ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

COLLEGE OF NATURAL SCEINCES

DEPARTMENT OF COMPUTER SCEINCE

Shape Based Customized Node Deployment Approach using Wireless Sensor Networks

Beza Diribu Desta

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Beza Diribu Desta

Advisor: Mulugeta Libsie (PhD)

Name and Signature of members of the Examining Board:

Name	Signature
1. Mulugeta Libsie (PhD), Advisor	________________
2. Fekade Getahun (PhD)	________________
3. Solomon Atnafu (PhD)	________________

Dedication

To my parents

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Abstract

Wireless sensor networks consist of many nodes with capability of sensing, computation, and wireless communications. The use of wireless sensor networks has become an essential technology in many application domains including precision agriculture. Node deployment is a key issue in Wireless Sensor Networks (WSNs). An appropriate node deployment scheme can increase coverage, connectivity and network lifetime of a WSN.

In this thesis, we developed an approach to address the challenges associated to node deployment in WSNs. The proposed approach enables to handle different shapes of a monitored region for achieving an optimal deployment scheme. In here, the nodes will be deployed over a network in a deterministic fashion in which the position of sensor nodes is known before deployment. These nodes are arranged regularly using triangular grid node deployment strategy over the given shape of monitored region either regular or irregular. This approach computes the minimum number of nodes needed to construct a sensor network and determine the position of sensor nodes using spatial coordinates with corresponding node deployment scheme and network topology. This approach uses real world deployment scenarios (i.e., taking the real shape of the monitored region of farmland) and determines the position of sensor nodes using spatial coordinates and this makes it more practical than others. This approach has to meet various requirements, such as coverage area, network lifetime, cost and ease of deployment, number of nodes and adaptability.

The implementation and the performance evaluation of the proposed node deployment are made with MATLAB. Moreover, we compared hierarchical routing algorithms called PEGASIS and LEACH to evaluate the network lifetime of the proposed scheme since node deployment scheme has an effect on routing. The results obtained by the implementation and evaluation are measured in comparison with other previously proposed node deployment strategies using mathematical modeling, theoretical analysis and formula deduction. The results show that the proposed approach can achieve full coverage with the minimum number of sensor nodes for the given shape of farmland. Hence, it is applicable to practical environments such as irregularly shaped farmland. We also show that the node deployment have been affected by the shape of the farmland. Thus, the required number of nodes and their positions can be adjusted adaptively to different shape of farmland.

Keywords:

Node Deployment, Coverage, Deployment Scheme, Precision Agriculture, Wireless Sensor Networks (WSNs), Sensor node, Network Lifetime

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Chapter 1: Introduction

1.1 Background

Wireless Sensor Networks (WSNs) have gained worldwide attention in recent years and emerged as one of the most promising technologies for the future [8, 29]. A WSN is composed of a number of sensor nodes which is usually deployed in a geographical area to collect information from their surrounding environment and send their sensed data to a Base Station (BS) or a sink node to monitor the environment [30]. On the other hand, a WSN is a resource constrained system while sensor nodes have limited energy, computational capabilities and storage. Moreover, it is also a design constrained system while it is application dependent and environment dependent (i.e., on network size, deployment scheme and network topology) [29]. Therefore, it is proper to carefully plan, design and manage WSNs by taking into consideration those constraints to meet the application's requirements such as coverage area, network size, cost of deployment, etc.

WSNs have been used for various applications including habitat monitoring, health monitoring, agriculture, water pollution monitoring and nuclear reactor control. Precision Agriculture (PA) is one of the application domains of wireless sensor networks which help to make precise monitoring of farming lands at the time of its growth. Both precision agriculture and WSN applications will greatly improve quality in agricultural production and reduces cost [2]. A commonly accepted definition of PA is a comprehensive system designed to optimize agricultural production by carefully tailoring soil and crop management to correspond to the unique condition found in each field while maintaining environmental quality [31]. Precision agriculture is also alternatively defined as the technique of applying the right amount of input (water, fertilizer, pesticides, etc.) at the right location and at the right time to enhance production and improve quality, while minimizing the impact on the environment [1]. But, it relies on information technology to provide real-time and accurate information including a decision support system for treatments or taking differential action such as the variation of fertilizer or pesticide application [33]. Depending on the various kinds of sensors, thus, environmental temperature and humidity, wind speed, lighting condition, and the conditions of the crops and soil, etc can be monitored [23, 43].

Utilizing wireless sensor networks in agriculture is used to reduce problems associated with inefficient use of resources, decision making and farmland monitoring in traditional farming cannot overcome. This helps to know at any time information about the land and crop conditions. As a result, the crop productions are maximized. The necessity of using technology in agriculture in a developing country like Ethiopia can be seen as the optimal solution. This technology involves:

- Node deployment: an application dependent task which may be either deterministic or randomized. It should take into account the number of sensor nodes and the distance between them [30].
- A routing protocol is an algorithm used by nodes to determine a path for forwarding packets toward a destination [42].

One of the important issues in WSNs is node deployment which decides where the sensor nodes should be placed in order to satisfy the desired requirements like maximize the efficient coverage area ratio and minimize the size of the network and cost. The effectiveness of these networks is determined to a large extent by the coverage provided by the sensor deployment scheme. Determining the required number of sensors to be deployed is a critical decision for wireless sensor networks [9]. Therefore, the positions of sensor nodes are determined before deployment and the sensors are manually placed. The number and positions of sensor nodes can determine many basic properties of a WSN, such as coverage, connectivity, cost and lifetime [62].

A number of approaches, architecture and models have been proposed on node deployment in WSNs. But none of them are considering different shapes of a given monitored region belong to deterministic node deployment/controlled placement (i.e., when the node is carefully and deliberately positioned to serve its purpose). Thus, a node deployment scheme which is optimal for a region is not optimal for another region (of a different shape or different area) since the sensor node deployment scheme could be affected by the given geometry of monitored region. Therefore, this thesis will address those issues. In our case, we used real shape of farmland and proposed real position of sensor nodes using spatial coordinates instead of using mathematical coordinates like other works. This makes it more practical.

Hence, this thesis aims to investigate the use of wireless sensor networks in precision agriculture in order to overcome the agricultural problems. And it presents a node deployment approach which will enable to construct a sensor network with the minimum number of sensor nodes which are deterministically deployed with corresponding node deployment scheme. Hence, the position and the number of nodes are determined prior to deployment to enables more accurate monitoring of farmland. The proposed node deployment approach enables to generate optimal node deployment schemes for a given geometric feature of monitored region. Thus, this scheme used as references to guide real-world deployment. It is intended for precision agriculture monitoring for a given geometry of farmland with a network topology in a way that achieves the desired design considerations such as coverage area, deployment cost, the number of sensors/network size, location of sensors, etc. Moreover, we will choose a routing protocol which has a better network lifetime based on the proposed node deployment scheme. And we compared PEGASIS and LEACH in terms network lifetime based on our scenario. Both routing protocols are hierarchical based. Hierarchical routing protocols enable to perform energy efficient routing in WSNs by means of cluster or hierarchical schemes when compared to other techniques [36, 46]. Thus, by comparing the two, the proposed network topology performs better in terms of network lifetime using PEGASIS.

Finally, the resulting computation is implemented using MATLAB environment. This work also shows the appropriateness of the proposed system in solving the problems using different performance metrics by performing different experimental simulations in MATLAB environment, mathematical modeling, theoretical analysis and formula deduction.

1.2 Statement of the Problem

At present, WSNs are being applied in different applications including precision agriculture. Different techniques have been proposed to greatly improve activities in agricultural production. Sensor node deployment is one of the important tasks in WSNs. The way of nodes deployment influences on the effectiveness of whole WSN. There are a number of node deployment approaches have been proposed but a few of them were considered the given shape of the monitored region for random deployment and indoor environment. But, none of the proposed works do not take into consideration the geometric feature of monitored region in order to produce the appropriate and efficient node deployment scheme belongs to deterministic deployment for precision agriculture monitoring. Thus, a node deployment scheme which is optimal for a region may not be optimal for another region (of a different shape or different area) since the appropriateness of node deployment scheme could be affected by the given geometry of a monitored region. Hence, these could reduce the effectiveness of the networks. This shows that there is a need to have an approach that uses the given shape of farmland and then determine optimal allocation of sensor nodes with the minimum number of nodes. This helps to achieve maximum coverage, cost of deployment, reduce the number of sensors, etc.

In addition to the node deployment, a sensor network routing protocol that has better network lifetime will select based on the proposed scheme. Because routing protocols are necessary for efficient and effective communication between these sensor nodes [30, 36]. A number of works have been done either on node deployment or routing protocol. But they did not perform any simulation to select the best routing protocol for their node deployment scheme and network topology. Therefore, this work will show that the necessity of selecting a routing protocol for the proposed node deployment scheme and network topology.

Generally, lots of previous works have been done on sensor node deployment but less attention has been paid for the sensor node deployment strategy for the given monitored region including the application called precision agriculture and selecting a routing protocol performs well for a given node layout or network topology. This research work is aimed to fill the gap of the aforementioned problems.

1.3 Motivation

The motivation of this study is to apply wireless sensor network for precision agriculture because wireless sensor network have been used in different application including agriculture. In Ethiopia, the economic system is relied on agriculture. So this was one of the reasons to choose this application in order to put our contribution. After this, a few literatures have been considered the boundary of the monitored region but it was for random deployment and indoor environment. This shows that there is a need of node deployment approach that considers the given shape of the monitored region particularly on node deployment including in precision agriculture. The wireless sensor network have large number of nodes deployed, so if the number of node will be high then the cost of overall network will become very high. Even if they are not costly we should not have populating the farm area with large number of node if we have the opportunity to optimize it. Therefore, we have to generate anode deployment scheme with the position of sensor nodes and a minimum number of sensor nodes. Since the number of sensor nodes decreases, the deployment cost will decreases. So we need a deployment approach that considers all those points. Furthermore, it deals with the advantages of the precision agriculture approach to help make valuable decisions which could not only maximize the land production and also minimize the use of resources.

1.4 Objectives

General Objective

The general objective of this research work is to develop shape based customized node deployment approach using WSNs.

Specific Objectives

In particular, this thesis work has the following specific objectives:

- Study the works and the current practices that have been done in the area of sensor node deployment in WSNs.
- Design architecture for the proposed node deployment approach.
- Develop sensor node deployment approach for any geometric feature of monitored region which will enable to construct a sensor network with the minimum number of sensor nodes by determining their position.
- Develop a simulated prototype for the shape based node deployment approach and demonstrate the suitability and applicability of the proposed system.
- Select sensor network routing protocol that can cope up with this specific application.
- Test and evaluate the proposed system.

1.5 Methodology

In order to achieve the objectives of the study, the following methods will be employed:

Literature Review

Extensive literature review will be made on different related works to obtain an in-depth understanding of the area and to identify the actual problem. Moreover, to find useful approaches that can efficiently solve the problem.

Designing the Proposed System

We will propose the desired requirements that should be addressed while conducting this work and designed its architecture.

Prototype Implementation

The implementation of the proposed approach will be done using MATLAB software.

Testing and Evaluation

Results from the proposed solution will be tested and evaluated in terms of its goals and contributions in comparison to previous works, mathematical modeling and theoretical analysis to show the applicability and effectiveness of the solution. All the experimental analysis will be done using MATLAB software.

1.6 Scope and Limitations

The scope of this research is the design and implementation of a deterministic sensor node deployment using wireless sensor network system in precision agriculture application. The system is designed to increase the coverage area, low cost and ease of deployment by reducing the number of sensor nodes and determining the position of sensor nodes with a concern about the shape of the monitored farmland and which is applicable from small to large scale farmlands.

However, this work does not focus on heterogeneous WSN (i.e., consists of sensor nodes with different ability, such as different computing power and sensing range) and other deployment strategies other than triangle node deployment strategy. Moreover, it doesn't directly focus on energy consumptions. Hence, we are observing the effect of sensor node deployment scheme in energy consumption since the position of sensor nodes can affect the energy consumption, network lifetime, coverage, etc.

1.7 Application of Results

Precision agriculture is the ability to use techniques, technologies and management strategies to enhance crop production. WSN is a main technology to overcome the agricultural problem in precision agriculture. In this thesis, we focus on node deployment approach that enables to produce a node deployment scheme for both regular and irregular shapes of the monitored area in precision agriculture. This helps reduce problems associated with inefficient use of resources in traditional farming to maximize production. Moreover, it would contribute to increased crop yields and the improvement of quality in the agricultural field by dealing with the design, optimization and development of a practical solution for application to precision agriculture monitoring using WSNs. This helps to reduce losses of water, fertilizer, pesticides, etc and to determine the optimal quantities of agricultural inputs (like irrigation, etc.) required in different locations and at different times in the monitoring field.

1.8 Organization of the Thesis

The rest of the thesis is organized as follows: Chapter 2 presents the literature review on wireless sensor networks, sensor nodes components, unique features and design, resource constraints of WSNs and precision agriculture, sensor node deployment and routing protocols. Chapter 3 discusses about different research works related to sensor node deployment in wireless sensor networks. In Chapter 4, we present the design of the proposed system. It discusses about the design considerations, system design and major components. Chapter 5 presents an implementation and discussion of the experimental result and its evaluation. Finally, conclusions, contributions and future work are presented in Chapter 6.

Chapter 2: Literature Review

In this Chapter, a number of literatures have been reviewed to provide background information about wireless sensor networks, sensor nodes components, unique features and design, resource constraints of WSNs and precision agriculture. Then, we will introduce one of the important tasks in WSNs called sensor node deployment. Furthermore, the different routing protocols for WSN including their classification and performance metrics of routing in WSNs are also reviewed and presented.

2.1 Wireless Sensor Networks

A Wireless Sensor Network is a type of wireless network which consists of a collection of wireless devices called sensors which are capable of sensing, processing and communicating. The sensor nodes are distributed in a geographical area, which are deployed either inside the phenomenon they monitor or very close to it. These sensors have the ability to communicate either among each other or directly to a Base Station (i.e., a node capable of connecting the sensor nodes to an existing communication infrastructure or to the Internet where the user can have access to the reported data). Each of these nodes gathers the information from its surrounding environment and sends the sensed data to the Base Station (BS) or sink node [4, 5, 13, 14]. The architecture of a WSN system comprises of a set of sensor nodes and a base station that communicate with each other and gather local information to make global decisions about the physical environment. Example architecture is illustrated in Figure 2.1 [63].

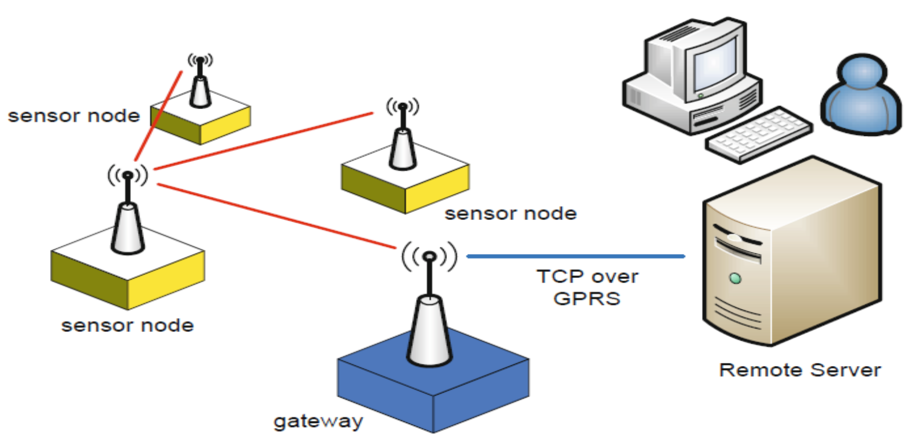

Figure 2.1: Wireless Sensor Network System

Basically, a sensor node is comprised of four basic units: a sensing unit, a processing unit, a transceiver unit and a power unit as it is shown in Figure 2.2. They may also have application dependent additional components such as a location finding system, a power generator and a mobilizer. Sensing units are usually composed of two subunits: sensors and analog to digital converters (ADCs). The analog signals produced by the sensors based on the observed phenomenon are converted to digital signals by the ADC, and then fed into the processing unit. The processing unit, which is generally associated with a small storage unit, manages the procedures. A transceiver unit connects the node to the network. One of the most important components of a sensor node is the power unit. Power units may be supported by a power unit such as solar cells. Most of the routing techniques and sensing tasks require knowledge of location with accuracy. Thus, it is necessary that a sensor node has a location finding system. Sometimes a mobilizer may be needed to move sensor nodes when it is required to carry out the assigned tasks [4, 5, 13, 14]. These sensor nodes are deployed in large farm-fields to collect data to determine the optimal application of agricultural inputs to maximize production and minimize the impact on the environment [1].

