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Performance Analysis of Cluster Based Communication Protocols for Energy Efficient Wireless Sensor Networks

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Performance Analysis of Cluster Based Communication Protocols for Energy Efficient Wireless Sensor Networks

Design, Analysis and Performance Evaluation of Communication Protocols under Various Topologies to Enhance the Lifetime of Wireless Sensor Networks

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Abstract

Sensor nodes are deployed over sensing fields for the purpose of monitoring certain phenomena of interest. The sensor nodes perform specific measurements, process the sensed data, and send the data to a base station over a wireless channel. The base station collects data from the sensor nodes, analyses this data, and reports it to the users. Wireless sensor networks are different from traditional networks, because of the following constraints. Typically, a large number of sensor nodes need to be randomly deployed and, in most cases, they are deployed in unreachable environments; however, the sensor nodes may fail, and they are subject to power constraints.

Energy is one of the most important design constraints of wireless sensor networks. Energy consumption, in a sensor node, occurs due to many factors, such as: sensing the environment, transmitting and receiving data, processing data, and communication overheads. Since the sensor nodes behave as router nodes for data propagation, of the other sensor nodes to the base station, network connectivity decreases gradually. This may result in disconnected sub networks of sensor nodes. In order to prolong the network's lifetime, energy efficient protocols should be designed for the characteristics of the wireless sensor network. Sensor nodes in different regions of the sensing field can collaborate to aggregate the data that they gathered.

Data aggregation is defined as the process of aggregating the data from sensor nodes to reduce redundant transmissions. It reduces a large amount of the data traffic on the

network, it requires less energy, and it avoids information overheads by not sending all of the unprocessed data throughout the sensor network. Grouping sensor nodes into clusters is useful because it reduces the energy consumption. The clustering technique can be used to perform data aggregation. The clustering procedure involves the selection of cluster heads in each of the cluster, in order to coordinate the member nodes. The cluster head is responsible for: gathering the sensed data from its cluster's nodes, aggregating the data, and then sending the aggregated data to the base station.

An adaptive clustering protocol was introduced to select the heads in the wireless sensor network. The proposed clustering protocol will dynamically change the cluster heads to obtain the best possible performance, based on the remaining energy level of sensor nodes and the average energy of clusters. The OMNET simulator will be used to present the design and implementation of the adaptive clustering protocol and then to evaluate it.

This research has conducted extensive simulation experiments, in order to fully study and analyse the proposed energy efficient clustering protocol. It is necessary for all of the sensor nodes to remain alive for as long as possible, since network quality decreases as soon as a set of sensor nodes die. The goal of the energy efficient clustering protocol is to increase the lifetime and stability period of the sensor network.

This research also introduces a new bidirectional data gathering protocol. This protocol aims to form a bidirectional ring structure among the sensor nodes, within the cluster, in order to reduce the overall energy consumption and enhance the network's lifetime. A

bidirectional data gathering protocol uses a source node to transmit data to the base station, via one or more multiple intermediate cluster heads. It sends data through energy efficient paths to ensure the total energy, needed to route the data, is kept to a minimum. Performance results reveal that the proposed protocol is better in terms of: its network lifetime, energy dissipation, and communication overheads.

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Publications

Journal Publications

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- Bajaber, F. and Awan, I. (2010) "Energy Efficient Clustering Protocol to Enhance Lifetime of Wireless Sensor Network", *Journal of Ambient Intelligence and Humanized Computing*, Springer, 2010, DOI: 10.1007/s12652-010-0019-x.

- Bajaber, F. and Awan, I. (2010) "Adaptive Decentralized Re-Clustering Protocol for Wireless Sensor Networks", *Journal of Computer and System Sciences*, Elsevier, February 2010, ISSN 0022-0000, DOI: 10.1016/j.jcss.2010.01.007.

Conferences and Workshops

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- Bajaber, F. and Awan, I. (2009) "Centralized Dynamic Clustering for Wireless Sensor Network", *Advanced Information Networking and Applications Workshops, WAINA '09, International Conference*, pp. 193-198, 26-29 May 2009.

- Bajaber, F. and Awan, I. (2008) "Dynamic/Static Clustering Protocol for Wireless Sensor Network", *Computer Modeling and Simulation, EMS '08, 2nd UKSIM European Symposium*, pp. 524-529, 8-10 Sept. 2008.

- Bajaber, F. and Awan, I. (2008) "Improvement of Low-Energy Adaptive Clustering Hierarchy in Wireless Sensor Networks", *Proceedings of the 9th Informatics Workshop, Bradford*, UK, ISBN: 978 1 85143 251 6, pp. 98-100.

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List of Abbreviations

ACQUIRE   Active Query forwarding In Sensor Networks

ADRP   Adaptive Decentralised Re-Clustering Protocol

APTEEN   Adaptive Periodic Threshold-Sensitive Energy Efficient Sensor Network

BDGP   Bidirectional Data Gathering Protocol for Wireless Sensor Networks

CDC   Centralised Dynamic Clustering

CPU   Central Processing Unit

EAD   Energy-Aware Data-Centric

EECPL   Energy Efficient Clustering Protocol to Enhance Lifetime

EESH   Energy Efficient Strong Head Clustering

ERA   Energy Residue Aware

GEAR   Geographic and Energy Aware Routing

GPS   Global Positioning System

HEED   Hybrid, Energy-Efficient, Distributed Clustering

LAN   Local-Area Network

LEACH	Low-Energy Adaptive Clustering Hierarchy
MAC	Medium Access Control
MECH	Maximum Energy Cluster Head
MESH	Maximum Energy Routing Protocol Based on Strong Head
PEGASIS	Power-Efficient Gathering in Sensor Information Systems
PREMON	Prediction based Monitoring
RICA	Ring-Based Information Collection Architecture
RRCH	Round-Robin Cluster Header
SPIN	Sensor Protocol for Information via Negotiation
TDMA	Time Division Multiple Access
TEEN	Threshold Sensitive Energy Efficient Sensor Network Protocol
UDACH	Uniformly Distributed Adaptive Clustering Hierarchy
WSN	Wireless Sensor Network

Chapter 1

Introduction

1.1 Background

In recent years, a new class of networks appeared called Wireless Sensor Networks [42, 48]. They aim to provide efficient and effective connections between physical and computational worlds. Proposed applications of sensor networks include: environmental monitoring; natural disaster prediction and relief; security; healthcare; manufacturing; transportation; and home appliances.

