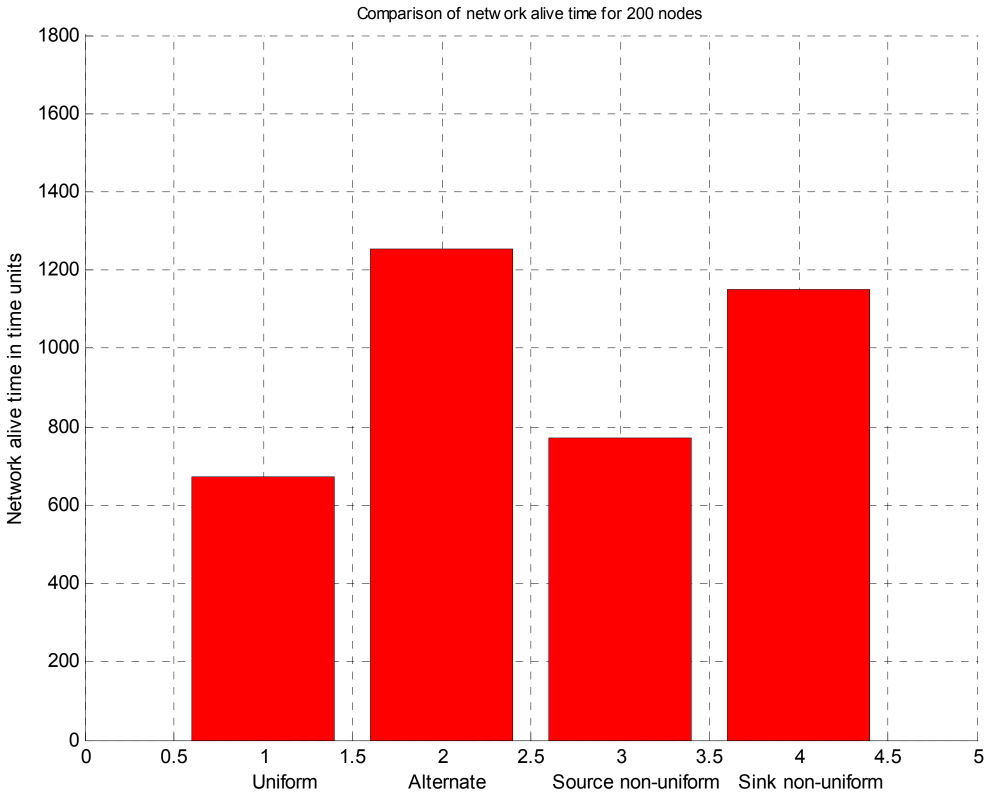


Figure 5.18 Graph representing the network lifetime for 200 nodes for each type of grid.

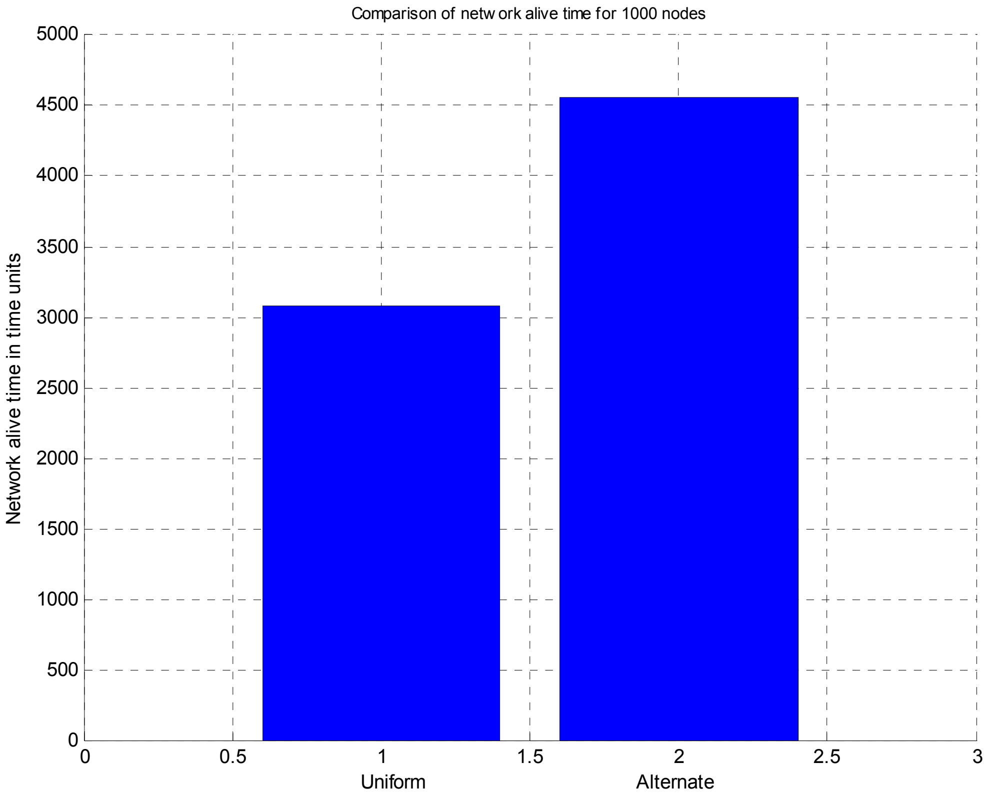


Figure 5.19 Graph representing the network lifetime for 1000 nodes for uniform and alternate grid structures.