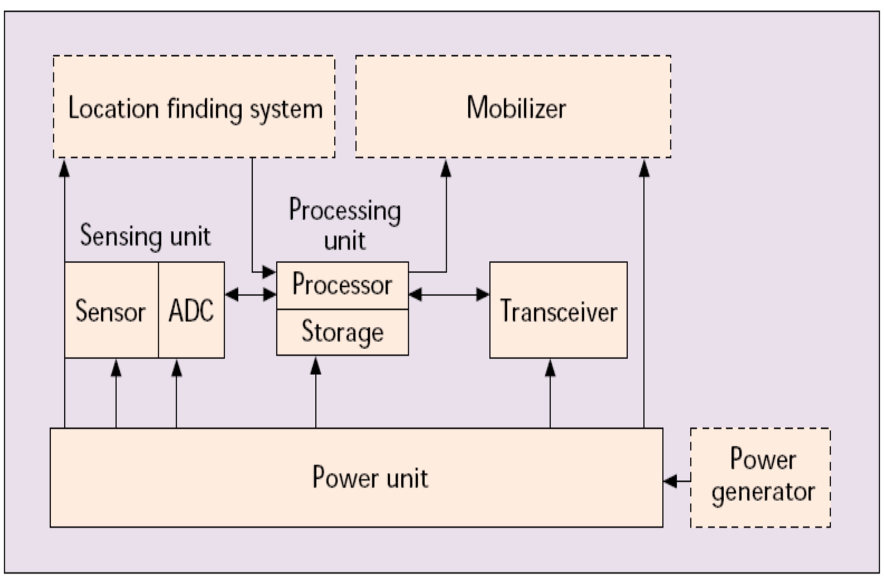

Figure 2.2: Sensor Node Components

Wireless sensor networks have gained a lot of attention for their broad applications and potentials. The use of wireless sensor networks was motivated by military applications such as battlefield surveillance. Today such networks are used in many industrial and consumer applications, industrial process and machine health monitoring, fire detection, water/wastewater monitoring and precision agriculture [23, 37].

A wireless sensor network is a major technology that drives the development of precision agriculture. Precision Agriculture (PA) is one of the most promising applications areas of WSNs. Improving the yields of agricultural farms could be achieved by automating the activities to monitor different attributes in the farm. PA refers to the use of information and control technologies in agriculture to enhance crop production. Agricultural inputs such as irrigation and fertilizers can be applied in preferred quantities as determined by modeling of crop growth patterns to maximize the crop yield and to minimize the impact on the environment [1, 13, 28, 35]. Continuous measurement of temperature, humidity, soil conditions, the fertilizers and pesticides help to apply just the required amount at every point in the farm location. This can therefore be performed by a network of hundreds or thousands of sensors in a field [18].

The concept of precision agriculture has been around for some time now. Blackmore in 1994 [31] defined it as a comprehensive system designed to optimize agricultural production by carefully tailoring soil and crop management to correspond to the unique condition found in each field while maintaining environmental quality. But, it was unprofitable and the instances in which was implemented were few and infrequent [2]. However, the advancements in the field of sensing, computing and communications technologies have significantly brought down the cost of deployment and running of a feasible precision agriculture framework. Emerging wireless technologies with low power needs and low data rate capabilities have been developed for precision agriculture [32]. The wireless sensors are cheap enough for wide spread deployment and offer robust communication through redundant propagation paths [33]. So WSN has become a promising technology for precision agriculture and we can make proper decision for each zone in the farm using WSN in precision agriculture [37]. Now, precision agriculture is being applied in different crops in different countries like Egypt [38], India [39], Brazil [41], Morocco [18], and Malawi [40], etc.

Wireless sensor networks have all the basic features of ad hoc networks but several unique features exist in WSNs that do not exist in general ad hoc networks. Some of the characteristic features of sensor networks include the following: [23, 24, 30]

- Number of nodes can be orders of magnitude higher.
- Sensor nodes are densely deployed.
- Sensor nodes are prone to failure.
- Frequent topology changes due to factors such as node failures, node additions and environmental interference.
- Communication is typically data-centric rather than address-centric, meaning that routed data may be aggregated/compressed/prioritized/dropped depending on the description of the data.
- A large number of broadcasts are sent in WSNs for various stages of network operation like network set up, neighborhood discovery, data transmission and network maintenance.
- Limited storage, processing and power capabilities
- There is no fixed standard of node identifiers in WSNs.

These unique features of WSNs makes the protocols designed for Wireless Ad hoc Networks not usable in WSNs directly.

Unlike traditional networks, a WSN has its own design and resource constraints. Resource constraints include a limited amount of energy, short communication range, low bandwidth and limited processing and storage in each node. Design constraints are application dependent and are based on the monitored environment. The environment plays a key role in determining the size of the network, the deployment scheme, and the network topology. The common design factors that influence WSNs are reliability, scalability, production costs, hardware constraints, network topology, operating environment, transmission media, and energy consumption [29, 47].

2.2 Sensor Node Deployment

The positions of nodes have a dramatic impact on the effectiveness of a WSN and the efficiency of its operation. There are different deployment demands and optimization goals in different environments because node deployment in wireless sensor networks is application dependent [9, 11]. The positioning of sensors affects coverage, communication cost, resource management and routing. The term positioning of nodes in a sensor network seems to be more general and divided into two fundamental issues. These are localization (locating where the nodes are placed) and deployment/placement (determining where the nodes should be placed) [15]. The positions of sensor nodes (their deployment) must be in such a way to provide maximum coverage with longer lifetimes. In this section, we present the literatures that focus on sensor deployment strategies in WSNs.

Node deployment is a fundamental issue to be solved in wireless sensor networks. A proper node deployment scheme can affect network functions such as routing, data fusion, communication, etc. Furthermore, it can extend the lifetime of WSNs by minimizing energy consumption [7]. A good deployment should consider both *coverage* (i.e., every location in the sensing field is monitored by at least one sensor or every point in it must be covered by at least one sensor without allowing any uncovered points); it is used to determine the quality of service of the networks [7] and *connectivity* (i.e., no sensor gets disconnected or the ability to report information to the sink node) [6] since both are basic requirements in a wireless sensor network.

Careful node placement can be a very effective optimization means for achieving the desired design goals. For cost-effective deployment, it is critically important to determine optimal locations for these sensor nodes. The locations of the sensor nodes strongly affect the energy consumption, operational lifetime, and sensing coverage [44]. Thus, careful sensor node placement is needed. Romoozi *et al*. [45] stated that there is a tradeoff between energy consumption of sensor nodes and network coverage. Closer sensor nodes will reduce the energy consumption but the network coverage will become smaller. It can not only reduce the node redundancy and the network costs, but also can prolong the network lifetime. Therefore, node deployment influences the network’s effectiveness in the whole WSN and an optimal deployment of sensor nodes has a strong influence on the performance of a WSN [20].

The typical problems that have been encountered during deployment can be classified in to four classes according to the number of nodes [26].

Node problems: involve only a single node. Node death, node reboot, wrong sensor readings are problems found in a node.

Link problems: involve two neighboring nodes and the wireless link between them. In here, discovering neighbors, message loss, latency and network congestion are encountered as link problems.

Path problems: involve three or more nodes and a multi-hop path formed by them. These path problems include discovering paths and loops.

Global problems: are properties of the network as a whole. Partitions are considered as global problems.

2.2.1 Classification of Node Deployment

We can categorize the placement strategies into static and dynamic depending on their application. The choice of the deployment scheme depends highly on the type of sensors, application and the environment that the sensors will operate in [9, 11, 29].

The static deployment chooses the best location according to the optimization strategy and location of the sensor nodes has no change in the lifetime of the WSN. Static network operation models often assume periodic data collection over preset routes. At present, the static deployment includes the deterministic deployment and the random deployment.

In *deterministic situations*, the locations of sensor nodes are determined prior to deployment and the sensors are manually placed. Furthermore, the data is routed through pre-determined paths. The WSN coverage in predetermined deployment is improved by carefully planning the positions of the sensors prior to their deployment [51]. Whereas in *self-organizing systems*, the sensor nodes are scattered randomly creating an infrastructure in an ad hoc manner. Different with the deterministic deployment, the random deployment is also preferable in some applications where the network locations are inaccessible like forest surveillance, wildlife monitoring, earthquake observation, and battlefield. Large quantity of wireless sensor nodes are thrown in these areas, and then a self-organized network formed.

The dynamic deployment may be executed by robots. In order to make the sensor networks perform to the maximum possible performance, sensor nodes need automatically move to proper locations, then start to work.

A sensor network deployment can also be categorized as either a dense deployment or a sparse deployment. A dense deployment has a high number of sensor nodes in the given field of interest while a sparse deployment would have fewer nodes. The dense deployment method is used in situations where it is very important for every event to be detected and reported. Sparse deployments may be used to minimize network cost while attempting to cover a large area as possible with the minimum number of sensors or when we want to achieve maximum coverage using the bare minimum number of sensors. Random deployment of sensor nodes usually results in dense networks, so it is necessary to deploy additional sensors in order to achieve total coverage if the sensor nodes are stationary.

A WSN typically has little or no infrastructure. It consists of a number of sensor nodes working together to obtain data about the environment to monitor a region. There are two types of WSNs: structured and unstructured. An unstructured WSN is one that contains a dense collection of sensor nodes. Sensor nodes may be deployed in an ad hoc manner into the field. Once deployed, the network is left unattended to perform monitoring and reporting functions. In an unstructured WSN, network maintenance such as managing connectivity and detecting failures is difficult since there are so many nodes. In a structured WSN, all or some of the sensor nodes are deployed in a pre-planned manner. The advantage of a structured network is that fewer nodes can be deployed with lower network maintenance and management cost. Fewer nodes can be deployed now since nodes are placed at specific locations to provide coverage while ad hoc deployment can have uncovered regions [29].

2.2.2 Objectives of Sensor Node Deployment

Most of the proposed node deployment schemes in the literature have focused on increasing the coverage, enhance network connectivity, prolong the network lifetime and data fidelity. A number of secondary objectives such as tolerance of node failure and load balancing have also been considered. In general, the optimization objectives of sensor nodes deployment is discussed as follows [9, 11, 15]:

a. Coverage Area

Maximizing the coverage area of the network is the objective that has always received the most attention in wireless sensor network deployment. It is related to energy saving, connectivity and network reconfiguration. It mainly solves how to deploy the sensor nodes to achieve effective coverage of the service area so that every point in the service area is monitored at least by one sensor node. A good coverage is crucial for the effectiveness of wireless sensor networks.

b. Network Connectivity

Network connectivity is the communication between the wireless sensor nodes, the node and base station, base station and the client, the client and the server. Connectivity requires that the network is not partitioned in terms of nodes' communication capability (i.e., no sensor gets disconnected). Note that coverage is affected by sensors' sensitivity, while connectivity is influenced by sensors' communication ranges.

c. Network Lifetime

One of the most important requirements of WSN is to reduce the energy consumption. Extending network lifetime has been the optimization objective for sensor node deployment. The positions of nodes significantly impact the network lifetime. Hence, there is a need for energy efficient communication and routing techniques that will increase the network lifetime.

d. Data Fidelity

One of the important design goals of WSNs is ensuring the credibility of the gathered data. A sensor network basically provides a collective assessment of the detected phenomena by fusing the readings of multiple independent (and sometimes heterogeneous) sensors. Data fusion enhances the fidelity of the reported incidents by lowering the probability of false alarms and of missing a detectable object.

2.3 Routing Protocols for WSN

Many routing, power management and data dissemination protocols have been specifically designed for WSNs, where energy consumption is an essential design issue, which preserves longevity of the network to maintain a reliable information delivery. Data aggregation and data fusion are necessary for efficient and effective communication between these sensor nodes. Routing protocols have a critical role in most of these activities [4, 36]. A routing protocol is an algorithm used by nodes to determine a path for forwarding packets toward a destination [42].

Routing in WSNs is a challenging task than routing in contemporary communication and wireless ad-hoc due to several characteristics. The challenges are summarized as follows [3, 36]:

- First of all, it is not possible to build a global addressing scheme for the deployment of a large number of sensor nodes. Therefore, classical IP-based protocols cannot be applied to sensor networks.
- Second, in contrary to typical communication networks almost all applications of sensor networks require the flow of sensed data from multiple regions (sources) to a particular sink.
- Third, generated data traffic has significant redundancy in it since multiple sensors may generate same data within the vicinity of a phenomenon. Such redundancy needs to be exploited by the routing protocols to improve energy and bandwidth utilization.
- Fourth, sensor nodes are tightly constrained in terms of transmission power, on-board energy, processing capacity and storage and thus require careful resource management.

Due to such differences, many new routing protocols emerge continually to solve the challenging tasks of routing in sensor networks [36].

2.3.1 Classification of Routing Protocols for WSNs

WSN routing protocols may be classified in different ways, according to the way routing paths are established, according to the network structure, according to the protocol operation and according to the initiator of communications. Figure 2.3, which were compiled from different sources [3, 4, 5, 36, 46], shows the classification of WSN routing protocols.

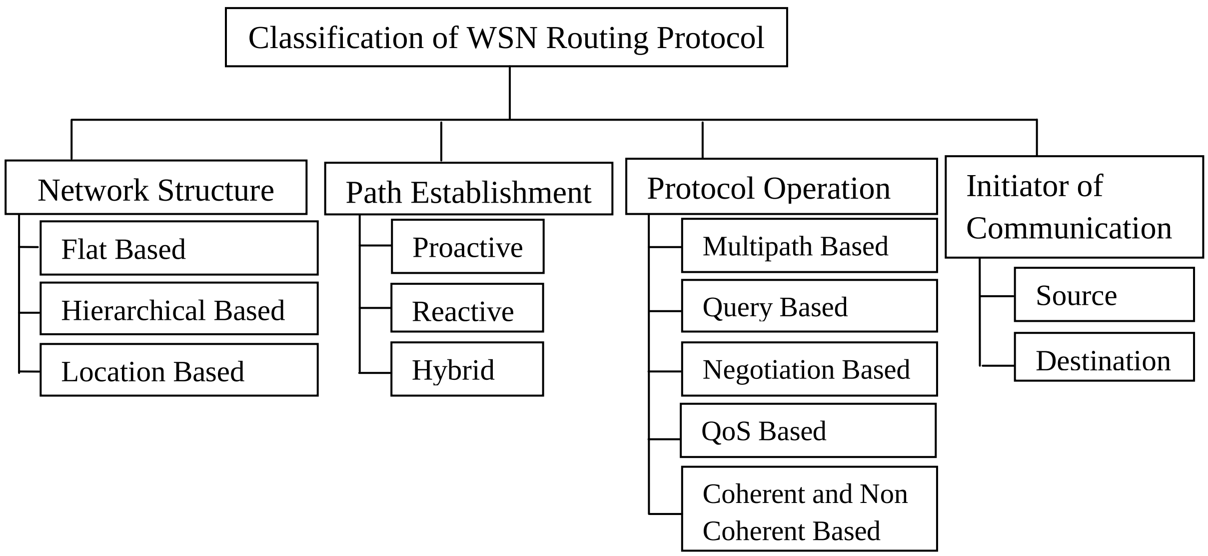

Figure 2.3: Classification of WSN Routing Protocols

a. Classification Based on Network Structure

Depending on the network structure, routing in WSNs can be divided into *flat-based* routing (*data-centric* routing), *hierarchical-based* routing, and *location-based* routing.

In flat-based routing, all nodes are typically assigned equal roles or functionality and sensor nodes collaborate together to perform the sensing task. Disadvantage of this routing technique is data redundancy and energy consumption.

In hierarchical-based routing, nodes will play different roles in the network. The main aim of hierarchical routing is to efficiently maintain the energy consumption of sensor nodes by means of involving them in multi-hop communication within a particular cluster or hierarchical schemes. Moreover, performs data aggregation and fusion in order to decrease the number of transmitted messages to the sink.

In location-based routing, sensor nodes' positions are exploited to route data in the network. In most cases location information is needed in order to calculate the distance between two particular nodes so that energy consumption can be estimated. Since there is no addressing scheme for sensor networks like IP-addresses and they are spatially deployed on a region, location information can be utilized in routing data in an energy efficient way.

b. Classification Based on Path Establishment

To reduce the redundancy in flat-based routing, proactive, reactive, and hybrid routing protocols were developed depending on how the source finds a route to the destination In *Proactive* routing, all routes are computed before they are really needed and each node has one or more tables that contain the latest information of the routes to any node in the network. The *Proactive* protocols are not suitable for larger networks, as they need to maintain node entries for each and every node in the routing table of every node. This causes more overhead in the routing table leading to increases energy consumption. To reduce this regular update, *Reactive* Routing protocols were developed. Routes are computed on demand. Reactive routing protocols discover routes on demand which means only when a source node wants to communicate with destination. The major drawback with *Reactive* routing technique is high routing overhead due to *RouteRequest* (RREQ), *Route Reply* (RREP) & *Route Error* (RERR) messages to maintain the network and there is higher energy consumption [5]. Finally, we have observed that the *Reactive* protocol is far better than *Proactive* protocol in terms of performance metric like routing overhead and throughput. On the other hand, hierarchical scheme namely LEACH, consumes less energy than *Reactive* routing protocol. When sensor nodes are static, it is preferable to have table-driven (proactive) routing protocols rather than reactive protocols.

c. Classification Based on Protocol Operation

The protocols are classified into multipath-based, query-based, negotiation-based, QoS-based and Coherent and non-coherent processing routing techniques depending on protocol operation.

Multipath routing protocols: Multiple paths are used to enhance network performance. It includes the algorithms that route the data through a path whose nodes have the largest residual energy. The path is changed whenever a better path is discovered.

Query based routing protocols: The destination nodes propagate a query for data (sensing task) from a node through the network and a node having this data sends back the data to the node that matches the query to the query that initiates. Usually these queries are described in natural language, or in high-level query languages.