A sensor network consists of a large number of sensor nodes. A sensor node integrates hardware and software for sensing, data processing, and communication [45, 48]. They can sense their environment, perform some computations on the data that they have sensed or received from other sensor nodes, and they can communicate over wireless channel, to other sensor nodes or to a base station, as shown in Figure 1-1.
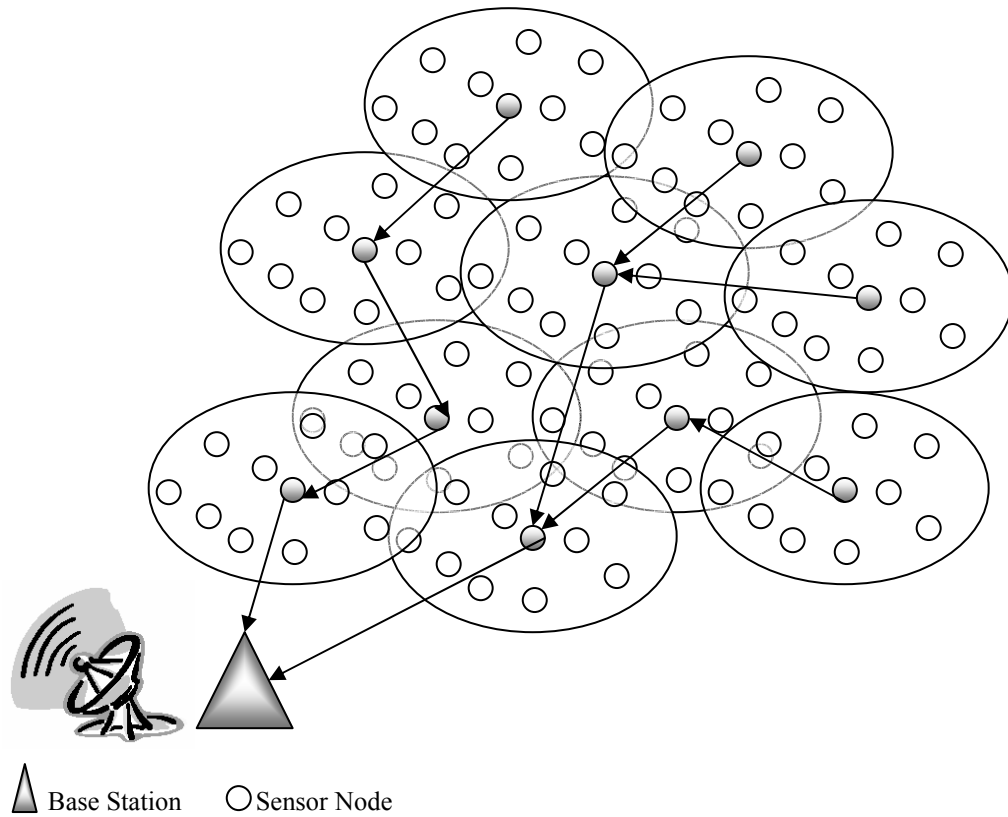
Figure 1-1: The architecture of a wireless sensor network.

Figure 1-2 shows the basic structure of a sensor node. A basic sensor node is comprised of five main components: CPU, memory, sensors, transceiver, and a power supply [20, 48]. The CPU can process all relevant data and is capable of executing code. The memory is used to store programs and data. The sensors can observe physical parameters of the environment. The transceiver sends and receives information over a wireless channel, and in terms of the power supply, the sensor nodes are often powered by batteries.
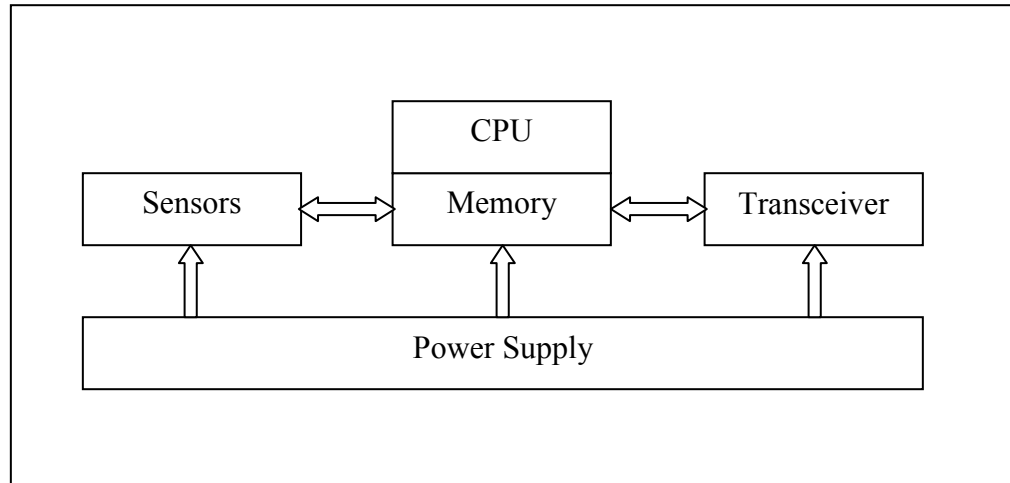
Figure 1-2: Sensor node architecture.