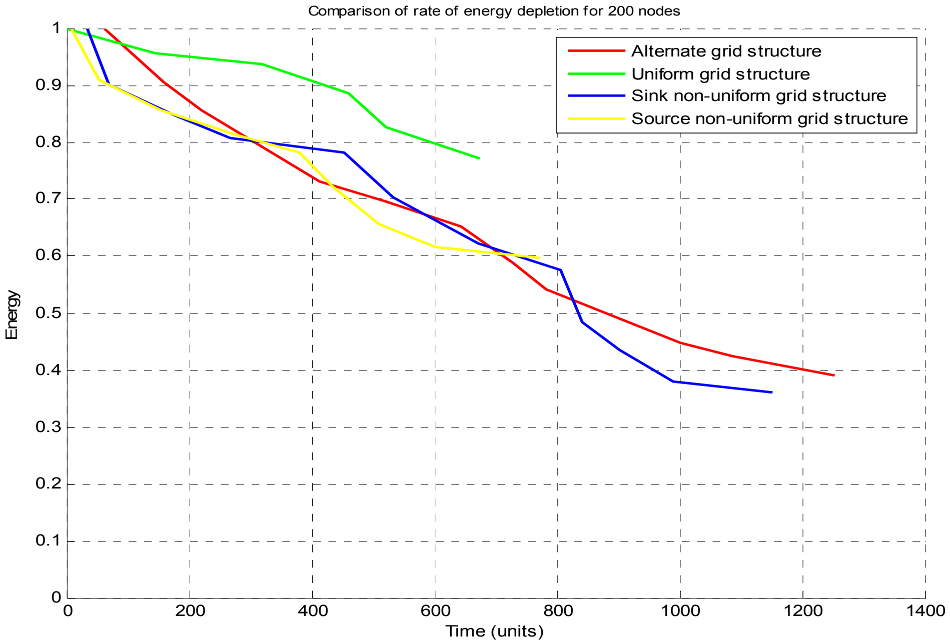


Figure 5.20 Graph representing decrease in network energy for various grid structures.

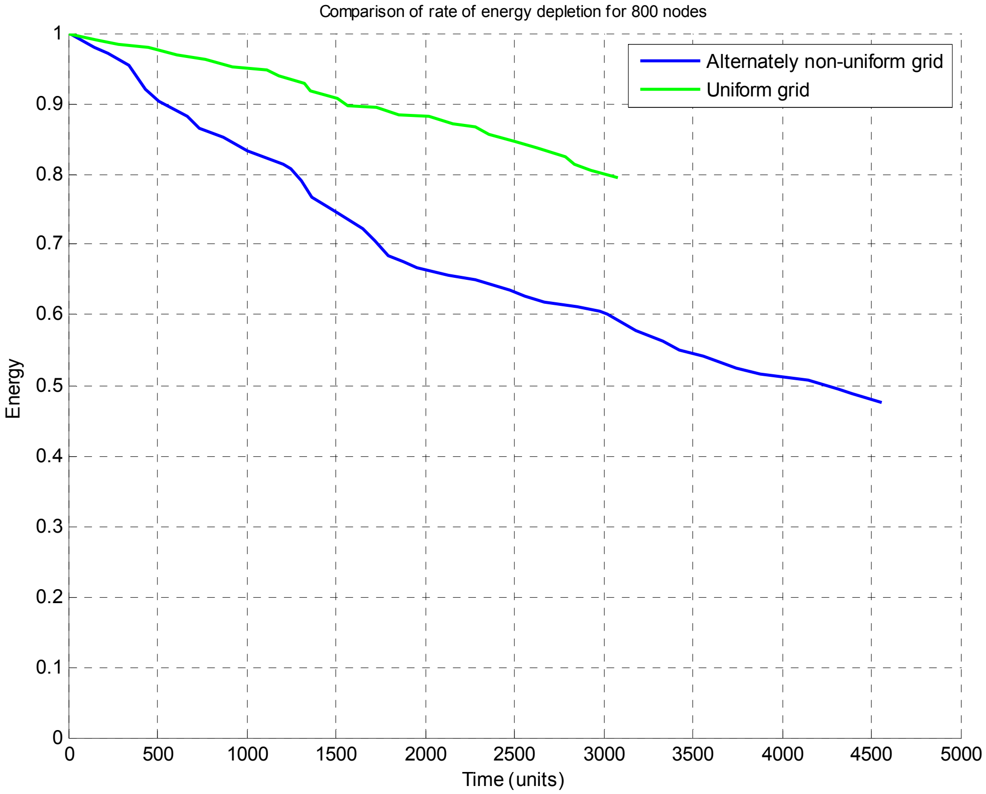


Figure 5.21 Graph representing decrease in network energy with time for 1000 nodes.