Negotiation based routing protocols: In order to eliminate redundant data transmissions, these use high level data descriptors through negotiation. Based on the resources that are available to them, communication decisions are taken. The main idea of negotiation based routing in WSNs is to suppress duplicate information and prevent redundant data from being sent to the next sensor node or the base-station by conducting a series of negotiation messages before the real data transmission begins.

QoS-based routing protocols: the network has to balance between energy consumption and data quality. The network has to satisfy certain QoS metrics (delay, energy, bandwidth, etc. When delivering data to the Base Station, the network has to balance between energy consumption and data quality.

Coherent and non-coherent processing: Data processing is a major component in the operation of wireless sensor networks. Hence, routing techniques employ different data processing techniques. In non coherent data processing routing, nodes will locally process the raw data before being sent to other nodes for further processing. The nodes that perform further processing are called the aggregators. In coherent routing, the data is forwarded to aggregators after minimum processing.

d. Classification Based on Initiator of Communication

Depending on the initiator of communication, the protocols are classified into source and destination. Communication can be initiated either by the source of the data or by the destination. In *source initiated* protocols, the nodes send data to the base station soon after they take new measurements. Source initiated protocols use either time driven or event driven data reporting. *Destination initiated* protocols use query driven reporting and the nodes respond to the queries that they receive. Destination initiated protocols incur a large amount of overhead because the requests are usually flooded through the network.

2.3.2 Performance Metrics of Routing in WSNs

The performance of routing is measured based on quantifiable parameters called performance metrics [4].

Network Lifetime: is defined as the number of data aggregation rounds till x % of sensors die where x is specified by the system designer. For instance, in applications where the time that all nodes operate together is vital, lifetime is defined as the number of rounds until the first sensor is drained of its energy.

Data accuracy: The definition of data accuracy depends on the specific application for which the sensor network is designed.

Latency**:** is defined as the delay involved in data transmission, routing and data aggregation. It can be measured as the time delay between the data packets received at the sink and the data generated at the source nodes.

Average Energy Dissipated: This metric shows the average dissipation of energy per node over time in the network.

Total Number of Nodes Alive: This metric is also related to the network lifetime. It gives an idea of the area coverage of the network over time.

Bandwidth, Capacity and Throughput: These indicate the capacity of data which can be sent over a link within a given time, however since the data size is very small bandwidth rarely matters.

Hop Count: Number of hop in communication determine the cost of path, and eventually the energy consumed in the process.

Furthermore, the most common challenging factors affecting the routing protocols design are node deployment, node/link heterogeneity, data reporting model, energy consumption without losing accuracy, scalability, network dynamics, Quality of Service, data aggregation, data delivery models, node capabilities, transmission Media, coverage, fault tolerance [3, 4, 5, 30, 36].

Chapter 3: Related Work

In this Chapter, different research works related to sensor node deployment in wireless sensor networks are reviewed. Those works follow different approaches to ensure coverage in WSNs. These works are categorized based on the node deployment approaches they used.

3.1 Force Based

There are different papers which implement force based deployment strategies that rely on the sensors mobility. Using virtual repulsive and attractive forces, the sensors are forced to move away or towards each other so that full coverage is achieved. The sensors will keep moving until equilibrium state is achieved where repulsive and attractive forces are equal. Thus they end up cancelling each other [51, 52, 59]. The work presented below is an example in this category.

A virtual force algorithm (VFA) as a sensor deployment strategy is proposed to enhance the coverage after an initial random placement of sensors and sensors will be moved by the attractive and repulsive forces of neighboring sensors with obstacles [34]. For a given number of sensors, VFA attempts to maximize the sensor field coverage within a cluster in cluster-based Distributed Sensor Networks (DSNs) using a combination of attractive and repulsive forces. Both the binary sensor detection model and probabilistic detection model are considered to handle sensors with both high and low detection accuracy and once the effective sensor positions are identified, a one-time movement is carried out to redeploy the sensors at these positions. A novel target localization approach is also proposed based on the information received from the sensor and the knowledge of the sensor deployment within the cluster. The cluster head executes a probabilistic scoring-based localization algorithm to determine likely position of the target. But the deployment only considers random deployment. Random deployment is not preferable for some applications like precision agriculture and the deployment cost is high.

3.2 Biologically Inspired Techniques

A number of research papers choose the artificial intelligence (AI) approach, particularly on biologically inspired techniques, in solving optimization problems in WSNs including the work presented below.

The work in [10] proposed a sensor node placement technique that utilizes a new biologically inspired optimization technique that imitates the behavior of territorial predators in marking their territories with their odors, known as territorial predator scent marking algorithm (TPSMA). It uses the maximum coverage objective function to be able to provide maximum coverage with longer lifetimes. Territorial predator scent marking behavior can be adopted in designing the sensor node placement technique where the territory of a sensor node can be scent-marked. This is done based on the scent marking by predator on the area that has the highest food resources. Then a sensor node will identify its monitored location through scent-matching by taking into consideration TPSMA with a single objective function that is the maximum coverage ratio. A study has been carried out by comparing the performance of the proposed technique with the minimax and lexicographic minimax (lexmin) sensor node placement schemes in terms of coverage ratio and uniformity. According to simulation results, the WSN deployed with maximum coverage TPSMA sensor nodes placement scheme offers considerably higher coverage ratio and lower uniformity value compared to minimax and lexmin schemes and expected to provide as long lifetime as possible.

3.3 Grid Based

Here, grid based deployment strategies are used to determine sensors positions, thus, sensor nodes are deployed at predetermined positions: triangular lattice, square or hexagonal grid. It is considered as a good deployment strategy in WSNs [51, 52, 59]. There are a number of works that belong to this category including the works presented below.

The work in [7] investigates random and deterministic node deployments for large-scale WSNs. It uses coverage, energy consumption, and message transfer delay as performance metrics and Triangle-Hexagon Tiling (THT) was also proposed in a comparison with random and square grid patterns in case of coverage, energy consumption and worst-case delay. They also presented a novel strategy for calculating the relative frequency of exactly k-covered points which apply k-coverage maps using basic geometry. The k-coverage map was modeled for square grid and THT deployments. For a uniform random deployment, it can be achieved by applying systematic sampling over a given field. Finally, the tradeoffs between these performance metrics were analyzed for each deployment strategy to show which strategy is preferable under the primary factors: the number of nodes, the number of sinks, and the sensing range. The result obtained from the experiments shows that THT is a well performing node deployment strategy for energy consumption and worst-case delay for WSN applications.

The work in [16] focuses on the different deterministic deployment patterns for Wireless Sensor Networks namely a regular hexagon based, an octagon-square based and a tri-beehive pattern for sensor nodes deployment and analyzed all the three sensor node deployment strategies on the basis of their average coverage provided in the application field. The K-coverage map has been studied to resolve the coverage issue which is the usual way of specifying conditions on coverage. The K-coverage map is used to check all possible coverage areas and to analyze the relative frequency of exactly K-covered points. The quality of coverage performance was measured using the idea of the K-coverage map for all the three considered node deployment strategies. Finally, it concluded that the Tri-Beehive node deployment pattern is a better option for Wireless Sensor Networks in terms of coverage than the other two strategies.

The work in [53] presents a novel sensor deployment algorithm based on the optimum node layout, called the adaptive triangular deployment (ATRI) algorithm, for large-scale unattended mobile sensor networks in order to maximize coverage area and minimize coverage gaps and overlaps by adjusting the deployment layout of nodes close to equilateral triangulation, which is proven to be the optimal layout to provide the maximum no-gap coverage. By using only the location information of one-hop neighbors for the adjustment of each node, the algorithm can make the overall deployment layout close to equilateral triangulations. To reduce the back-and-forth movement of nodes, the distance threshold strategy and movement state diagram strategy are adopted, which limit the oscillation and reduce the total movement distance of nodes. The simulation results show that the ATRI algorithm achieves a much larger coverage area and smaller average moving distance of nodes than existing algorithms. It is also shown that the ATRI algorithm is applicable to practical environments and tasks such as working in both bounded and unbounded areas and avoiding irregularly shaped obstacles. In addition, the density of nodes can be adjusted adaptively to different requirements of tasks. Even if the work seems much more like ours, the work focuses on mobile sensor nodes but in our case the nodes are deployed statically (i.e., the position of sensor node has no change in the entire lifetime of the WSN). Moreover, they don't consider the shape of the farm.

In [21], a tiling-based wireless sensor network deployment approach is proposed based on the polygon model for sensor nodes with directional sensing areas. In the tiling-based deployment approach, a hexagon tile is first generated from the polygon that represents the sensing area of a given directional sensor. Then, the deployment area is filled with generated tiles based on the calculated intervals. In order to maintain the network connectivity among sensor nodes, the intervals between tiles are adjustable. The proposed tiling based WSN deployment algorithm under the polygon model consists of three phases: Tile generation, Tile placement and Sensing coverage holes reduction. This work focused on the connected area coverage problem under the deterministic WSN deployment to determine the deployment locations of sensor nodes to achieve maximum sensing coverage of the deployment area and maintain network connectivity among deployed sensor nodes. The simulation results show that the proposed deployment approach can reach full sensing coverage under different types of sensor nodes and maintain network connectivity as compared to the sector model based approach in various deployment scenarios.

The work in [2] proposed two grid topologies for precision agriculture using Zigbee wireless sensor network. The topologies guarantee QoS while taking into consideration the limited power and optimization of communication. The simulation result is obtained by taking into consideration different performance metrics for comparing different topologies, including delay, through-put, and load. The WSN system developed in this paper is for use in precision agriculture applications, where real time data of climatology and other environmental properties are sensed and control decisions are taken based on it to modify them. But, this is not efficient, especially when there are arbitrary relationships between communication range (rc) and sensing range (rs). Besides, the proposed work does not take into consideration the geometric feature of each farmland instead it is limited on grid topologies.

The work in [48] focuses on deployment patterns that are able to achieve full coverage and k-connectivity (k<=6) under different ratios of the sensor communication range to the sensing range for homogenous WSNs. They proposed deployment patterns to achieve full coverage and 3-connectivity and full coverage and 5-connectivity for WSN. The authors discovered that there is a hexagon-based pattern that can generate all known optimal patterns. They also proposed a new polygon-based deployment to prove their optimality among regular patterns when Rc/Rs

>=1. As a result the set of patterns to achieve full coverage and k-connectivity (k<=6) is complete.

Another work in [49] proposed a new deployment pattern for WSNs in which sensor nodes are placed on two Archimedean spirals that are nested. Their objectives were to gain higher coverage and greater connectivity by using minimum number of nodes. The result of the proposed deployment is a five-coverage and five-connected network by taking into consideration homogenous sensor network and two dimensional areas. Based on both analytical and simulation results, the proposed model consumes less energy than the other three models such as triangle, square and hexagon. The reason is that in other models the distances of nodes is exactly the same as the communication radius but in their model nodes are placed in distances less than the communication radius, so they consume less energy for sending and receiving packets. Less energy consumption causes higher lifetime and greater fault tolerance.

3.4 Computational Geometry Based

Computational geometry is frequently used in WSN coverage optimization. The most commonly used computational geometry approaches are Voronoi diagram and the Delaunay triangulation [51, 52, 59]. The work presented below is an example under this category.

A more sophisticated deterministic deployment method is proposed in [27]. The authors propose to arrange the sensors in a diamond pattern which would correspond with a Voronoi polygon. The pattern achieves four way connectivity from each of the nodes with full coverage under different ratios of sensor communication range (denoted by Rc) over sensing range (denoted by Rs) for wireless sensor networks. They demonstrated that there exists a hexagon based universally elemental pattern which can be used to generate all other patterns and proposed a new deployment-polygon based methodology to prove the optimality of newly designed patterns. The drawback of this method is that the pattern is not practical for actual deployment. It assumes that the sensing range and the communication ranges of every node are a perfect circle and having the ability to place the sensors in exact locations [13].

3.5 Boundary Based

The proposed works which take into account the boundary of monitored region are presented below.

The work in [54] investigates coverage overestimation and addresses the challenge of designing coverage-guaranteed deployment strategies and proposed two deployment strategies, namely, the Expected-area Coverage Deployment (ECD) and BOundary Assistant Deployment (BOAD) in order to overcome these problems. Extensive simulation experiments have been done to justify correctness of their analysis. The simulation results show that both strategies alleviate the coverage overestimation significantly. They also evaluated their proposed strategies in the context of target detection application. The comparison results demonstrate that if the target appears at the boundary of the monitored region in a given random deployment, the average intrusion distance of BOAD is considerably shorter than that of ECD with the same desired deployment quality. But their proposed work considers randomly deployed sensor nodes and this is not appropriate for precision agriculture since it needs careful and controlled node deployment.

The aim of the work in [6] is to propose an approach which partitions the sensing field into smaller sub-regions based on the shape of the field, and then to deploy sensors in these sub-regions. The sensing field is modeled as an arbitrary polygon possibly with obstacles. An obstacle can have any shape too. So the results may model an indoor environment. In addition, an arbitrary relationship between the communication range and sensing range is allowed, thus eliminating the constraints of existing deployment schemes. Even if the boundaries and obstacles are considered, the algorithm was applicable in indoor environment and has the assumption that all sensors have the same Rc and Rs. This would increase the overlapping coverage between sensors. However, the result can be used in an indoor environment. Therefore the work is limited in indoor environment and fewer nodes are sufficient to form a network.

3.6 Others

A number of approaches and models have been proposed for sensor node deployment in different literatures. We present some literatures in this category which they do not fall under the above categories.

The work in [25] proposes a Billiards algorithm for sensor deployment. The algorithm aims to maximize the coverage of a given monitored field without overlapping among sensor areas by adapting the concepts of billiards physics and collisions laws. The fundamental idea of the billiards algorithm is based on the collision between two or more moving objects with given velocities. According to the mechanical laws, the collided objects repel each other with different velocities. During the deployment process, different characteristics and capabilities of the sensors such as their adjustable sensing ranges, mobility, and initial energy are considered. The proposed algorithm tries to utilize mobile sensors for the benefit of the field coverage. At the same time, it increases the lifetime of the sensors by using only their best sensing ranges. The deployment considers random and deterministic deployment, where the sensors can be homogeneous or heterogeneous. In addition, hostile and non-hostile fields have been taken into consideration. The conducted experiments point out the effect of expansion ratio, iterations between expansions, number of collisions, and mobility, on the overall coverage. The problem in here is the proposed algorithm relies highly on mobile sensor node and it consumes high energy and it wouldn't be suitable for applications like precision agriculture in WSNs.

A polygon model is proposed in [17] for the sensor node with directional sensing area and the corresponding WSN deployment algorithm. The proposed polygon model can represent different shapes of the communication and sensing areas of sensor nodes. The modeling of the sensing area of a sensor node is essential for the deployment algorithm of wireless sensor networks. The polygon model is composed of a list of vertices expressed in polar coordinates. Since the polygon model can use unlimited number of vertices to model the boundaries of an area, it is more suitable to represent various shapes of sensing areas compared to the disk model and the circular sector model. The disk model, the circular sector model, and the proposed polygon model are used to model the sensing area of each sensor node and different deployment algorithms are applied to deploy sensor nodes on a field with and without obstacles, respectively. In addition, a four-step randomized WSN deployment algorithm utilizes the topology control mechanism and scoring process to determine the appropriate deployment positions in order to maintain the network connectivity and improve the gains of the sensing coverage rate for the proposed polygon model.

Another work in [19] proposed a probabilistic model for each distributed cluster to perform data accuracy and energy consumption model in the network with an objective of reducing the number of sensor nodes by estimating a tradeoff between data accuracy and energy consumption in probabilistic approach to select an optimal number of sensor nodes in each distributed cluster. This reduces the node deployment and energy cost in the network. Simulation results show that energy consumption for the total number of sensor nodes deployed in the sensor region decays much faster than the optimal number of sensor nodes selected with respect to time. This increases life time of the network. Additionally, the data accuracy estimation model performs better than information accuracy model in each distributed cluster with respect to data accuracy.

In [22], a deployment and topology control method is presented for heterogeneous sensor nodes with different communication and sensing range based on the irregular sensor model is proposed to approximate the behavior of sensor nodes. An irregular sensor model is proposed based on the radio propagation model inspired from Radio Irregularity Model (RIM) and degree of irregularity (DOI). It assumes that the sensor nodes use the same radio propagation model for communication and sensing. The proposed irregular sensor model will be used to select a proper sensor node location and calculate coverage rate. In this paper, they define a heterogeneous WSN that consists of three types of nodes: sink node, high-end senor node (NH), and low-end senor node (NL). The deployment process has five steps. In the initialization step, a deployment area is initialized based on the configuration file. In the neighbor-info collection step, starting from the sink node, the information of adjacent sensor nodes within the communication range is collected. It can be used to decide the deployment ratio of high-end and low-end sensor nodes. In the candidate generation step, candidate positions are generated according to topology control policies, and a scoring mechanism based on the irregular sensor model is applied to each candidate. After all candidate positions are scored, the candidate with the highest score is selected to deploy a new sensor, which has the most coverage gains while maintaining the communication connectivity to center node. Based on the experimental results obtained, the proposed method can achieve higher coverage rate under the same deployable sensor nodes. Besides, the deployment cost is much lower with different configurations of sensor nodes.