A base station collects data from the wireless sensor networks. The sensor nodes collect data from the environment, perform local processing, and send the data to the base station. At the base station, the data is integrated and transmitted to the users by: LANs, the internet, or via satellite [19, 20]. Compared with the sensor nodes, the base station has an unlimited energy supply, and therefore has stronger communicating and processing abilities.

In wireless sensor networks, data sensing and reporting is dependent on the application. Sensor networks can be categorised as being: time driven or event driven [7, 20, 44]. In time driven networks, sensor nodes periodically switch on their sensors, sense the environment, and send sensed data at periodic time intervals. Whereas, in event driven

networks, the sensor nodes react immediately to sudden changes due to the occurrence of an event. In many event driven applications, such as sensor nodes to detect fires, data must arrive as quickly as possible to the base station.

Wireless sensor networks can involve single hop or multihop communications [11-18, 43]. To illustrate, in a single hop communication, a sensor node can communicate with other sensor nodes or with a base station; however, in multihop communication, sensor nodes may involve a sequence of hops to communicate with each other or with a base station.

1.2 Motivation

Wireless sensor networks have several restrictions which should be considered when designing a protocol for these networks. An important consideration in sensor networks concerns the amount of energy required for sensing, computation, and communicating [17, 19, 25, 45]. Since replacing batteries may be difficult or impossible, in many applications, and because the lifetime of a sensor node depends to a large extent on the battery lifetime, it is important to adapt energy efficient strategies for these networks.

The energy sources in wireless sensor networks are irreplaceable and their lifetimes are limited; therefore, researchers were motivated to design protocols to prolong the lifetime of the network and to prevent connectivity degradation by employing energy management techniques [7, 20, 49].

The sensor nodes are deployed randomly in the sensing field; they are expected to perform, without any maintenance, human attendance or battery replacement, which limits the energy available to the sensor nodes. Current routing protocols, designed for traditional networks, cannot be used in a wireless sensor network because:

- The data being collected by the multiple sensor nodes is based on a common event and there is a degree of redundancy in the sensed data. Data redundancy may consume the nodes' energy, as a result of replication of information. Therefore, aggregation of the data is needed to ensure energy efficiency. The aggregation is to exploit this redundancy by combining the data that comes from many sensor nodes into a set of meaningful information.

- Sensor networks are application specific.

- In most applications, sensor nodes are not mobile.

- The sensor networks have large numbers of sensor nodes which need not have unique addresses, because of the additional overhead of maintaining these addresses.

- In sensor networks, data are requested based on certain attributes such as temperature; while in traditional networks, data are requested from a specific node.

- The sensor network is unattended and all network organisation and configuration needs to operate automatically – the sensor nodes should therefore be self-organising.

- Data collection, in the sensor network, is based on location.

1.3 Research aims and objectives

Wireless sensor networks are capable of observing the environment, processing data, and making decisions based on these observations [20, 43, 44]. They have high potential impacts in many fields, including: education, healthcare, monitoring, retail, and science. Sensor networks pose many challenges which need further research and development, including the need for a new generation of low power protocols [42, 46, 47, 49]. The following objectives are identified in the design of wireless sensor network protocols.

- Auto-configuration: a sensor network might contain large numbers of sensor nodes; therefore auto-configuration needs to be executable in order to setup these network connections.

- Energy efficient operation: sensor nodes can extinguish their limited energy to perform computations and communications. Energy efficient protocols are in high demand, in order to prolong the lifetime of sensor networks. Power saving should be achieved via power aware routing. A system can be declared dead

when: the first sensor node exhausts its energy; when a certain fraction of sensor nodes die; or, when all sensor nodes die – each application uses different metrics.

- Fault tolerance: some sensor nodes may die or become damaged. The failure of sensor nodes should not affect the sensor network – the sensor network should be able to tolerate such faults.

- Scalability: the number of sensor nodes deployed in a sensing field can be large, sensor network protocols should be able to scale according to these large numbers.

- Adaptability: wireless sensor networks are highly dynamic; during their operation, sensor nodes transit among different states, including: sleep, start up, transmitting, receiving, and failure. The environment of a sensor network, and the sensor network itself change; therefore, the protocol has to adapt to monitor its status, to change operational parameters, and to maintain itself.

- Data aggregation: sensor nodes need to collaborate to eliminate data redundancy. They might, locally, filter the data according to the requirements, process the data, and then transmit the processed data.

1.4 Original contributions

The energy consumed by communication is much higher than that for sensing and computation [28]. A wireless sensor network usually contains a large number of sensor nodes, and the base station is often located at a distance from the sensor network.

Energy management, within sensor networks, is one of the most important design parameters, because replacing batteries may be difficult or impossible in many applications [50-54]. Cluster based routing protocols [7-10] are proposed as part of an energy efficient communication protocol for wireless sensor networks. The cluster heads collect data from member nodes, aggregate the data and then transmit the aggregated data to the base station for higher level processing.

It is important to focus on reducing energy consumption in the wireless sensor network, for data communication, in order to prolong the network's lifetime. Energy aware protocols were proposed, based on various topologies. The protocols divided the sensor network into clusters of nodes led by a cluster head; clusters can be used to form a logical hierarchy in a flat topology. Our clustering is therefore dynamic because it adapts to changes in network connectivity.

The simulation results indicate that a large amount of energy was saved by using the proposed protocols. These results illustrate the advantages of the protocols under

various topologies, ultimately, reducing energy consumption and communication overheads.

1.5 Outline of the thesis

The remainder of the thesis is organised as follows.

Chapter 2 describes wireless sensor networks and explains how they differ from the other types of networks. It also provides an overview of energy aware protocols, by identifying their advantages and disadvantages. The chapter provides a comprehensive survey of the routing protocols developed for sensor networks and highlights the main issues identified in the routing protocols.

Chapter 3 introduces adaptive re-clustering protocols for wireless sensor networks, by describing experimental scenarios and the setting of simulation parameters. This chapter also presents and analyses the performance results of adaptive re-clustering.