5.7 Comparison with Traditional Flooding Algorithm

The main disadvantage of the traditional flooding algorithm is that the information travels throughout the network before it can reach the destination. Flooding does not pick a particular route to send information from the source to the sink. Instead, a node is alive all the time and transmits and receives data continuously. Therefore, according to our energy model, a node nearly spends 2.5 units of energy each second for being alive. Thus, if the node has 50 units of energy, the node can only sustain 20 transmissions before it dies. If we consider in flooding from Figure 5.22 that the information takes approximately 5 time units for a network of 100 nodes to allow information from the source to the sink, the maximum network lifetime is 100 time units, which is very low as compared to uniform and non-uniform grid-based coordinated routing protocol.

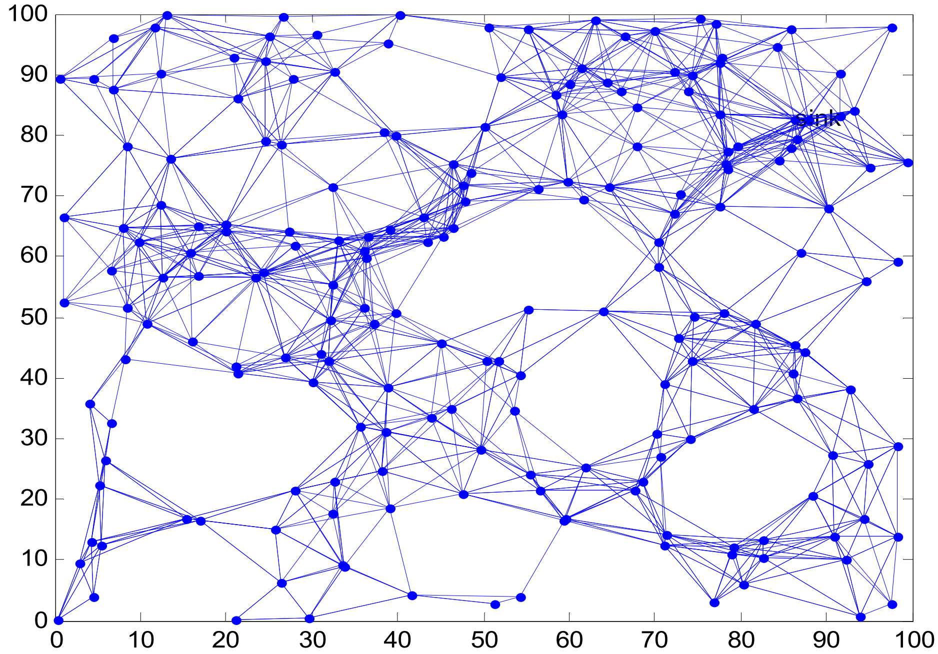


Figure 5.22 Simulation of the traditional flooding algorithm.

5.8 Analysis of Results

By varying the node density in multiples of hundred to a thousand, we have analyzed that the network lifetime for random node deployment is effectively more with non-uniform grid-based coordinated routing protocol. The variation of network life time for the different grid structures with varying node density is as shown:

NODE DENSITY	Lifetime for Uniform grid (time units)	Lifetime for Alternating non – uniform grid(time units)	Lifetime for Source non-uniform grid (time units)	Lifetime for Sink non-uniform grid (time units)
100 nodes	600	880	550	800
200 nodes	680	1250	780	1170
400 nodes	1800	1840	1660	1250
1000 nodes	3000	4500	4000	4300

Table 1: Comparison of network lifetime for uniform and non-uniform grid structures.

Figure 5.23 shows the simulation topology for alternating non-uniform grid for 400 nodes. From all the results, the alternating non-uniform grid structure shows to be the best non-uniform grid structure for randomly deployed wireless sensor networks.