In [12], the authors proposed an algorithm for producing a non-disjoint cover set to sense a field containing a certain number of targets. The nodes are deployed as per the graphical representation of nodes, which helps in easy estimation of number of nodes required to cover a particular area. Moreover this algorithm is carried out to solve the hole problem and to perform efficient monitoring with minimum number of nodes. Here nodes are deployed statically, one by one, sensing each target in a given field, and thus completing the entire field. This algorithm produces cover set, consisting of sensor nodes, which would monitor the field consisting of targets, completely. A number of cover sets can be generated using the same technique to improve the life period. Here the proposed approach has a concept of producing non-disjoint cover set. Non-disjoint cover sets are appropriate for area coverage than disjoint cover set. In disjoint case only one target is covered by one node whereas in the non-disjoint case a node can sense more than one target. This algorithm would help to deploy sensors in random fashion, one by one, completing each target in the field. But the algorithm focuses mainly on random deployment.

In [50] a genetic algorithm was proposed to solve the multi-objective optimization problem of wireless sensor node deployment that provides better optimization. The algorithm also accounts for total number of sensors placed in the set region. Moreover, Floyd-Warshall algorithm has been used for the construction of the spanning tree that considers a general WSN with node transmitting information to the sink using shortest connecting path with the following factors: coverage area, lifetime of the network, energy utilization of the network, and the reliability of the network along with the Sink Routing Hole Problem. Different parameter values and weights are implemented to test the convergence properties and robustness. Several tests were conducted in order to assure that the deployment solution is the optimal. Experimental results show that they have been effectively able to optimize the objectives in a finite time.

3.7 Summary

All the assessed works have different direction towards sensor node deployment using WSNs. But none of the approaches considers the given topology of each monitored region in order to produce the appropriate node deployment scheme in agriculture. This shows that there is a need for further research work to enable WSNs for monitoring of precision agriculture on sensor node deployment. Therefore, the primary focus of this thesis is on the development of a sensor node deployment approach that can generate optimal node deployment schemes for a given geometric feature of monitored region. This approach computes the minimum number of nodes needed to construct the system and determine optimal allocation of sensor nodes. This approach has to meet various requirements, such as keeping the network connectivity, maximizing the coverage, minimizing the cost of deployment, etc. So our solution is intended to fulfill these issues which were not addressed by the works reviewed. Finally we will choose a routing strategy to evaluate the performance of the proposed node deployment scheme.

Chapter 4: Design of the Proposed Node Deployment Approach

This Chapter presents the design of the proposed shape based customized node deployment approach monitoring using wireless sensor networks. First we will discuss the general overview of the proposed system. Then, the design considerations that we are taking into account while building the proposed system will be presented. Finally, the proposed model and architecture including the phases along with the components with the designed pseudo codes will be presented.

4.1 Overview

Node deployment is a process of determining where the sensor nodes should be placed which is an important issue to be solved in wireless sensor networks and is application dependent. Since the position of nodes have a great impact on the effectiveness of the WSN and the efficiency of its operation, the WSNs can be carefully managed through planning where the sensor nodes are to be placed in a careful way. Hence, this work aims to present an approach which will enable to construct a sensor network with the minimum number of sensor nodes which are deterministically deployed with corresponding node deployment scheme. This scheme is intended for precision agriculture monitoring for a given shape of farmland with a network topology in a way that achieves the desired design considerations such as coverage, lifetime, cost of deployment, etc. Here, the position and the number of nodes are determined prior to deployment and deploying the sensor nodes is made in an optimal way using equilateral triangle arrangement with Delaunay triangulation.

4.2 Design Considerations

There are a number of factors that should be taken into consideration when designing and implementing the proposed system. The required design considerations include the following and they are described in the sequel.

- Coverage Area
- Network Lifetime
- Cost and Ease of Deployment

- Size of the Network/Number of Nodes
- Adaptability

4.2.1 Coverage Area

The main objective of the sensor network in specific area coverage is to provide high quality information with the interest of that respective region of interest and to prolong network lifetime which is important for most WSN applications [7, 55].

Coverage area means a place where a set of sensors are distributed over a given geographical region to monitor that area and every point in that region must be covered by at least one sensor without allowing any uncovered points [7].

The coverage area depends on both the sensing ranges and the deployment scheme of the nodes. Therefore, node deployment strategy becomes very important to fulfill the desired coverage of a region with fewer number of sensor nodes by determining their position. Thus, our proposed approach aims to deploy the sensor nodes in equilateral triangular layout to maximize the WSN coverage for effective monitoring of precision agriculture since the effectiveness of the Wireless Sensor Networks depends on the coverage provided by the sensor deployment scheme.

4.2.2 Network Lifetime

Network lifetime is the amount of time that a WSN would be fully operative which is the time to the first sensor node failure. The expected lifetime is critical for wireless sensor network deployment [56]. Due to the limited energy resource in each sensor node, we need to reduce the energy consumption of sensors manner so as to increase the lifetime of the network.

Sensor nodes are finite lifetime devices since they are battery powered and recharging or replacing their battery in the network may be difficult or impossible. Because of this reason there are severe limitations in the communication and processing time between all sensors in the network [15, 56, 57]. Therefore, the coverage of the WSN should be guaranteed in order to maximize total network lifetime in our proposed solution. In short, a wireless sensor network designed for precision agriculture monitoring is intended to prolong the network life time by satisfying the desired coverage of a given region with a minimum number of sensor nodes. When the number of sensor nodes decreases, the energy consumption in the network also reduces and the total energy consumption is minimized as well. As a result, the lifetime of WSNs will be extended. Here, we will choose a routing protocol that has a better network lifetime according to our proposed node deployment scheme.

4.2.3 Cost and Ease of Deployment

One of the major benefits of optimal node deployment strategy of wireless systems is to reduce the node deployment cost and ease of installation.

In a sensor network, we have large number of nodes deployed and hence the cost of a single node will affect the overall cost of the sensor network. In short, when the number of sensor nodes increases, the node deployment cost and the total energy consumption in the network also increases. Hence, we have to reduce the node deployment cost by reducing the number of sensor nodes in order to achieve better and accurate observed data from the sensor nodes with less energy consumption [19]. This means we can also optimize the consumption of energy in the whole network as well as the node deployment cost by reducing the number of sensor nodes. Moreover, we don't have to populate the farmland with large number of sensor nodes as much as possible in order to make the activities done on farmland easy and comfortable. Therefore, the cost of each sensor node has to be kept low to make sensor network feasible [58] even if the cost of sensor node is high or low. This all shows that it is critically important to determine optimal locations of sensor nodes and reduce the number of sensor nodes for cost effective deployment since the position of sensor nodes can strongly affect the network lifetime, coverage, energy consumption, etc.

Furthermore, for system deployments to be successful, the proposed system must not be difficult for anyone. So anyone can use the proposed system without expecting to understand the detailed networking and communication mechanism within the wireless sensor network to achieve ease of installation.

4.2.4 Network size/Number of Nodes

An optimal deployment enables us to reduce the number of sensor nodes that helps to achieve data accuracy, reducing the energy consumption and the cost of deployment and maximizing the network lifetime. Hence the proposed node deployment strategy aims at optimizing the number of sensor nodes to construct a WSN and propose the corresponding node deployment scheme.

4.2.5 Adaptability

Adaptability is defined as the ease with which a system or parts of the system may be adapted to changing requirements.

Therefore, the proposed system should be adaptive for any shape of geometric features given by the user and will be able to satisfy the user needs.

4.3 System Architecture

In this section, we have proposed a generalized architecture to provide an optimized sensor node deployment scheme for a given farmland area that considers the aforementioned design requirements. The general architecture of the proposed approach is shown in Figure 4.1. The system contains two modules with different components. These modules are: Deployment and Wireless Sensor Network.

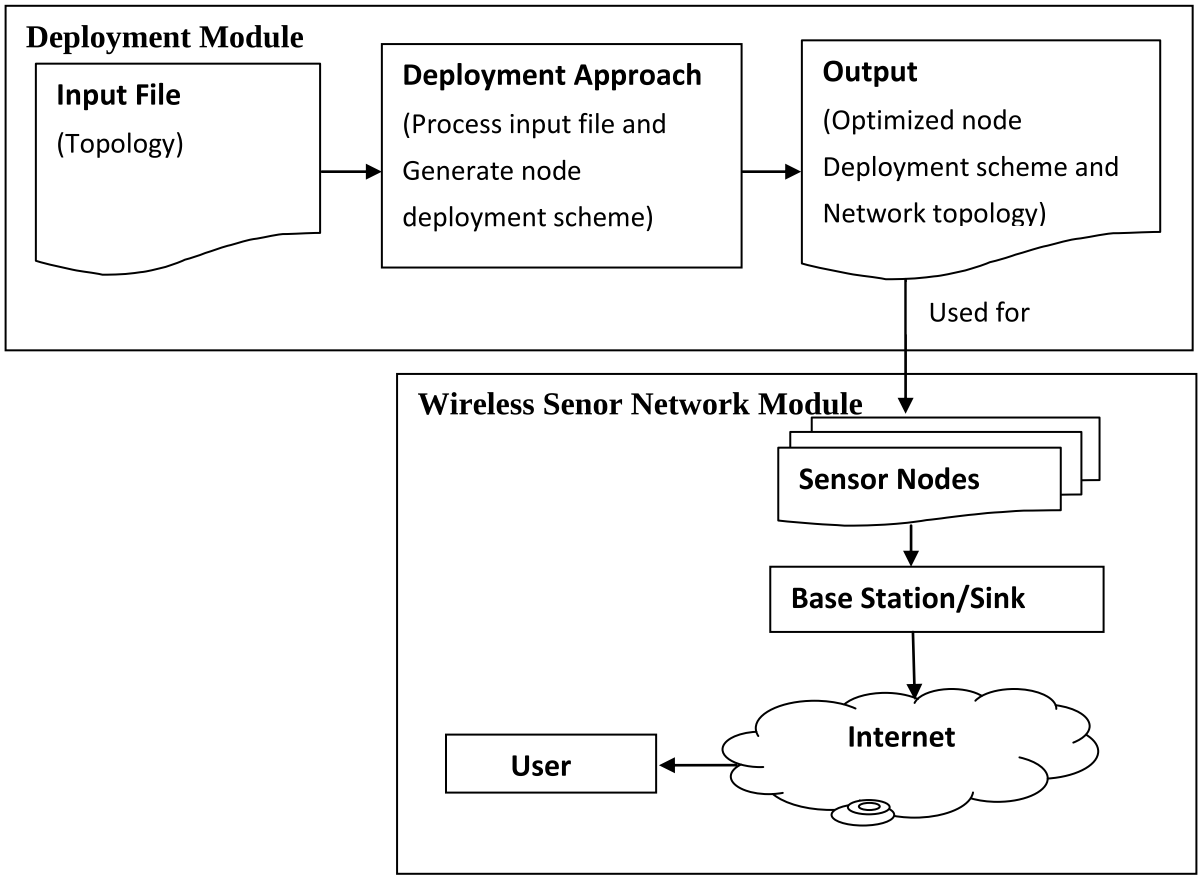

Figure 4.1: A Generic Architecture of the Proposed System

Deployment of nodes in WSNs is a basic issue to be addressed since it can influence the network's effectiveness in the whole WSN and an optimal deployment of sensor nodes has a strong influence on the performance of a WSN. So our proposed approach aims to provide an optimized node deployment scheme that can satisfy the above mentioned desired requirements. Hence, primarily we are using map and shape files as input for the proposed system from Google Earth and ArcGIS, respectively. Then deployment approach will use those inputs in which deterministic deployment is presented with an objective of determining the position and the number of sensor nodes before deployment with the corresponding node deployment scheme for any geometric feature of farmland. Later on the proposed node deployment scheme is used to construct the WSN that consist of a collection of sensor nodes and a base station that communicate with each other and gather local information to make global decisions about the physical environment [23].

4.3.1 Deployment Module

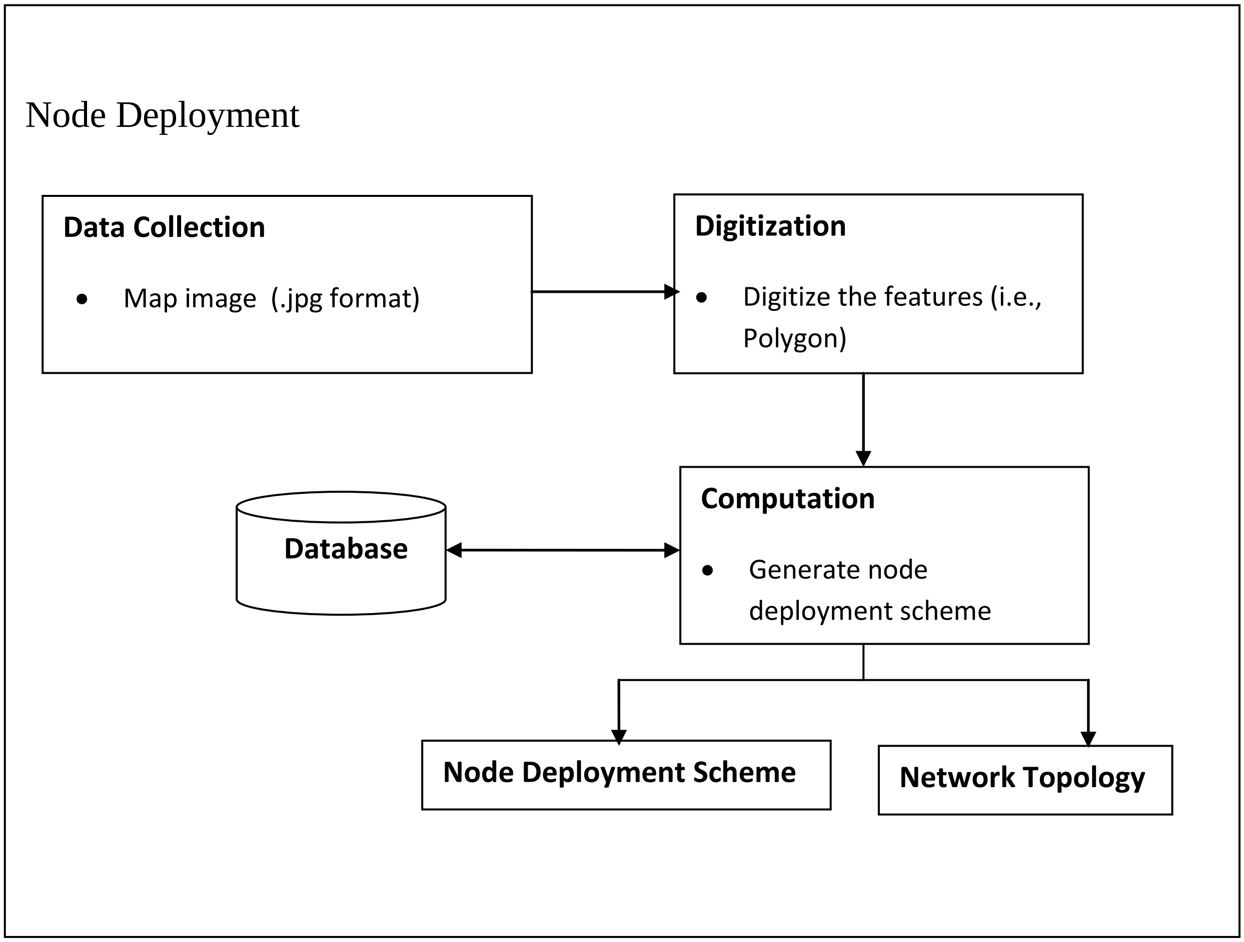

Figure 4.2: Detail Description of Node Deployment Module

As we mentioned above the sensor nodes should be placed properly to effectively monitor the environment. Thus, we intend to present a deterministic sensor node deployment for precision agriculture monitoring that is able to achieve full coverage and other desired requirements of a sensor network by using a minimum number of sensors. The positions of sensor nodes are also determined before deployment with the given boundary of farmland. The nodes are deployed according to a regular pattern in which all the sensors in the network are assumed to be homogeneous with identical transmission range and sensing range and the distances between neighboring nodes are equal. Therefore, all sensor nodes transmit their messages to similar distances. This balances the energy consumption throughout the network even if it is dependent more on routing protocol. The proposed deployment patterns belong to deterministic deployment, static coverage and area coverage as discussed in Chapter 2. In deterministic deployment, the sensors are manually placed and data is routed through pre determined paths. The proposed deployment approach goes from data collection up to generation of node deployment scheme. The detailed description of them is presented below.