Chapter 4 presents the energy efficient clustering protocol, which distributes the energy load among all the sensor nodes. It presents simulation scenarios, parameters, and a comprehensive performance evaluation.

Chapter 5 presents the design and implementation of the bidirectional data gathering protocol, designed to enhance the system's lifetime. It also considers an extensive performance evaluation of the protocols.

Finally, chapter 6 concludes the thesis and provides directions for future work.

Chapter 2

An Overview of Wireless Sensor Networks

2.1 Introduction

By integrating the sensing, processing and communicating, a sensor network provides a platform for hierarchical and efficient information processing. The sensor nodes are used to monitor parameters that may vary with place and time. Therefore, a large number of sensor nodes are required in order to monitor the environment. Moreover, these sensor nodes should be networked to allow the transmission of data to a collector site.

Many applications use sensor nodes to capture and monitor the status of a physical environment, such as: location data, temperature, pressure, rainfall, and wind speed. Sensor nodes send their measurements to a base station using wireless communications. In order to reduce the total number of messages sent by the nodes, some nodes perform data aggregation functions; these aggregator nodes collect data from the surrounding nodes, process the data locally, and then send the aggregated data to the base station.

The design of routing protocols for wireless sensor networks requires new approaches to be developed, to encompass the different characteristic and application requirements. This chapter will introduce some of the routing protocols for wireless sensor networks.

2.2 Characteristics of wireless sensor networks

A sensor network is a collection of small nodes which have sensors embedded within them. These sensor nodes are used to collect events from the environment where they are deployed. Each node has a processor, sensor, memory, and transceiver. Wireless sensor networks consist of large numbers of distributed sensor nodes that organise themselves to form a sensor network. These nodes are small in size and have limited energy resources.

A large number of sensor nodes can enhance the coverage of the field and reliability of the data retrieved. Sensor networks need to aggregate the data obtained from several nodes to ensure that the number of messages transmitted across the network are reduced [25, 28, 42]. Thus, reducing the energy exhausted in transmitting large volumes of data.

Networking in a wireless sensor network is distinguished from that in a conventional wireless data network [19, 20, 45, 55-58], because of the following reasons:

- Sensor nodes are limited in: energy, computational capacities and memory.

- The network organisation and configuration should be performed automatically.

- Sensor networks are application specific.

- The sensor nodes are supposed to transmit the data to the base station, so the typical mode of communication in wireless sensor networks is many-to-one.

- The data is collected by multiple sensor nodes; therefore, there is a redundancy in the sensed data.

- In most applications, sensor nodes are deployed randomly.

- Wireless sensor networks have large numbers of sensor nodes.

- Sensor nodes are prone to failure.

- The topology of sensor networks changes frequently.

- Most sensor nodes are static and the majority of applications focus on the sensor networks of static nodes.

- Sensor networks are data centric; the data is therefore requested based on certain attributes, while in traditional networks the data is requested from a specific node.

2.3 Architecture of wireless sensor networks

The wireless sensor network needs to cover a desired area for sensing and communication; this section discuses a number of different sensor network architectures [43, 46, 48, 49, 58].

- Hierarchical sensor networks are generally more suited for sensor networks as they allow data aggregation within a cluster, this minimises the data transmission over long distances. One node in each cluster is designated as the cluster head and traffic between the nodes of different clusters are routed through their cluster heads. Each cluster has a cluster head that periodically collects sensed data, from its member nodes, and sends it to an upper level as shown in Figure 2-1(a).

- In flat sensor networks, all of the sensor nodes are equal and the connections are setup between the nodes which are in close proximity, communication is established as shown in Figure 2-1(b). Each sensor node receives data and then broadcasts it to other nodes. In sensor networks, flooding is minimised because the sensor node has limited energy.

- Random or deterministic deployment involves the sensor node being deployed either randomly in a sensing field, or placed at a predetermined location.

- Indoor or outdoor environments allow the sensor nodes to be deployed throughout the geographical area; consequently, the system must be able to operate outdoors, in various weather conditions.

- Static or mobile, depending on the application, sensor networks can consist of either static or mobile nodes, or a mixture of both.

- Homogeneous sensor networks have nodes with identical capabilities and functionalities. Typical sensor networks can have hundreds of nodes, whereas homogeneous sensor networks are simpler and easier to deploy.

- Within heterogeneous sensor networks, each of the sensor nodes may have different capabilities and can execute different functions. The sensor nodes may have large battery capacities or powerful processing capabilities which may be required by certain applications. Heterogeneous networks are more complex and their deployment can be complicated because of the different types of sensor nodes.

(a)   (b)