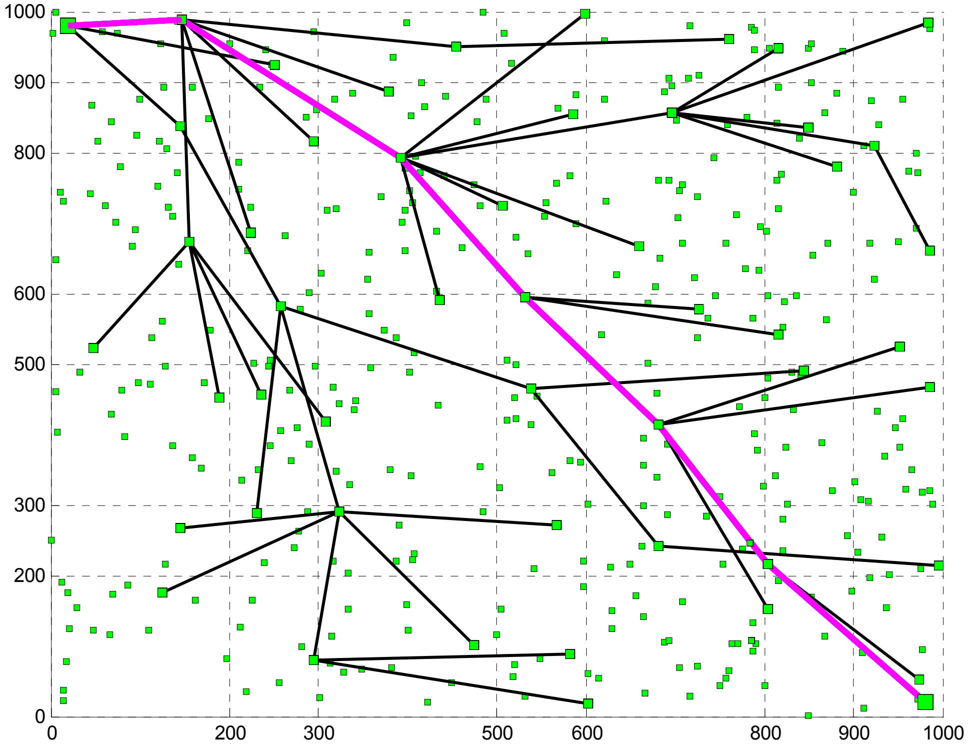


Figure 5.23 Simulation topology showing flooding in the alternating non-uniform grid structure that is most efficient for random node deployment of nodes for densities of 100 through 1000 nodes.

CHAPTER 6

CONCLUSIONS

6.1 Summary

Conservation of energy is a major area of research in routing in wireless sensor networks. Most of the routing protocols designed aim at conserving battery life of the sensor nodes, support scalability, and extending network partition time. The grid-based protocol has also been designed keeping the same view. This non-uniform grid-based routing protocol was derived from the grid-based routing protocol. It follows the grid-based routing protocol in conserving power and surpasses uniform grid routing in dense wireless sensor networks. If the nodes in the network are not put to sleep to conserve energy, the node energy of all the nodes in the network would deplete with time, and thus lead to early network partition. By using the non-uniform grid-based coordinated routing protocol I improved the lifetime of the network by a factor up to 15 percent as compared to protocols that do not let the nodes enter sleeping mode.

In Chapter 2, I present routing in wireless ad hoc networks. Between table-driven and on-demand protocols, on-demand protocols were determined as befitting the dynamic nature of wireless sensor networks. The different routing protocols designed for sensor networks are presented.

Chapter 3 describes the traditional flooding algorithm, along with the two main protocols that lead to the idea of grid-based routing protocol: GAF and Span.

In Chapter 4, I discuss the grid-based routing protocol and design the non-uniform grid-based routing protocol. The different non-uniform grid structures are proposed. I discuss the election of coordinator nodes, determine an upper bound on the grid size for successful communication links, and analyze the deterministic link model and the probabilistic link model. Also, I incorporate load balancing.

Chapter 5 presents the implementation of the non-uniform grid-based routing protocol. Simulations show that for dense randomly deployed sensor networks, non-uniform grid-based routing prolongs network partition. The protocol is tested for scalability by varying the node density from 100 nodes in the network to 1000 nodes in the network. It is shown that as the number of nodes increases the network lifetime increases by using the non-uniform grid routing protocol for randomly deployed sensor networks. The results are compared and contrasted to uniform grid-based routing protocol and the traditional flooding algorithm.

6.2 Future Research

In conclusion, the possible future extensions to this work can be listed as:

- Implementation on motes: The non-uniform grid-based routing protocol is simulated in Matlab. This can be extended onto actual motes and the results observed.
- Mobility of nodes: The nodes in our network are stationary. Mobility may be added to the nodes in the network and the working of the protocol can be observed.
- Irregular distribution of nodes: The protocol has only been simulated for node density distributed evenly across the network. There is no significantly dense area and sparse area in the network. The working of the protocol can be extended to observe results for dense and sparsely populated areas across the network.

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