Data Collection

In order to capture data our method utilizes Google Earth (i.e., a popular free Internet application which offers a library of satellite imagery and aerial photography of the Earth's surface). In Google Earth, we will add 4 control points on each corner of the image using place mark, record their latitude/longitude coordinates, and extract map in the form of an image. This is required to perform digitization in the next step in ArcGIS. The process is shown in Pseudo code 4.1.

```
Input: Location of Farmland
Process:
BEGIN
      Tag four control points using place mark associated to
      the farmland on Google Earth
      Extract the latitude/longitude coordinates of control
      points
      Extract the satellite image from Google Earth
END
Output: Map image
```

Pseudo code 4.1: A Pseudo code for Capturing a Map of Farmland

Digitization

Now that we have an image map, the next task is to geo-reference the image map based on the four control points created using ArcGIS. If the spatial reference of an image is undefined, assign it a coordinate system by setting the projection of a Data Frame and then define the spatial reference. Coordinate systems can provide a framework for defining real-world locations. In ArcGIS, the coordinate system is used as the method to automatically integrate the geographic locations from different datasets into a common coordinate framework for display and analysis for mapping, visualization, analysis, and so forth. Then, we create an ArcGIS ready shape file that contains our GPS points or geographic data (coordinates) in the form of an XY table (long, lat). With this geo-referenced image, we can now digitize new features from the map (i.e., polygon). In other words, we got a polygon feature layer in ArcGIS. Moreover, ArcGIS has a tool called calculate geometry which allows accessing the geometry of the features in a layer. The tool can calculate coordinate values, perimeter and area of our polygon. So we can easily calculate the area of the polygon or a given geometry of farmland using this tool. Finally all the geographic information can be taken out in the form of shapefiles. The process is shown in Pseudo code 4.2.

```
Input: Map Image
Process:
BEGIN
     Use the coordinates of the control points to geo-
     reference the image/digitize new features from map
     Calculate the area of the polygon
     Extract the shapefile of the digitized farmland
END
Output: Shapefile
```

Pseudo code 4.2: Pseudo code of Geo-referencing and Digitization

Database

It is a data repository used to store basic information needed by the user. It holds the geometric topology of the farm land in .jpg format, the coordinates of the node, the number of nodes, number of grids, coverage percentage, etc. so that it can easily be accessed, managed and updated by the user. We are maintaining such kinds of information for ongoing use. For instance, when the farmer wants to know where the sensors are located, it is easy to track and retrieve the positions of sensor nodes from the database. This makes it more practical. Moreover, it is helpful to generate reports based on the information. So we can easily monitor the farmland and reduce the overall costs. However, this database cannot be used to store and mange the data collected by the sensor nodes. Hence, it keeps only the input and results produced by the proposed system.

Computation

Now we can start our approach which mainly concentrates on finding the optimal deployment scheme for sensor nodes using WSNs. The proposed scheme would cover the maximum area with small number of senor nodes and minimum overlapping as possible with the given radius of the sensing range of a sensor node and the area of a given shape of farmland. The sensor node deployment scheme can affect the design and performance of all aspects of the system. While generating the node deployment scheme, there are different and important tasks to be done and decisions to be made like:

- determine the number of sensor nodes required to effectively cover and monitor a farmland,
- determine the positions of sensor nodes in a given farmland,
- determine the distance between the sensor nodes (sensor density), and
- select the deployment pattern or distribution of the sensor nodes (i.e., types of regular patterns).

Moreover, the architecture and topology of a sensor network has impact on several network aspects, including power consumption, network lifetime and routing mechanisms. For our specific scenario, these should be considered as the desired requirements of the proposed system.

Here, the network architecture and topology design will be delivered with the node deployment scheme. The process of computation is shown in Pseudo code 4.3.

```
Input: Shapefile
Process:
BEGIN
  Read vector features and attributes from shape file
  Find the minimum and maximum for both geographic coordinates (X
  and Y)
  Get the bounding box of the given polygon
  Get all corner points from the coordinate vector (i.e., spatial)
  in shapefile and store it into an array.
  Remove NaN separators from the array.
  Initialize the sensing range Rs
   If the sensing range, the boundary box, the coordinates vector
   are found then
    Distribute the nodes with the bounding box in triangular node
    deployment pattern
    Check the points whether they are in or out of polygon
    Remove nodes outside the boundary
    Determine the position of nodes with a distance √3Rs (i.e.,
    equilateral triangles)
    Count the number of nodes inside the polygon
    The generated points are triangulated using the Delaunay
    triangulation
    Determine the triangle grid
    Shared edges by two triangles are removed
    Generate the node deployment scheme and the network topology
    Store all the outputs into a database
   EndIf
  END
Output: Number of Nodes, the position of nodes, Triangle grids,
Node deployment scheme and Network topology
```

Pseudo code 4.3: Pseudo code of the Proposed Sensor Node Deployment Approach

4.3.2 Wireless Sensor Network Module

This work is intended to present the precision agriculture monitoring system using wireless sensor nodes and base station to record the farmland information. The sensor nodes have several capabilities like sensing, computation and communication. It allows gathering the agricultural parameter like soil moisture, humidity, light intensity, the level of pesticides, fertilizers etc. They are capable to communicate with each other or with the base station in order to exchange and process the information collected by their sensing units using routing technology. Therefore, these sensor nodes send all captured data to a Base Station (BS) for processing and further analysis. This base station is responsible for collection of the data from all the sensor nodes and critically evaluates the data. The information is transmitted to the user/farmer terminal through the Internet. Then, the farmer utilizes the received information to control the agricultural parameters. Generally, this wireless sensor network system and all the control mechanisms improve the effectiveness and efficiency of resources used and they have the ability to maximize production.

4.4 Summary

In this Chapter, the design of the proposed solution is presented. At first, the general overview and the design considerations that are taken into consideration while designing and implementing the proposed system such as coverage area, network lifetime, cost and ease of deployment, size of the network and adaptability are presented. Then, the general architecture of the proposed system is presented. It is composed of two modules (i.e., Deployment and WSN) along with the components. But we mainly concentrate on the deployment module since we aimed to propose a node deployment approach using WSNs. The main components in this module are described in detail. Therefore, these components will be implemented to determine the minimum number of sensors and their position in terms of real spatial coordinates within the given geometry of farmland and evaluated based on the specified design requirements.

Chapter 5: Implementation and Evaluation

In this Chapter, the implementation details of the proposed system are presented. The chapter is organized as follows: the overview of the implementation will be discussed under section 5.1. The assumptions made while implementing the system are presented under section 5.2. The tools used during the implementation of the system will be described under section 5.3. The experimental scenario that will be considered during implementation is presented under section 5.4. Then, the MATLAB implementation and the results will be presented under section 5.5. Finally, the performance of the proposed node deployment system will be measured using numerical computation and theoretical analysis in comparison with other previously proposed node deployment strategies and the result of this evaluation is presented in section 5.6.

5.1 Overview

The proposed sensor node deployment approach enables to generate optimal node deployment schemes for a given geometric feature of farmland. This scheme considers the following parameters such as the number of sensors/network size, location of sensors, network lifetime and coverage. The resulting computation and evaluation is implemented using MATLAB environment (particularly Matlab 2011a).

Utilizing wireless sensor networks in applications like precision agriculture is essential to gather the necessary information and control the technology. Our approach determines the required number of sensors to be deployed so that these sensor nodes cover every point of the monitored region. These nodes are deployed over a network in deterministic fashion. In deterministic node deployment, the position of sensor nodes are known prior to deployment and it is often desirable to determine the required number of nodes. In our work, we consider the practical shape of farmland and the position of sensor network specified by using spatial coordinates. These nodes are arranged regularly using *triangular grid node deployment strategy* over the given shape of farmland, either regular or irregular. The spatial coordinates of the sensor nodes are triangulated using *Delaunay triangulation algorithm* for generating meshes of equilateral triangles with the edge length $\sqrt{3}Rs$ where the vertices represent sensor nodes. Then, a sensor network is constructed with these sensor nodes.

Almost all of the literature we have reviewed considered regular shaped region particularly on square monitored region in their simulation. For both deterministic and random deployment strategies, the works assumed a monitored region of size 100mx100m. Unfortunately, this is not an efficient and appropriate approach to ensure the required network coverage and connectivity in real world applications due to the irregular shape of farmlands. A node deployment scheme for a region may not be appropriate for another region. In our case, we used real shape of farmland and proposed real position of sensor nodes using spatial coordinates instead of using mathematical coordinates like other works. This makes it more practical.

Moreover, most literatures produce their node deployment scheme with a given number of sensors and the area to be covered while in our work a shape of farmland is given. Here, the corresponding number of sensor nodes needed to entirely cover a given region, the position of these sensor nodes and node deployment scheme is calculated. A proper node deployment scheme is one of the effective optimization means for achieving the desired design goals such as coverage, communication cost, routing, etc. It can serve as reference to guide real-world deployment. Thus, the network topology can be established at setup time. With this approach, the coverage of the monitored region can be ensured. In addition to coverage, the position of sensor nodes can affect various network performance metrics like energy consumption, delay, etc.

Performance evaluation of the proposed system and comparisons are made with previously proposed works using mathematical computation, theoretical analysis and simulation.

5.2 Assumptions

In this work, the following assumptions are made:

- The sensor network used in our system is homogeneous, i.e., the sensor nodes are similar in terms of sensing and computation capabilities.
- We use disc model for both sensing and communication. The coverage area of sensor nodes assumed a circular area with known radius and transmission ranges of nodes.
- The communication range Rc of sensor nodes is larger than sensor range Rs of nodes.
- The sensor nodes are static in their place once deployed (i.e., no mobility of sensor nodes).

- Sensor nodes can communicate with other sensor nodes and base stations within their radio transmission range and in which the transmission is omni-directional.
- The sensors are deployed in a two dimensional area.

5.3 Tools

In conducting this thesis work, we have to select different tools that are necessary to collect the data and implement the proposed system. So that Google Earth and ArcGIS are selected to get the map of the farmland and to digitizing it, respectively. During the selection of the implementation tool, we were reviewed different literatures. As a result, MATLAB environment is selected to be the implementation and simulation tool of wireless sensor network (WSN). A detailed description of these tools is presented below.

MATLAB 7.12.0 (R2011a): is recommended to implement our proposed sensor node deployment approach. The name MATLAB stands for matrix laboratory. It is a high performance language for technical computing. It integrates computation, visualization and programming in an easy to use environment where problems and solutions are expressed in familiar mathematical notations. It contains a number of toolboxes such as mapping, database, image processing, etc. It is typically used for data acquisition, algorithm development, modeling, simulation, prototyping, math and computation, data analysis, exploration, visualization, application development, including graphical user interface building.

Google Earth: is a popular free Internet application/geo-browser, which offers a library of satellite imagery, aerial photography, ocean bathymetry, and other geographic data of the entire Earth's surface over the internet.

ArcGIS 9.3: is GIS (geographic information system) software developed by ESRI for working with maps and geographic information. ArcGIS for Desktop consists of a number of separate programs: ArcCatalogue, ArcMap, ArcToolbox. It is designed for advance mapping and spatial analysis. ArcGIS can be used to store geographic data, make maps and analyze spatial data, sharing and discovering geographic information, using maps and geographic information in a range of applications and managing geographic information in a database. Map data is organized into layers so that users can choose which layers they want to view or query.

5.4 Experimental Scenario

The study area lies in Bishoftu town located in south east of Addis Ababa, Ethiopia. It was formerly known as Debre Zeyit, which has modern agriculture areas in Ethiopia, with an area of 4470.5 hectare with clay soil type. The experiment area has a mean annual temperature of 18 °C and the mean annual rainfall is 800 -1200 mm. All these are suitable for the harvesting of different varieties of crops.

The parameters and values for the simulation are shown in Table 5.1.

Table 5.1: Simulation Parameters

Parameter	**Value**
Monitored farmland area (i.e., Irregular)	0.08864 km^2 (88640 m^2)
Sensing range, Rs	10m (0.01 km)

5.5 Implementation and Results

In this section, we discuss about the experiments we made on our simulation model and the results produced.

Wireless sensor networks have been used in different applications in many fields. Sensor node deployment is one of the important aspects in WSNs since it has a vital role on the network's function and lifetime. The deployment of sensor nodes can be either random or deterministic. In this work, we used *deterministic/controlled deployment* strategy in which the locations of the nodes is known before deployment. Since the nodes are located to meet the desired design requirements, it is suitable and acceptable for applications like precision agriculture. Moreover, we considered that the position of the sensor nodes would not change in the lifetime of the WSN (i.e., Static).

We used a disc-based sensing model to represent sensor nodes. This model assumes that the effective communication and sensing ranges of a sensor node is a circle with fixed radius. The sensing and communication ranges of sensor nodes are represented by Rs and Rc, respectively. So a circular field with sensing radius Rs is considered in our approach. Hence, the detection by each sensor is modeled as a circle, the center of the circle denotes the sensor while the radius denotes the detection range Rs of the sensor node as shown in Figure 5.1(a). So these sensor nodes can only sense the environment and detect events within their sensing range according to this model. To realize a total coverage, creating an overlapping area is necessary since the circles do not fit exactly together. However, the area of the overlap must be the smallest as much as possible to cover the farm area with the least number of sensors. The idea is related to circle packing using a specified pattern in a given farm area. So the next step will be selecting the strategy that we are going to follow in our approach which helps to achieve our design requirements (i.e., coverage area, size of the network, cost of deployment, etc).

Hence, we require such an approach that enables to deploy the minimum number of sensor nodes and determine their exact positions within the given geometry of farmland that provides full coverage and better life time. Based on this, we used the *triangular grid deployment,* which helps to determine the position of sensor nodes. Previous works have proved that the triangular node deployment pattern performs better than other regular deployment strategies like square, hexagon and octagon. It has the largest efficient coverage area ratio and uses least number of sensors compared to the other node deployment strategies. Equilateral triangles are used in our deployment approach. The nodes are deployed according to regular triangular pattern and the distance between neighboring nodes are equal as shown in Figure 5.1(a). Thus, the sensor nodes are arranged in an equilateral triangle pattern without gaps and overlaps that is shown in Figure 5.1(b). The sensors are deployed at the vertices of the triangles. Each equilateral triangle is also equiangular, meaning that each angle is pi/3 radians or 60° angles. Then, the edge length/the distance between the sensor nodes need to be known to achieve full coverage, because the distance between pair of nodes should be within the communication range so that the nodes can communicate. The distance should not be too short to make sure the network covers large area. As it will be mathematically proven, full coverage can be achieved when the edge length of each equilateral triangle is $\sqrt{3}$ times the sensing range Rs. Hence, the overlapping of coverage areas can be minimized. Since the communication range Rc of sensor nodes is assumed to be larger than sensing ranges, the connectivity is not an issue. In other words, the coverage and the connectivity are guaranteed when $Rc/Rs \geq \sqrt{3}$. This result naturally provides three-coverage and six connectivity, where every point of the specified area is covered by at least three sensor nodes and, if five neighbor sensor nodes fail, the network remains connected using one sensor node. In our case, the distances between neighboring nodes D depends on the given sensing range while D is √3 times the sensing range Rs. As a result, as the sensing ranges of the sensor nodes increases, the total number of nodes required will reduce.

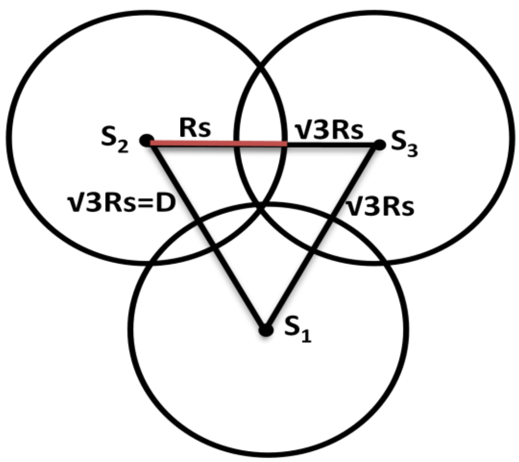

Figure 5.1 (a): Maximum coverage Area with Three Sensors

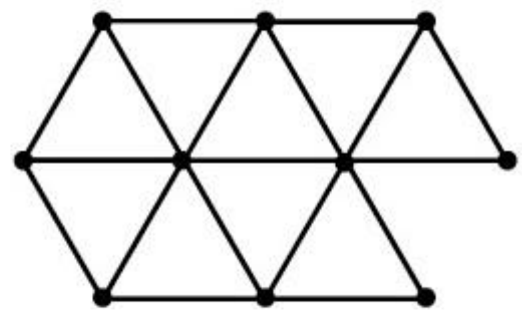

Figure 5.1(b): Regular Triangular Pattern

In this work, the boundary (i.e., the geometric feature of the farmland) is considered, although most literatures ignore the boundary effect (i.e., the geometric feature of the farmland). Therefore we need to generate the circles (i.e., the node coverage area) in range Rs that can cover a given farm area. As much as possible, the number of nodes is minimized. In other words, we need to put several triangles together to form a grid that fills the entire farmland within a given boundary. The boundary helps us to keep the sensor nodes from moving outside the monitored region. Thus, we need to have an algorithm that enables to generate triangular meshes for sensor node deployment in WSNs. So we used one of the most commonly used computational geometry approaches called *Delaunay triangulation algorithm* for generating meshes of triangles (i.e., equilateral) with the edge length √3Rs. It is often used in WSN coverage optimization and formed by three points (sensors) provided the sensors' circumcircles do not contain other sensor nodes [59]. A Delaunay triangulation algorithm starts its work from triangulation and refines until the element qualities are sufficiently high. A triangulation of a set of vertices of sensor nodes is a set of triangles. Each generated triangle is equilateral whose union completely fills the monitored region without gaps and overlaps.

We begin our work by taking a satellite image of a farmland from Google Earth. In Google Earth, we added 4 control points on each corner of the image using place mark. Then, we recorded their latitude/longitude coordinates, and save the image as a .jpg file as depicted in Figure 5.2.