△ Base Station   ◉ Cluster Head   ○ Sensor Node
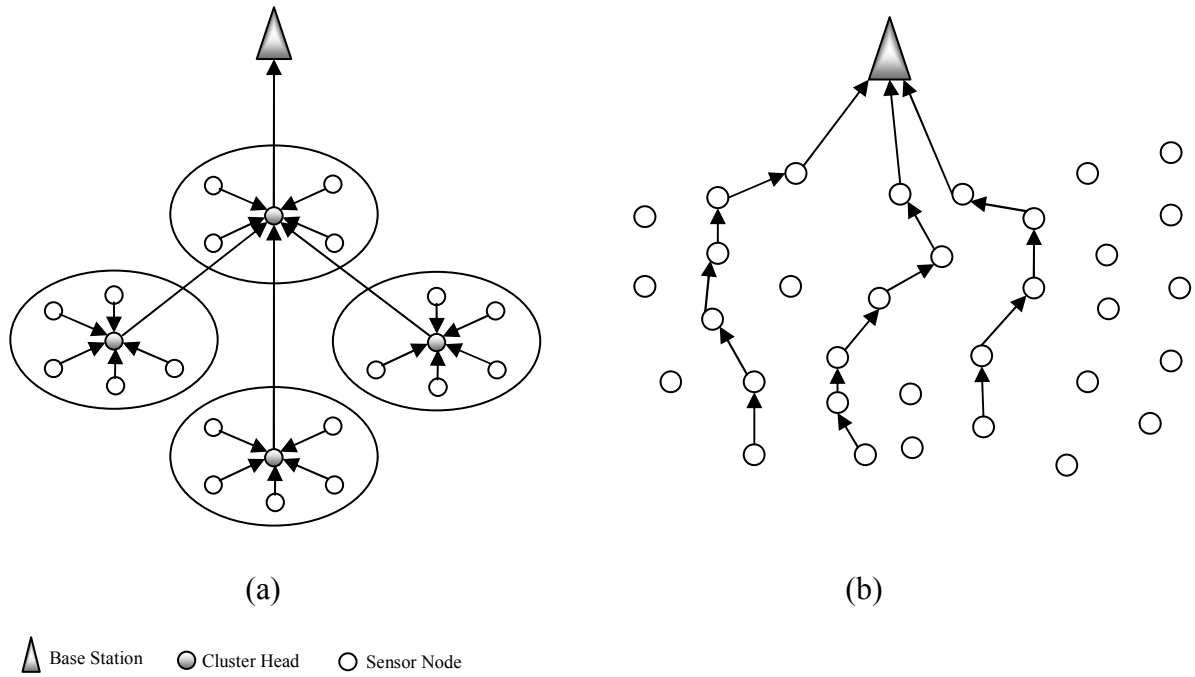
Figure 2-1: Wireless sensor networks: (a) Hierarchical sensor network, (b) Flat sensor network.

2.4 Classification of sensor networks

An important operation in a sensor network is data gathering. Thus, wireless sensor networks can be classified in terms of the data gathering required, this will be different depending on the application [23, 24, 49] being a proactive, reactive or hybrid network.

2.4.1 Proactive networks

The sensor nodes periodically switch on their sensors, sense their environment and transmit their sensed data. The nodes are organised into clusters, the cluster members

sense the parameters specified and send the sensed data to the cluster head. The cluster head aggregates this data and sends it to the base station. Thus, the user has a complete picture of the sensing field at that point in time [28, 43].

2.4.2 Reactive networks

Reactive networks are suited to time critical applications because the sensor nodes can react immediately to sudden changes in the value of a sensed attribute.

The TEEN [23] protocol starts with the formation of clusters. The cluster heads inform the member nodes about the attribute to be sensed, using a hard and soft threshold. The hard threshold tries to reduce the number of transmissions by allowing the nodes to send only when the sensed event is in the range of interest. The soft threshold further reduces the number of transmissions. The nodes sense their environment continuously; when a parameter from the attribute set reaches its hard threshold value, the node sends the sensed data. This protocol is therefore well suited for time critical applications.

2.4.3 Hybrid networks

A hybrid network may be needed because it can react immediately to time critical situations and can also provide an overall picture of the network at periodic intervals. APTEEN [24] is hybrid protocol; the cluster head broadcasts hard thresholds and soft thresholds to its member nodes to reduce data transmission. The sensor node senses the environment continuously and only reports sensed data to the cluster head when the

value of the sensed data is greater than or equal to the hard threshold value. Once a node senses a value greater than the hard threshold, it transmits data when the value of the specified attribute changes by an amount equal to or greater than the soft threshold. If a sensor node does not send data for a specified time period, it senses the environment and transmits data. APTEEN therefore implements a hybrid network by combining proactive and reactive schemes.

2.5 Applications of wireless sensor networks

Wireless sensor networks offer significant advantages over wired sensors. The organisation of a wired sensor network should be pre-planned and it should be installed appropriately. The failure of a single node could corrupt the whole network or leave a region completely uncovered. The main problem with wired sensor networks is the cost and the delay in deployment. Wireless sensor networks can reduce costs, wired sensors can be replaced which can also enable new applications.

Applications can be classified into: environment observation, forecast systems, habitat monitoring, healthcare, and other commercial applications [60-65]. The following sections will discuss a list of application areas for wireless senor networks.

2.5.1 Environmental monitoring

Sensors can be used to monitor the conditions and movements of wild animals or plants, in wildlife habitats; they can also monitor the air quality and track environmental pollutants, wildfires, or other natural disasters.

Engineers installed 190 sensor nodes to monitor the habitat of ocean birds on Great Duck Island [59, 61]. In the past, researches had to travel to these types of locations to study the nesting behaviours of these birds, but now these researchers can monitor the birds on this island from their offices.

A total of 190 sensor nodes were placed in the area to be sensed, these were grouped into sensor patches to transmit the sensed data to a gateway which was responsible for forwarding the data to a base station, as shown in Figure 2-2.
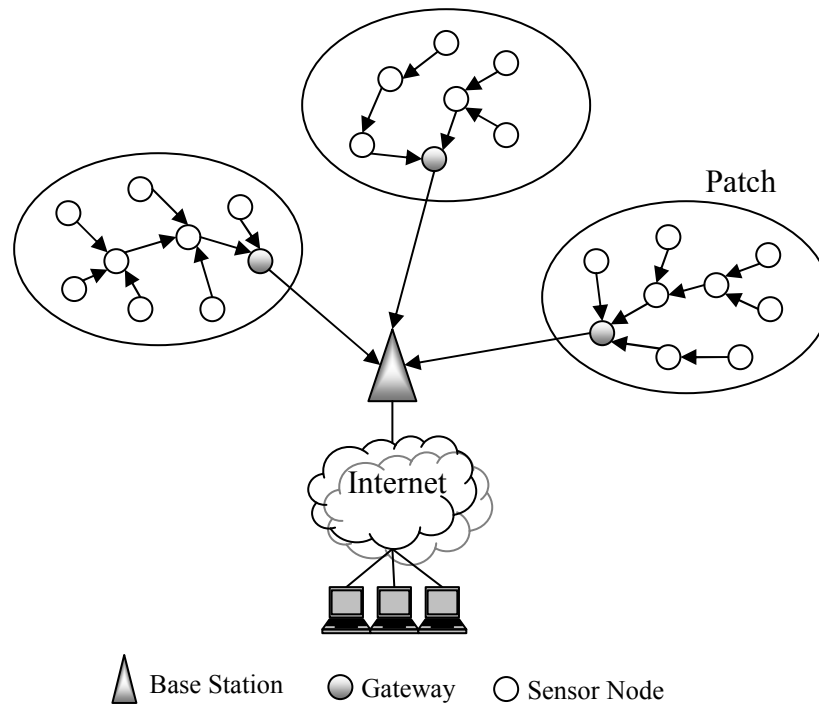
Figure 2-2: Island monitoring system architecture.

The Hawaii University [60] built a wireless sensor network to investigate why some plants were growing in one area but not in neighbouring areas. They deployed sensor nodes in the Hawaii Volcanoes National Park. The sensor nodes contained processors, transceivers, environmental sensors, and digital cameras. Each sensor collected its own data and also forwarded data coming from other units towards the base station. Two types of data were collected: every ten minutes the system would collect weather data and every hour the system would collect image data.

2.5.2 Asset management

Sensor networks could be used to monitor and track specific assets, such as building equipment, without a fixed networking infrastructure. Companies could significantly improve their asset utilisation by using real time information about equipment condition. The tracing of lorries and railcars, and the tracking of parameters regarding carried goods, is possible by using GPS systems and wireless sensor networks [64].

Medical centres have many medical assets, some are mobile and others are stationary. The medical asset tracking application has valuable benefits for patients, nurses and physicians. When patients arrive at hospitals, the nurses can provide appropriate medical assets to the patients in accordance with their medical problems [64].

2.5.3 Smart transportation

Sensor nodes, embedded in highways or cars, can measure traffic flow and monitor speed and other conditions [64, 67]. Wireless sensor networks could be used to make the roads safer and reduce congestion. During an emergency brake, an alert message could be broadcasted to other cars to optimise their routes and reduce congestion. Cars can also monitor their own condition and transmit emission data to a service centre for maintenance.

An objective of a smart system [79, 80] was to provide real data about the distribution of empty parking lots and to guide drivers to them. Wireless sensor nodes were deployed to

the parking lots to monitor and detect the occupation status of the space, and to transmit the sensed data to the smart system through the base station. The use of the smart system allowed the administrators to obtain sensed data about the parking field, including statistics and real-time data. In addition, the smart system could direct drivers towards the empty parking lots.

2.5.4 Healthcare

There are many applications within the healthcare category, including remote monitoring of physiological data, tracking and monitoring doctors and patients, and drug administration [63, 66, 68]. Patients can benefit from the use of sensor networks that monitor patient's vital signs and which are remotely connected to doctor's offices.

A medical supervision system [63] proposed a three layer network structure. The first layer involved a medical sensor which provided physiological information, such as: pulse, heart rate, and blood pressure. These sensors formed a start topology; a gateway node could be elected manually or by a self organising protocol.

The second layer provided reliable transmission. If the patient was outside their home, the physiological information would be sent by a mobile phone or a PDA device. When the patient was at home, the physiological information would be sent to the nearest sensor nodes. These nodes would route the data to a PC with an internet connection.

The third layer of the system was responsible for data aggregation of the physiological information in a medical centre, for analysis and for providing feedback data to the patient.

2.5.5 Home/office applications

Homes and offices waste vast amounts of energy through the use of inefficient humidity appliances – air conditioning. Wireless sensor networks can monitor temperature, air flow, humidity, and other parameters in homes and offices to reduce energy consumption [69, 70].

The sensor nodes can be embedded into furniture and appliances, and they can communicate with each other to become self-organised, self-regulated, and adaptive systems. Smart home vacuum systems are replacing the old vacuum cleaners; the smart vacuum systems consist of vacuum sensor nodes and an intelligent cleaning station.

Each vacuum sensor moves, sweeps, and senses in its responsible area, it then sends all data to the intelligent cleaning station. After collecting and analysing the data, the intelligent cleaning station selects an appropriate cleaning head and issues the commands to perform the cleaning job [53, 63].

2.6 Routing strategies for wireless sensor networks

2.6.1 Flooding

The flooding [19, 82] technique is used for path discovery and information distribution in data communication networks. The sensor node receives a data and then transmits this data to all of its neighbours. After transmission, the data will have followed all of the possible paths. Each node that receives the data firstly stores a copy of the data and then broadcasts it. Figure 2-3 shows the concept of flooding in data communication networks.
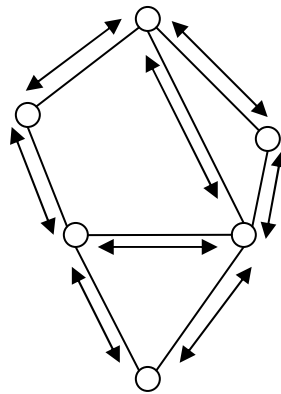
Figure 2-3: Flooding in data communications networks.

To avoid data circulating endlessly, a hop count field is added in the data packet. As the data packet travels in the network, the hop count is decremented by one; when the hop count reaches zero, the data packet is discarded. As shown in Figure 2-3, flooding may

cause data packets to be replicated by the sensor nodes. Each node could receive multiple copies of the same data packet, thereby resulting in wasted energy resources due to replication.

2.6.2 Gossiping

In gossiping [19, 42], the source node sends the data to a randomly selected neighbour. Each node that receives the data randomly selects a neighbour and sends the data to it. This process is repeated by all the nodes that receive the data, until the data reaches its destination.

Since gossiping sends the data to only one neighbour, this is energy saving. However, the latency that a data suffers, on its way to the destination, may be too much due to the random nature of the protocol.