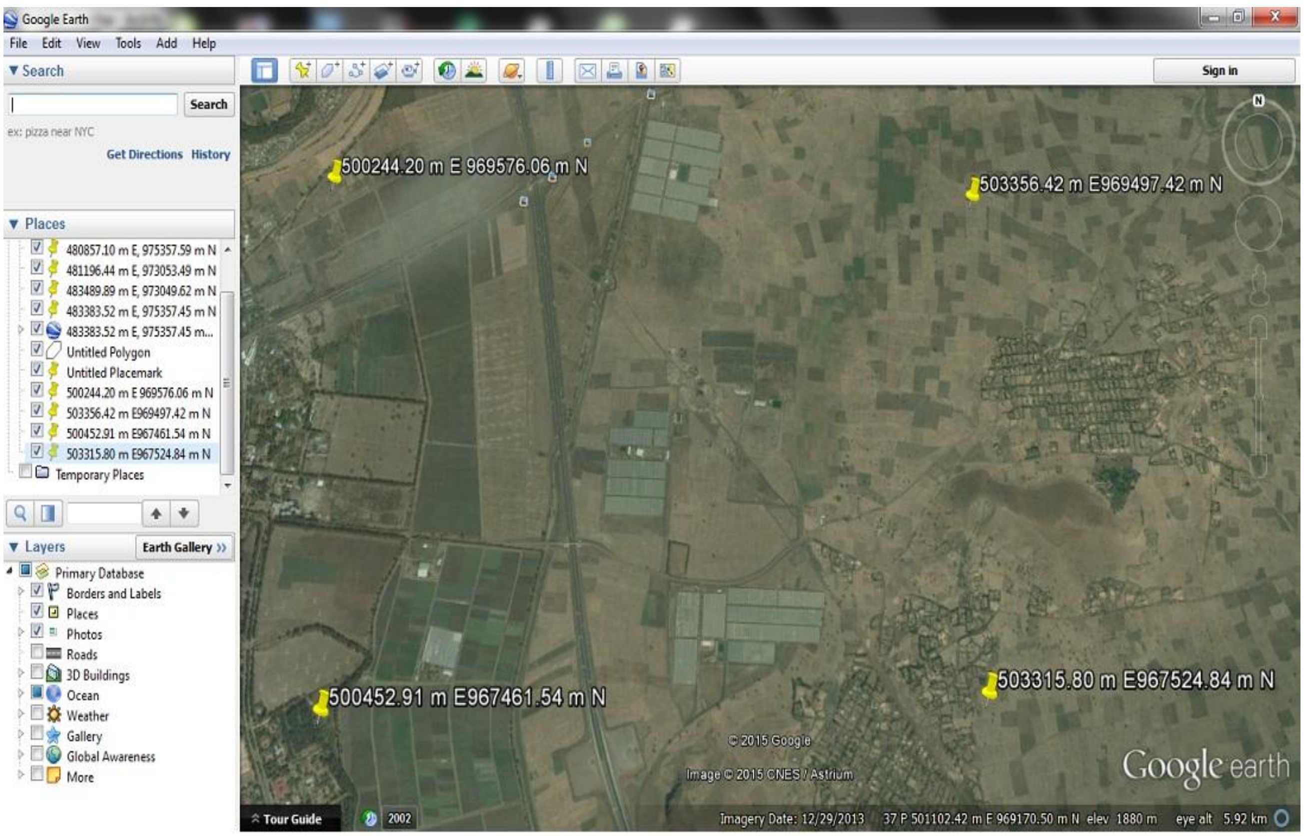

Figure 5.2: Screenshot of Agricultural Monitored Area

The next step is importing our Google Earth image, and geo-reference it based on the four control points we created using ArcGIS. If the spatial reference of an image is undefined, we assign it a coordinate system by setting the projection of a Data Frame and then define the spatial reference. Coordinate systems can provide a framework for defining real-world locations.

In ArcGIS, the coordinate system is used as the method to automatically integrate the geographic locations from different datasets into a common coordinate framework for display and analysis for mapping, visualization, analysis, and so forth. Then we create an ArcGIS ready shape file that contains our GPS points or geographic data (coordinates) in the form of an XY table (long, lat), bounding box, shape type, attributes, file name, the number of spatial features in the shapefile, etc. With the geo-referenced image, we can now digitize new features from the map. In other words, we got a polygon feature layer in ArcGIS as illustrated in Figure 5.3. ArcGIS has a tool called calculate geometry that allows accessing the geometry of the features in a layer. The tool can calculate coordinate values, perimeter and area of our polygon. Therefore, we can easily calculate the area of a polygon or a given geometry of farmland using this tool.

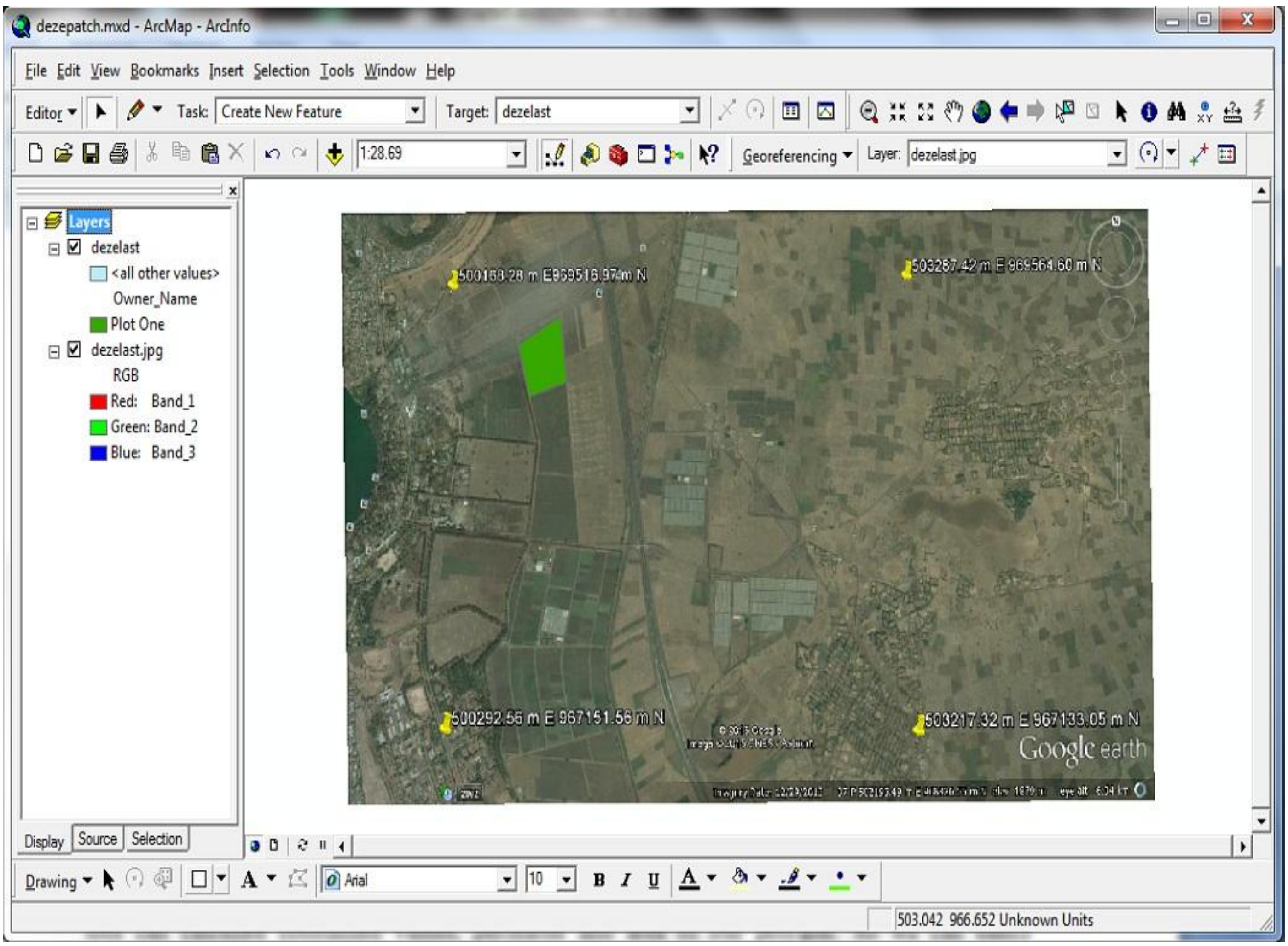

Figure 5.3: Screenshot after Digitizing a Farm Region from Satellite Image

Finally, we can output our data from ArcGIS in the form of shape files and export it into MATLAB, which is proposed to develop the node deployment approach. It can directly read the shape file format using Mapping Toolbox capabilities and we can display geographic information in it.

Our approach mainly concentrates on finding the optimal deployment scheme for sensor nodes using WSNs. The proposed deployment scheme would cover the maximum area with minimum overlapping nodes as much as possible, given the sensing range of sensor nodes and the area of a given shape of farmland.

Now we have the geometry/the shape of the region with boundary that is represented by shapefiles. This shapefiles contain some geographic information in the form attribute about the given polygon like the coordinate system and attribute of the data, number of spatial features, etc.

The position of sensor nodes are determined based on the given sensing range given that the distance between neighboring nodes is $\sqrt{3}Rs$. So first, we compute the spatial coordinates where the sensor nodes are deployed. The nodes are distributed in an equilateral triangle pattern within the farm region as shown in Figure 5.4. The figure shows the distributed nodes within the bounding box of the given polygon. The generated coordinates of each sensor node *n* are represented by an N by 2 array *Sp*. As a result, the nodes can lie inside or outside the polygon. Therefore, it cannot directly fit with the shape of the farmland.

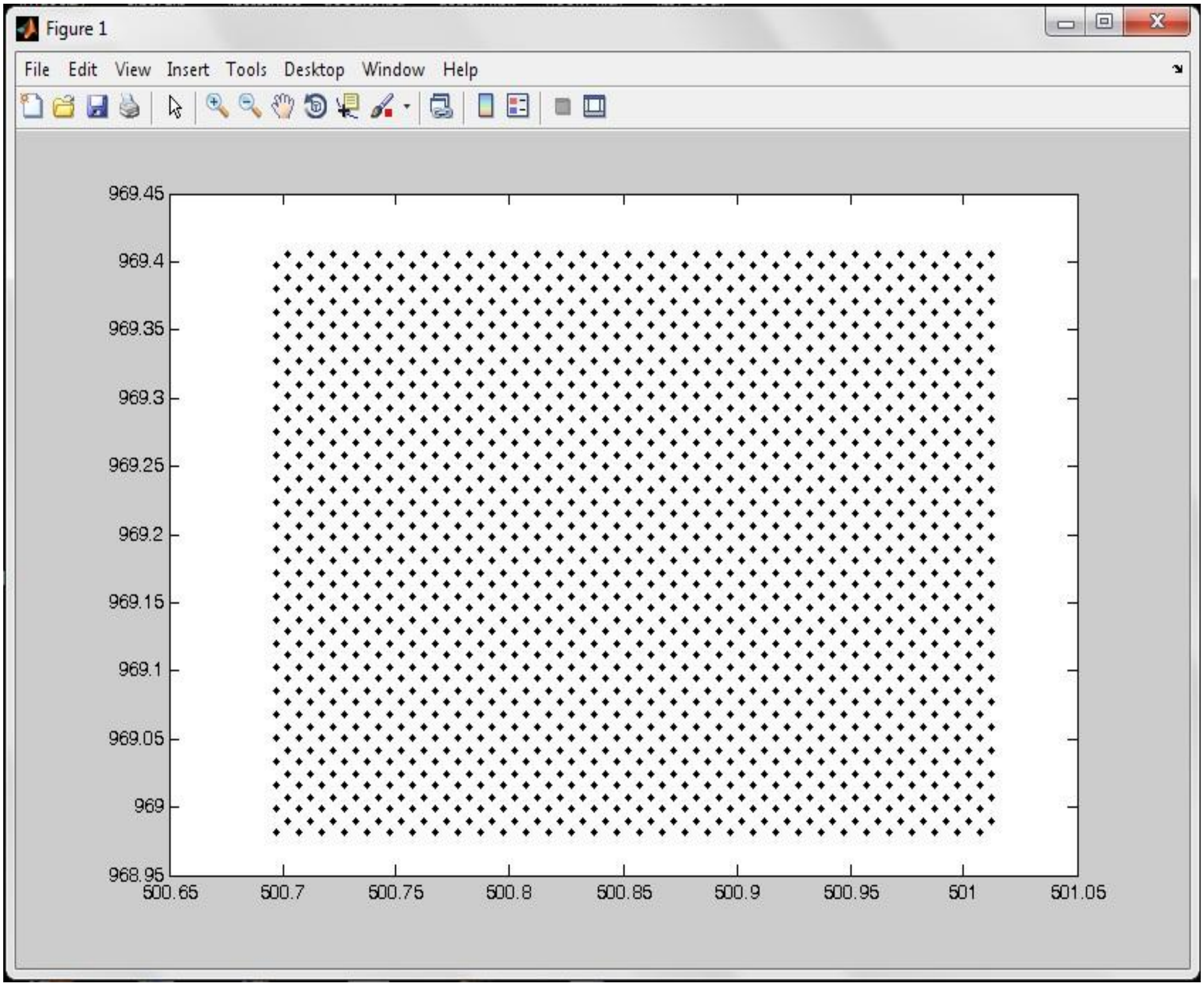

Figure 5.4: Screenshot of Distributed Sensor Nodes in Triangular Grid

Then we can determine that a sensor node *n* lies inside or outside the region of farmland using MATLAB's inpolygon function which identifies the points (sensor nodes) are inside or outside the polygon as shown in Figure 5.5. Then, we can project points to the closest boundary by using the gradient limiting equation (i.e., non-linear partial differential equation). Because, the spatial coordinates of the farmland boundary are used to specify the polygon and permanent points. Hence, we can determine the next position from these points. After that, we have to remove the points outside the region using this probability 1/s(x, y)2. Next, we evaluated s(x, y) at each node and reject points with a probability proportional to 1/s(x, y)2. After the rejection method is applied, we can count the number of nodes.

In our case, we have 1027 nodes with their position in terms of spatial coordinates. Some the positions of sensor nodes generated by the proposed approach are shown below.

***Sp*=**

500.6969 969.2573	500.7219 969.2499	500.7369 969.1547
500.7633 968.9815	500.7219 969.2673	500.7369 969.1720
500.9714 969.4111	500.7269 969.1374	500.7369 969.1893
501.0117 969.0553	500.7269 969.1547	500.7369 969.2066
500.7019 969.2499	500.7269 969.1720	500.7369 969.2240
500.7069 969.2240	500.7269 969.1893	500.7369 969.2413
500.7069 969.2413	500.7269 969.2066	500.7369 969.2586
500.7069 969.2586	500.7269 969.2240	500.7369 969.2759
500.7119 969.1980	500.7269 969.2413	500.7419 969.0767
500.7119 969.2153	500.7269 969.2586	500.7419 969.0941
500.7119 969.2326	500.7319 969.1287	500.7419 969.1114
500.7119 969.2499	500.7319 969.1460	500.7419 969.1287
500.7169 969.1893	500.7319 969.1633	500.7419 969.1460
500.7169 969.2066	500.7319 969.1807	500.7419 969.1633
500.7169 969.2240	500.7319 969.1980	500.7419 969.1807
500.7169 969.2413	500.7319 969.2153	500.7419 969.1980
500.7169 969.2586	500.7319 969.2326	500.7419 969.2153
500.7219 969.1633	500.7319 969.2499	500.7419 969.2326
500.7219 969.1807	500.7319 969.2673	500.7419 969.2499
500.7219 969.1980	500.7369 969.1027	500.7419 969.2673
500.7219 969.2153	500.7369 969.1200	500.7469 969.0508
500.7219 969.2326	500.7369 969.1374	500.7469 969.0681

Now we can denote the sensor nodes number given their positions. We get 1027 nodes position so we have 1027 nodes. The number/ID of sensor nodes are depicted in Figure 5.5.