2.6.3 SPIN

In SPIN [72], the nodes learn about the content of the data before any data are sent between the nodes. The sensor nodes associate metadata with the data they produce and use these metadata before transmitting the actual data. There are three types of message: ADV, REQ, and DATA; ADV advertises new data, REQ requests data, and DATA is the actual message.

When a node obtains new data, it broadcasts an ADV message to all of its neighbours – the metadata describes the new data. Upon receiving the ADV message, which contains metadata, a node interested in receiving specific data sends a REQ message to the sender of the ADV message. The sender responds with a data message containing the requested data.

The behaviour of SPIN is illustrated in Figure 2-4, where node A advertises its data by broadcasting an ADV message and nodes B, D, and E respond by requesting the data using a REQ message.
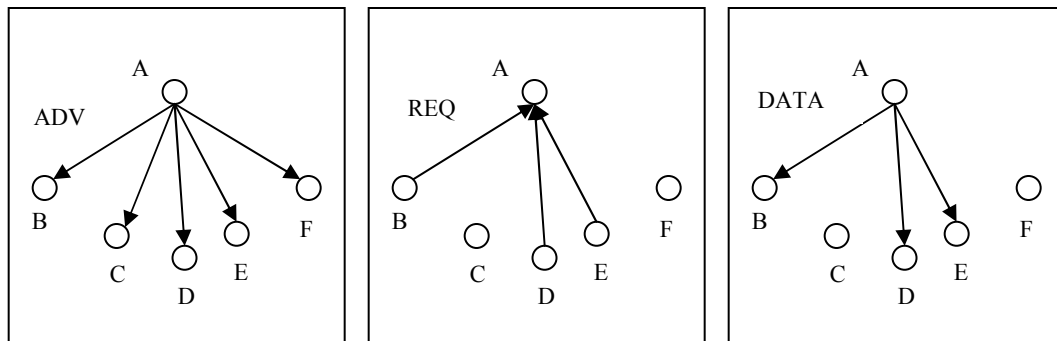
Figure 2-4: SPIN protocol operation.

2.6.4 LEACH Protocol

The low energy adaptive clustering hierarchy [1] (LEACH) is a cluster based protocol; LEACH randomly selects a set of sensor nodes as cluster heads. In LEACH, the cluster heads have many responsibilities: firstly they are responsible for collecting data from the member nodes; secondly, they transmit the aggregated data to the base station; and

thirdly, they are responsible for creating a TDMA schedule which specifies the time slots allocated for each member of the cluster.

The operation of LEACH is organised into two phases, the setup phase and the steady state phase, as shown in Figure 2-5. In the setup phase, the cluster heads are selected and the clusters are formed; while the steady state phase focuses on data collection and the transferring of data to the base station. During the setup phase, a set of sensor nodes select themselves as cluster heads as follows: a sensor node chooses a random number between zero and one; the sensor node then becomes a cluster head if its generated random number is less than a threshold value, $T(n)$.

$$T(n) = \begin{cases} \dfrac{p}{1 - p \times (r \bmod \dfrac{1}{p})} & if\ n \in G \\ 0 & otherwise \end{cases} \qquad (1)$$

Where p is the predetermined percentage of the cluster heads (e.g. $p = 0.05$), r is the current round, and G is the set of nodes that were not cluster heads in the last $1/p$ round.
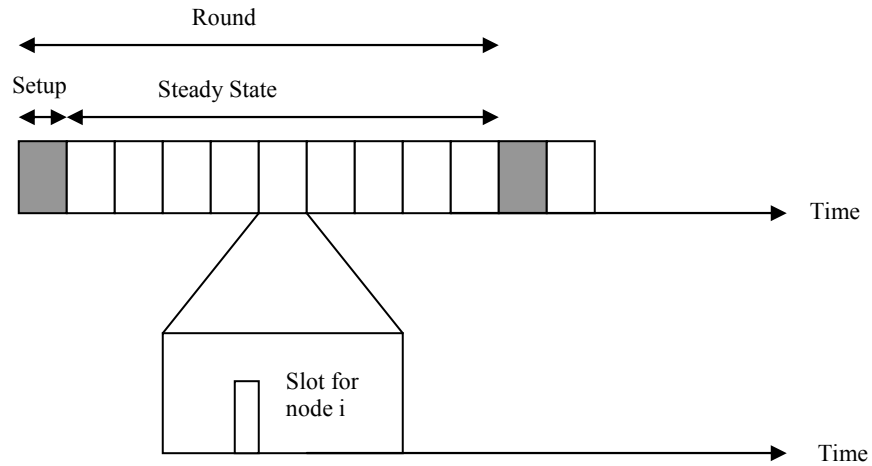
Figure 2-5: LEACH phases.

The cluster heads broadcast an advertisement message to the remaining sensor nodes. Each sensor node selects a cluster head, based on the received signal strength. The cluster head creates a TDMA schedule and assigns each sensor node a time slot when it can transmit; this schedule is broadcasted to all member nodes.

During the steady state phase, sensor nodes sense the environment, collect data and send the sensed data to the cluster heads. After receiving all data, the cluster heads aggregate the data and send it to the base station. The length of the steady state phase period is critical to achieving the energy reduction: a short steady state period increases the communication overhead; whereas, a long steady state period can lead to cluster head energy exhaustion.