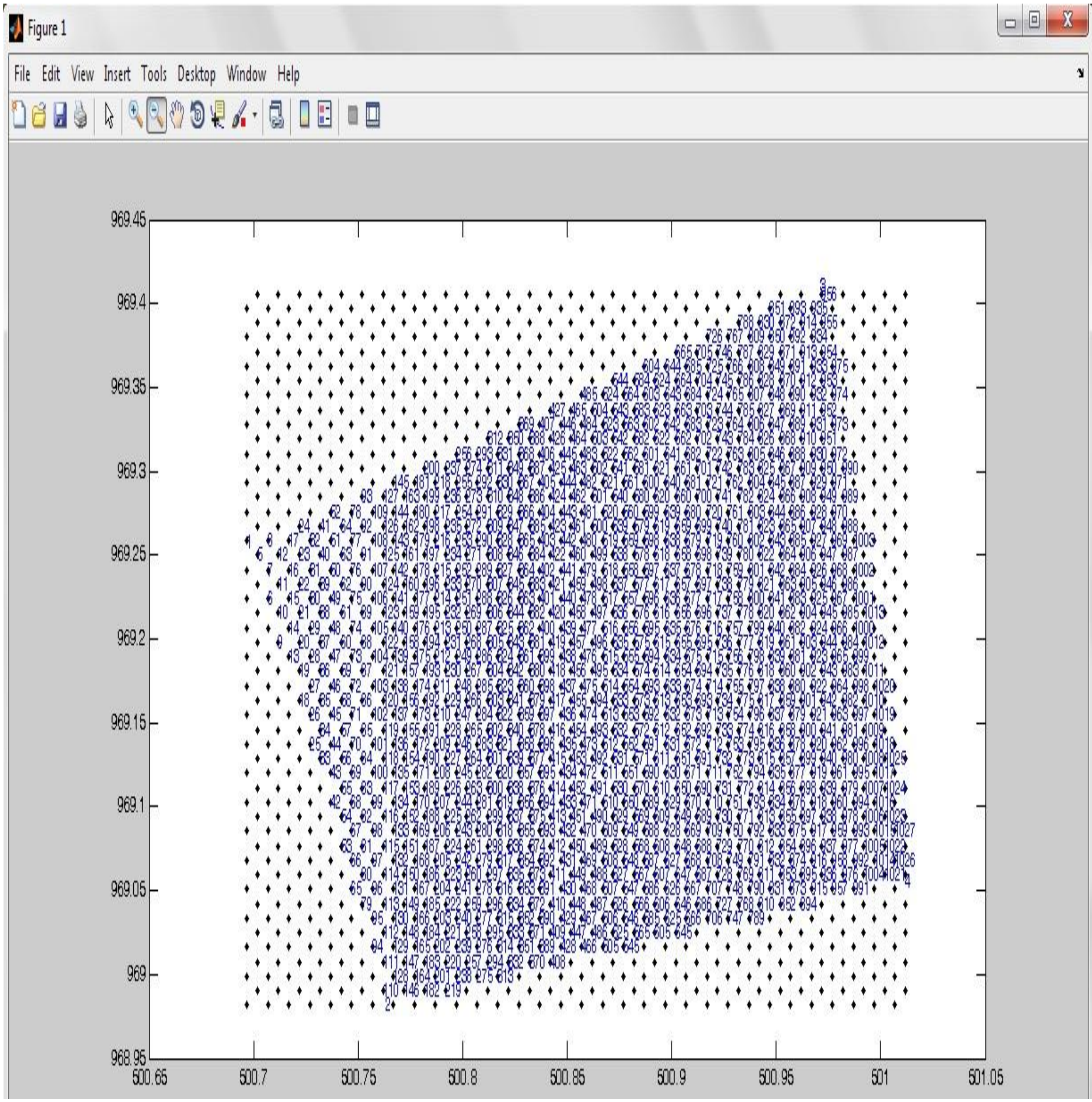

Figure 5.5: The Number of Nodes that are Inside the Given Geometry of Farmland/ Sensor nodes Position

Then, the Delaunay triangulation algorithm triangulates those generated points. This algorithm determines the triangle grids that fill the given shape of farmland and the topology of the sensor nodes. Then it generates an equilateral triangle grid using triangulation that is represented by t from the node points since the number of sensors controls it. Moreover, the triangles that lie outside the geometry have to be removed if the centroid of a triangle $d>0$. The number of the triangle grid and the node number/id that are involved in forming that triangle or the sensor node that are deployed at three vertices of the triangles are known. The nodes forming the triangle are stored in the N by 3-array *t*. However, in such a case every edge is shared by at most two triangles so the duplicates have to be removed. Therefore, we are going to find unique elements of a vector from the row. After this, the node numbers that are involved to form a triangle is stored in an N by 3-array t; some values of t are shown below. So now, we know the number of grids that fill the entire geometry of the farmland.

***t*=**

851	3	1	1013	975	1003	1	6	5
18	9	25	9 9	988	1003	788	851	1
1	9	6	26	18	25	1	726	788
25	9	65	35	26	45	3	851	893
1	2	65	18	26	35	13	20	9
65	9	1	894	789	4	9	18	13
219	789	545	545	789	645	18	19	13
219	2	4	1	200	256	10	6	9
4	789	219	256	312	1	991	894	4
1020	1025	4	369	407	427	545	645	605
4	975	1020	369	427	1	1012	1020	1013
1020	975	1013	1	312	369	34	26	25
145	200	1	1	52	93	45	26	34
1	665	726	93	145	1	25	44	34

The initial generated triangular grid is improved using piecewise linear force-displacement relations until all the edge lengths become same/equal or the distances between all neighboring nodes is equal to √3Rs. Because, curved boundaries can often be approximated by piecewise linear force-displacement [64]. Then, the Delaunay triangulation algorithm iteratively adjusts the topology (it decides the edges). This algorithm enables to adjust the network and produce the layout of the network. Finally, we can display the final output from the triangulation that is illustrated in Figure 5.6.

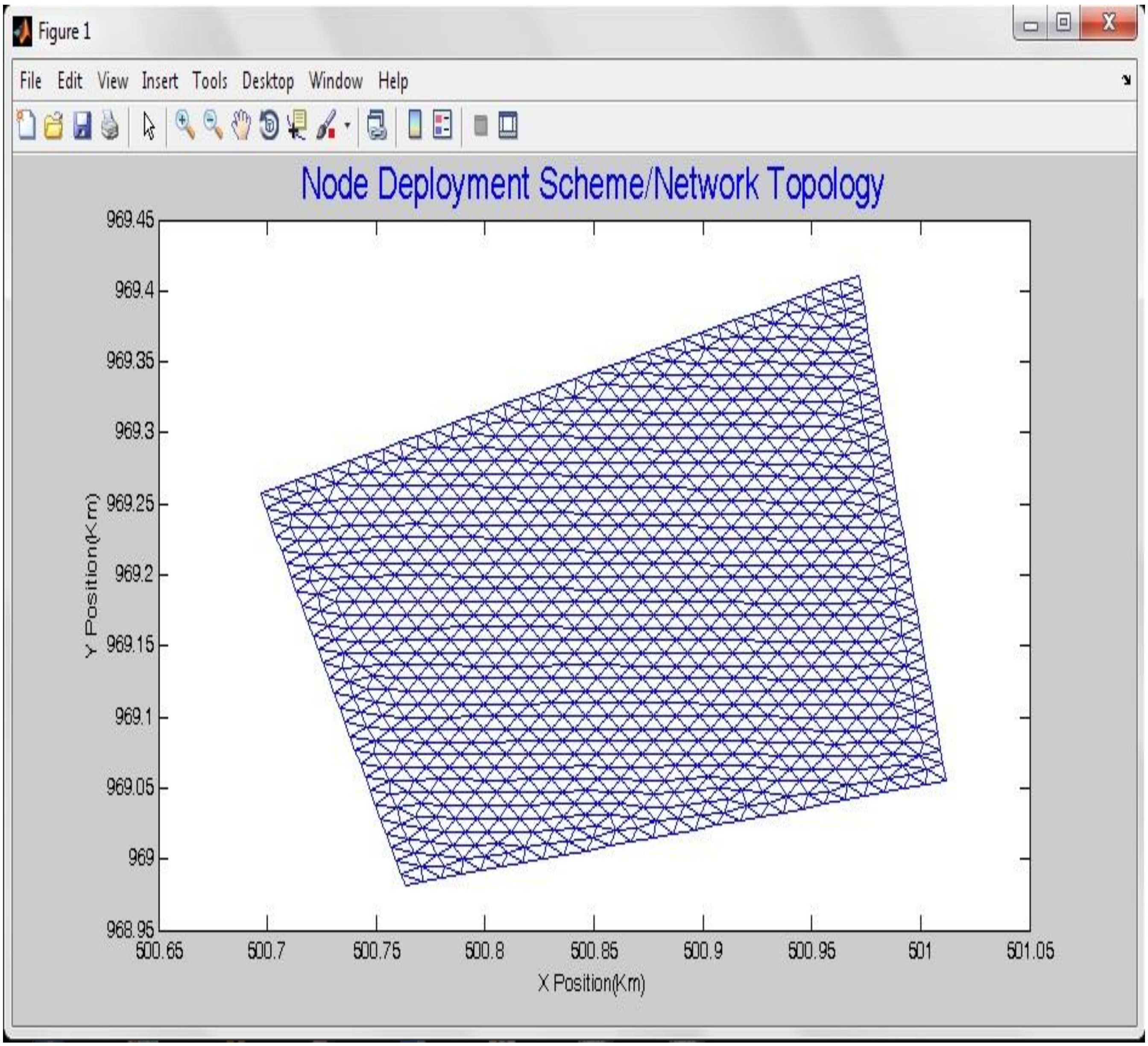

Figure 5.6: Screenshot of the Proposed Node Deployment Scheme for the Given Shape of Farmland

As we have seen in the design in Chapter 4, we need a database to record and store information like the position of sensor nodes, the node number, number of grids, maps, etc. which are important for the user. In our case, we are just recording some information in the form of csv, xls and text files. Figure 5.7 shows the position of sensor nodes which are produced during the computation and we are going to keep this information in the form of a csv file.

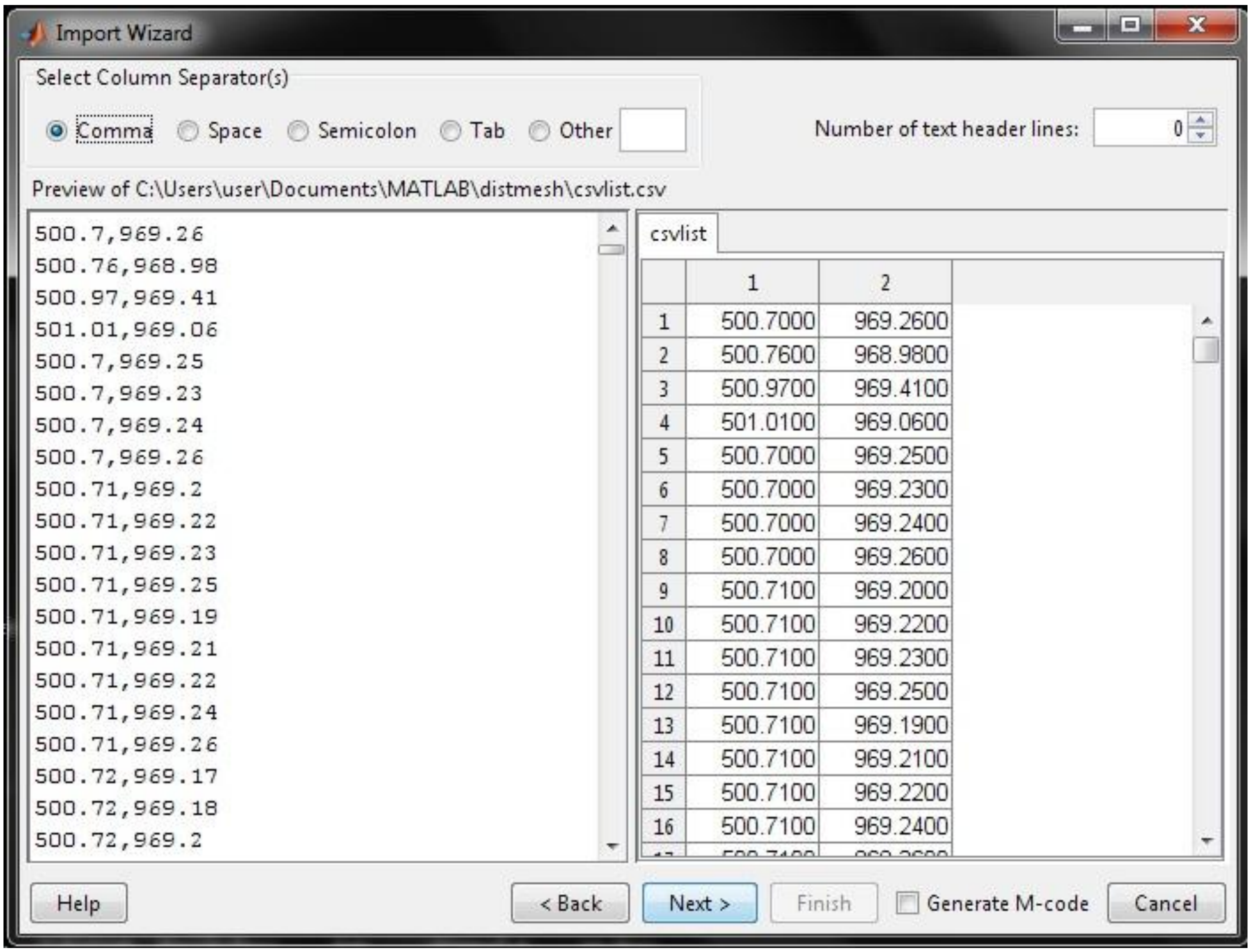

Figure 5.7: Screenshot of the Position of Sensor Nodes Stored in csv Format

Energy consumption is one of the main issues to be considered in the deployment of sensor networks. It has a great impact on extending the lifetime in WSNs. Moreover, the coverage of a sensor network is related to energy conservation. In fact, the network lifetime of the proposed node deployment scheme is evaluated by PEGASIS compared with LEACH. In fact, there are different routing protocols that are proposed which enable to consider that the sensor nodes are limited in power computation capacities. In this work, PEGASIS (Power-Efficient GAthering in Sensor Information Systems) is used as a routing protocol. It is near optimal chain-based protocol, which is an improvement of the LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol. The PEGASIS protocol achieves between 100 to 300% improvement when 1%, 20%, 50% and 100% of nodes die compared to the LEACH protocol. However, PEGASIS introduces excessive delay for distant nodes on the chain. In addition, the single leader can become a bottleneck [3]. It is hierarchical type of routing protocol, i.e., maintains the energy consumption of sensor nodes by involving them in multi-hop communication within a particular cluster or hierarchical scheme [36, 46]. It performs data aggregation and fusion in order to decrease the number of transmitted messages to the sink [4].

Since we proposed deterministic deployment strategy, the sensor nodes are manually placed and data is routed through pre-determined paths. The sensor nodes are deployed to collect the information from their surrounding environment and send their data to the sink/base station. Routing is defined as a process of determining a path between source and destination for data transmission [5]. It is very crucial for energy consumption to operate the sensor network for a long period since we select an optimal path for data transmission. In a wireless multi-hop network, the role of a routing protocol is not only finding a path but also finding an optimal path that satisfies the needed performance requirement. PEGASIS forms chains from sensor nodes so that each node transmits and receives from a neighbor and only one node is selected from that chain to transmit to the base station (sink). Gathered data moves from node to node, aggregated and finally a designated node transmits it into the BS as shown in Figure 5.8 [3]. The chain construction is performed with a greedy approach. It uses multi-hop routing by forming chains and selecting only one node to transmit to the base station instead of using multiple nodes.

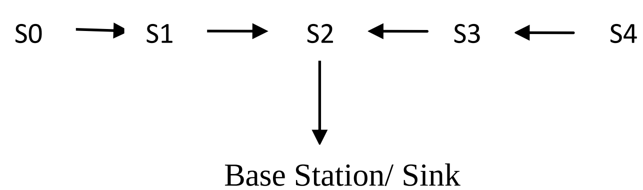

Figure 5.8: Chaining in PEGASIS

We initially used 0.08864 Km^2 area of farmland, sink location, 1027 nodes, all the position of sensor nodes so the nodes are deployed in a deterministic manner and the location of sensor nodes. We used PEGASIS routing protocol algorithm with those parameters. Then, the nodes will be organized to form a chain as shown in Figure 5.9, which is accomplished by the sensor nodes themselves using a greedy algorithm starting from some node. The sensed data moves from node to node, gets aggregated, and finally a designated node transmits it to the BS. The average energy spent by each node per round is reduced while the nodes take turns transmitting to the BS. Hence, the result of the first round is shown in Figure 5.9.

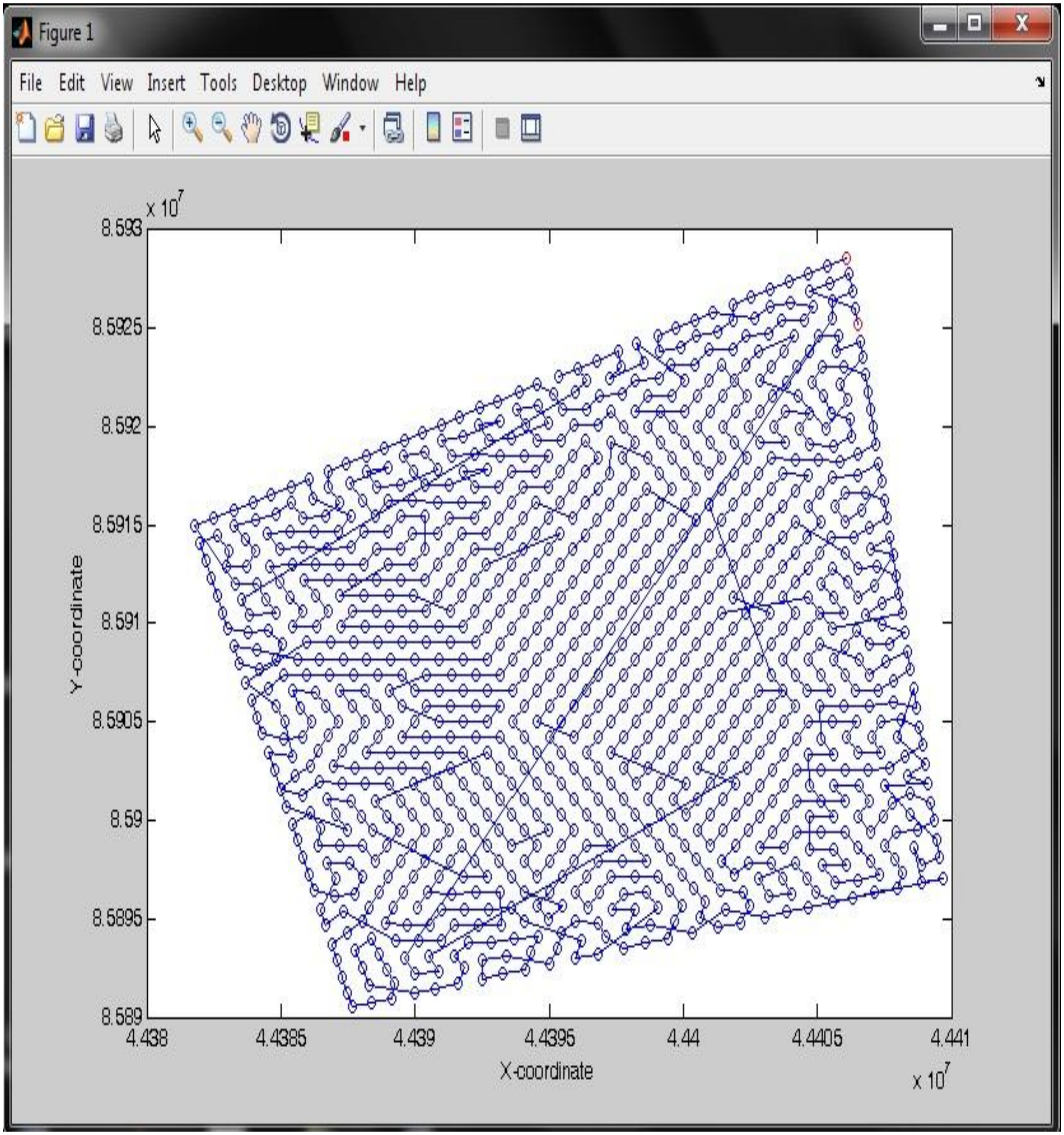

Figure 5.9: Routing Paths Generated by PEGASIS for the Given Farm Area

5.6 Evaluation

In this section, the performance of the proposed deployment approach is measured and compared with other previously proposed node deployment strategies using numerical computation, simulation and theoretical analysis. To conduct the evaluation, we consider all the design requirements specified in Chapter 4. Therefore, the evaluation metrics for the proposed systems are efficient coverage area, network lifetime, cost and ease of deployment, size of the network/ number of nodes and adaptability. Thus, the evaluation includes the following five parts.

5.6.1 Performance Evaluation: Coverage Area

As mentioned earlier, the effectiveness of wireless sensor networks depends on the coverage offered by the sensor deployment scheme. We used an equilateral triangle deployment because it is better in coverage as well as connectivity, has the smallest overlapping area, and uses the least number of sensors as shown in Figure 5.10. As we have seen earlier, this allows a full coverage in the farm area. However, we have to make sure that our proposed node deployment scheme provides maximum coverage with minimum overlapping nodes. We use efficient coverage ratio to show here the boundary effect in it. So we compute efficient coverage area for three sensors at vertexes of the triangle and their efficient coverage area ratio. The efficient coverage area AEs1s2s3 of the three nodes is the coverage that is overlapping coverage area subtracted from the coverage area provided by S1 (As1=πRs2) [9, 61].

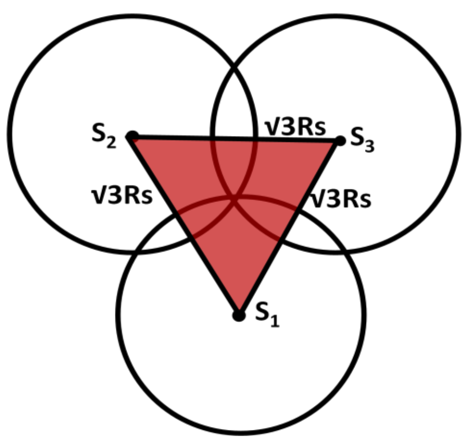

Figure 5.10: Sensor Deployments Based on Equilateral Triangle

In order to evaluate our model, a formula is required to get the coverage ratio provided by the proposed approach. So the area of the triangle can be calculated as:

$$A_t = \frac{1}{2} \text{ x b x h, where b} = \sqrt{3Rs} \quad h = Rs \sin 30 = \frac{3Rs}{2}$$

$$= \frac{1}{2} \text{ x} \sqrt{3Rs} \text{ x } \frac{3Rs}{2}$$

$$A_t = \frac{3\sqrt{3}\ Rs^2}{4} \qquad (1)$$

The formula for computing efficient coverage area for equilateral triangle $A_{Es_1s_2s_3}$ of the three nodes is [61]:

$$A_{Es_1s_2s_3} = \frac{(4\pi + 3\sqrt{3})\ Rs^2}{2} \qquad (2)$$

The efficient coverage area ratio REs1s2s3 is calculated by [61]:

$$REs1s2s3 = \frac{AEs_1s_2s_3}{3x\ \pi Rs^2}$$

$$= \frac{(4\pi + 3\sqrt{3})\ Rs^2}{2X3x\ \pi Rs^2} \qquad (3)$$

The coverage performance of the proposed system can be evaluated to show that the proposed system provides maximum coverage ratio based on the calculation made by using Equations (2) & (3). The maximum efficient coverage area for a single equilateral triangle is 0.0008878 km^2 and its efficient coverage area ratio is 0.942 where the sensing radius Rs=10. It achieves the maximum coverage area ratio provided by the triangle grid. This result indicates that our proposed model would be able to offer higher coverage with fewer sensor nodes. This is due to the fact that, the main aim of the proposed system was on the maximum coverage ratio with the minimum number of sensors (the farm area to be monitored).

5.6.2 Performance Evaluation: Number of Nodes/Size of the network

This work proposed an equilateral triangle pattern for deploying sensor nodes. It is proved that the approach can provide maximum coverage without gap with the least number of sensor nodes. When the number of sensor nodes is reduced, the energy consumption and the cost of deployment also reduce simultaneously and the network lifetime is maximized. As shown earlier the required number of sensor nodes to cover the entire region is determined. However, the minimum number of sensor nodes required in triangle was determined by using the following equation that was derived by [60]:

$$\text{Number of Sensor Nodes} = 1.15\ \frac{A}{Rs^2} \qquad (4)$$

where A is the monitoring area of the given farmland and Rs is the sensing range of the sensor node.

Based on the calculation using Equation (4), the minimum number of sensor nodes needed for this model is approximately 1020 sensor nodes. However, the number of sensor nodes needed to construct the WSN based on our proposed model is 1027 nodes. There is some deviation because the sensor nodes could be affected by the given geometry of farmland. The result shows that our proposed model satisfies 99.32% of the required number of sensor nodes.

5.6.3 Performance Evaluation: Network Lifetime

In this work, the coverage of the WSN is guaranteed to maximize total network lifetime in our proposed solution. Therefore, we consider extending the network lifetime while ensuring the coverage area ratio, because the sensor nodes are constrained with energy supply. So maintaining a maximum coverage area ratio will increase the network lifetime. Furthermore, we compare the energy consumption of our node deployment scheme using two protocols (i.e., LEACH and PEGASIS) using the same parameters. Our network performs better interns of network lifetime using PEGASIS. Hence, we choose PEGASIS over LEACH protocol. In addition, it performs better since the nodes take turns transmitting to the BS. As a result, the average energy spent by each node per round is reduced.

5.6.4 Performance Evaluation: Cost and Ease of Deployment

a. Cost of Deployment

The number of grids and the number of sensor nodes determine the deployment cost of grid based deployment strategies including triangular node deployment strategy [59]. To get cost effective deployment, we determined the position of sensors, the number of sensors, and number of grids. Therefore, we can say the cost of node deployment is reduced while we used practical deployment scenarios.

Deploying the minimum number of sensors needed certainly is most desirable for economic reason (i.e., cost saving) since the sensor nodes still cost $100 apiece, to easily control the topology, minimizing message collisions, better network management, etc. [48].

b. Ease of Deployment

The proposed system can be used by anyone without Knowledge of the details of networking and communication mechanism of the wireless sensor network, because the proposed approach allows specifying its outputs in understandable way like the position of sensors using spatial coordinates, the scheme, etc. Furthermore, all the information needed by the user is stored in a database so that it can easily be accessed, managed and updated by the user.

5.6.5 Performance Evaluation: Adaptability

As mentioned in Chapter 4, the proposed system should be adaptive for any shape of geometric features to satisfy the user needs. In order to show adaptability of the system we have taken another geometric feature of farmland with an area of 0.08851 Km^2. The proposed system easily accepts the shapefiles and performs the required computation without any difficulties. The node deployment scheme for a given farm area with 1026 nodes is shown in Figure 5.11. Thus, this shows that the system is adaptable to any geometric feature of farmland.

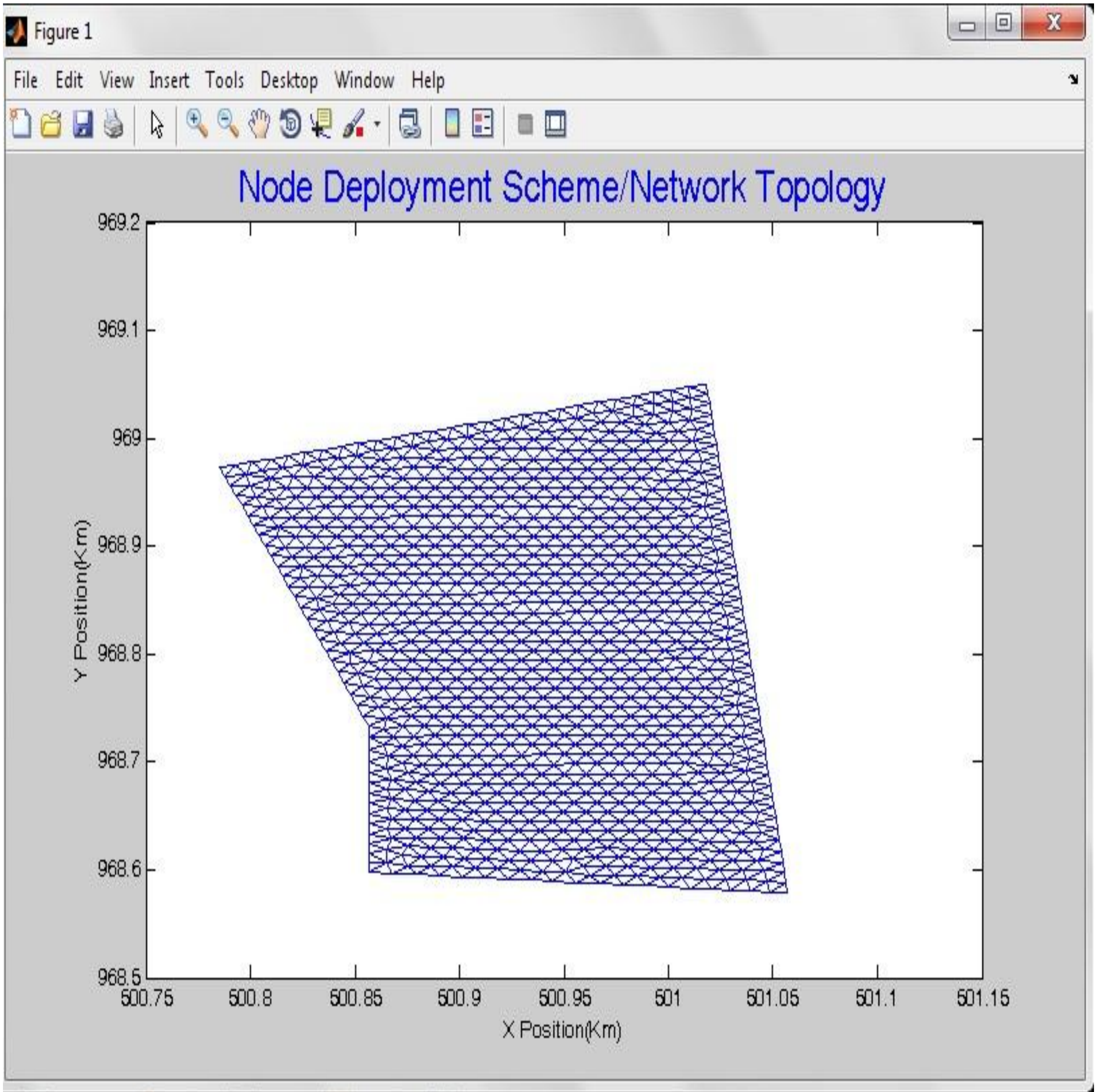

Figure 5.11: Screenshot of the Node Deployment Scheme for the second Farmland

Chapter 6: Conclusions and Future Work

6.1 Conclusions

In this thesis, the use of wireless sensor networks in precision agriculture has been explained where the sensor nodes are distributed in a geographical area to periodically collect environmental data from the monitoring region of farmland. Node deployment is an important issue in WSNs. This work presents a node deployment approach that takes a shape of a given farmland and calculates an optimal number of nodes. A deployment scheme is proposed with the minimum number of sensor nodes to form a sensor network. To conduct this, first we formulated the general optimization problems related to the shape of farmland since the optimality of a given deployment scheme can be affected by the given shape of farmland. Next, a number of literatures have been reviewed to provide background information about wireless sensor networks, node deployment, precision agriculture and routing protocol and different research works related to sensor node deployment in wireless sensor networks. Then, the design of the proposed solution was presented. After that, we demonstrated the shape based customized sensor node deployment using WSNs in agriculture. Hence, for the given shape of the farmland, our approach produces the corresponding node deployment scheme. The approach was able to determine the minimum number of sensors and their exact position in terms of real spatial coordinates within the given geometry of farmland. To achieve this, we considered the following requirements: coverage area, network lifetime, cost and ease of deployment, number of nodes and adaptability. A routing protocol was also selected which performs better in terms of network lifetime to preserve the energy consumption of our node deployment scheme.

To achieve this, a deterministic deployment strategy was proposed in which the nodes are arranged in an equilateral triangular deployment pattern. The proposed approach enables to generate triangular meshes using Delaunay triangulation algorithm. It determines the triangle grids that fill the given shape of farmland and the topology of the sensor nodes using piecewise linear force-displacement until the deployment becomes regular. It is an efficient coverage strategy since the nodes are deployed in triangle pattern.

The thesis has also shown the appropriateness of the proposed deployment strategy by means of performing different experimental simulations using different performance metrics in MATLAB environment, mathematical modeling, theoretical analysis and formula deduction. The performance of the proposed node deployment system was measured in comparison with other previously proposed node deployment strategies. Results show that, in the sense of coverage performance evaluation, the proposed node deployment scheme can achieve full coverage area. The efficient coverage area ratio was 0.984 and the minimum deployment quality was 0.82. This shows that, the proposed sensor nodes placement scheme offers considerably higher coverage ratio with high deployment quality.

The proposed scheme was intended to prolong the network lifetime by satisfying the desired coverage of a given region with a minimum number of sensor nodes. The energy consumption of the proposed scheme was evaluated by comparing two protocols (i.e., PEGASIS over LEACH). PEGASIS is selected because it has a better network lifetime than LEACH.

Based on the cost of deployment, the number of nodes implies that the WSN deployed with the proposed scheme provided higher coverage with low cost. Moreover, it was easy to say anyone can use the proposed system and it is adaptable.

Based on the evaluation results obtained, it can be concluded that the proposed node deployment strategy (i.e., scheme) is a better option for precision agriculture in Wireless Sensor Networks (WSNs) in the sense of efficient coverage ratio, network lifetime, cost and ease of deployment, number of nodes and adaptability.

6.2 Contribution

In general, the contributions made by this thesis can be summarized as follows:

- We proposed a sensor node deployment approach for precision agriculture that can be used for both regular and irregular shapes of the monitored farm area. This helps reduce problems associated with inefficient use of resources in traditional farming to maximize production. Hence, we were able to provide the optimal node deployment scheme using different geometric shapes.

- We proposed a deterministic deployment strategy in which the nodes are placed in order to achieve the design requirements such as coverage area, network lifetime, number of nodes, cost of deployment, etc.
- We provided a node deployment scheme with minimum number of sensor nodes that has a maximum coverage area without any gap since it uses triangular node deployment.
- We determined the position of sensor nodes in terms of spatial (geographic) coordinates which is different from the previously proposed position determining techniques in node deployment strategies. This makes it more practical.
- Our system enables large scale environmental monitoring.
- A routing protocol with better network lifetime was selected considering the nature of the node deployment scheme used.
- The proposed design and implementation described in this thesis can be a guideline for further research in this area.

6.3 Future Work

We have proposed a shape based node deployment scheme towards precision agriculture using WSNs and achieved an encouraging result. However, we would like to suggest the following points as a future work.

- This work can be extended to other aapplications with different scenarios to check the applicability of the proposed system.
- The sensor network used in our system is homogeneous so our future work will extend this to heterogeneous sensor nodes.
- The sensors are deployed in a two dimensional area but it can be extended to three-dimensional area to see the effect of the crop size in sensors communication.
- This deployment considers only triangular node deployment so the next work must consider other deployment strategies like hexagon, square, etc.
- An extensive evaluation of the proposed solution can be done using different approaches in different literatures.
- This work will also be enhancing by dynamically selecting appropriate deployment based on shapes.

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Declaration

I, Undersigned, declare that this thesis is my original work and has not been presented for degree in any other university, and that all sources of material used for the thesis have been acknowledged.

Declared by:

Name: **Beza Diribu Desta**

Signature: ____________________________

Date: _______________________________

Confirmed by advisor:

Name: **Mulugeta Libsie (PhD)**

Signature: _____________________

Date :___________________________

Place and date of submission: Addis Ababa University, February 2015.