2.6.5 PEGASIS

The power efficient gathering in sensor information systems [22] (PEGASIS) is an improvement of the well known LEACH protocol, for clustering based communication in sensor networks. Rather than forming multiple clusters, PEGASIS forms chains from the sensor nodes, each node transmits and receives from a neighbour and only one node is selected from that chain, as a leader node, to transmit information to the base station. The main objectives of PEGASIS are to increase the lifetime of a network and to only allow local coordination between the nodes that are close together, this ensures that the bandwidth consumed in communication is reduced.
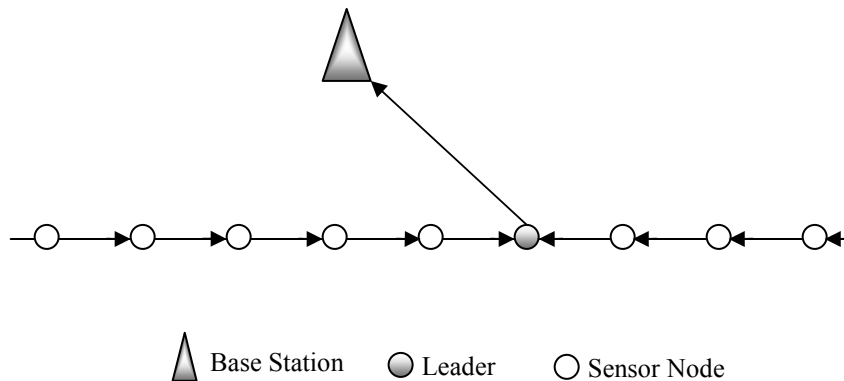
Figure 2-6: Data gathering in PEGASIS.

As show in Figure 2-6, the data gathering in PEGASIS is achieved along the chain. The leader node issues a token to the last node in the one side of the chain. Upon receiving the token, the end node transmits its data to the next neighbour. That neighbour

29

aggregates this data with its own data and transmits this to the next neighbour, heading towards the leader. Upon receiving the data from that side, the leader node issues a token to the other side, and same process is repeated. Upon receiving the data from the left and right sides, the leader node aggregates the data and sends this to the base station.

The PEGASIS system eliminated the overheads caused by the dynamic cluster formation in LEACH, and decreased the number of transmissions and receptions by using data aggregation. Despite this achievement, there was an excessive delay introduced by the single chain for the distant nodes.

2.6.6 Directed diffusion

Directed diffusion is a data centric routing protocol, for data gathering, in wireless sensor networks [71]. The main idea of the data centric is to combine the data coming from different sources and send it to the base station, as shown in Figure 2-7(a). While in address centric routing, the source nodes detect an event and use an end-to-end path to send data to the base station, as shown in Figure 2-7(b).
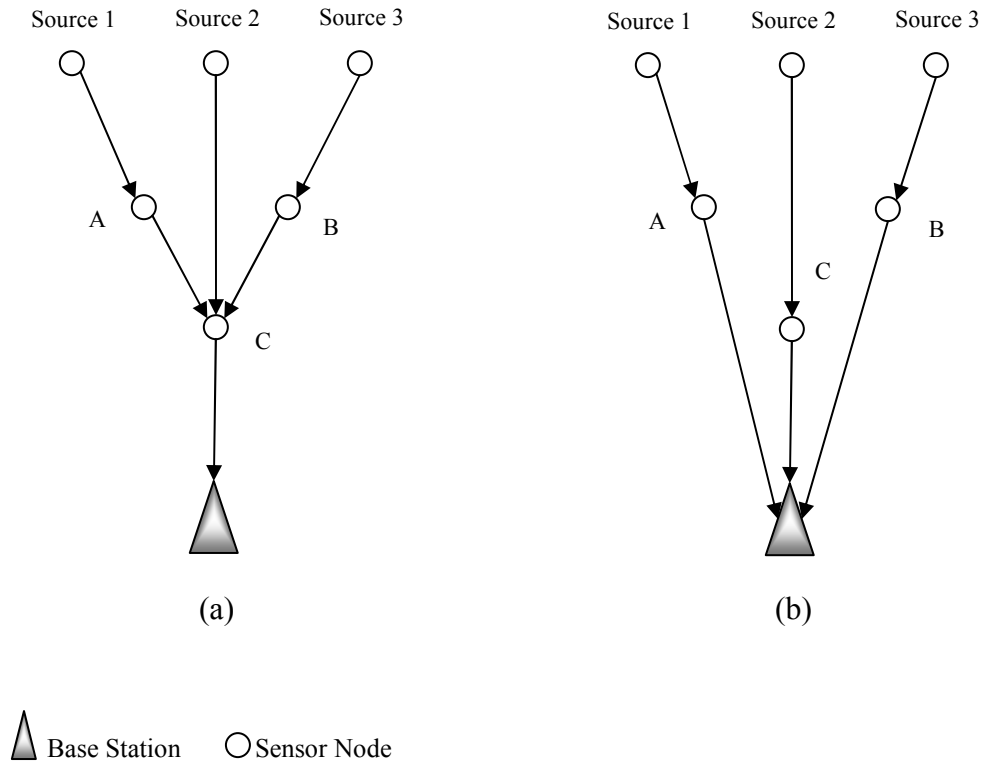
Figure 2-7: Data centric routing (a) and address centric routing (b).

In directed diffusion, the query is flooded throughout the network and gradients are setup to send data towards the base station. The base station requests data by broadcasting interest to all sensor nodes. Each node stores the interest entry in its cache. The cache entry contains several fields, including a multiple gradient field which specifies the data rate and the direction in which the data are to be sent.

When sensor nodes detect an event, they search the interest cache for an entry matching the interest. If a match is found, the sensor node sends the data along the interest's

gradient path. The disadvantage of directed diffusion is that the base station periodically resends the interest which decreases the network's lifetime.

2.6.7 GEAR

GEAR [56, 81] performs the delivery of data in two phases. First, it delivers the data from the source node to a node in that region. Each node knows its neighbours, their positions, and their remaining energy; upon receiving a data, it is forwarded to the neighbour node that is closet to the destination.

In the second phase, when a data reaches the destination region, it can be routed to all nodes in that region by recursive geographic forwarding. The destination region is divided into sub regions and a copy of the data is sent to each sub region. When a copy of the data reaches the sub region, the same procedure is repeated in that sub region, consequently, it is divided into sub regions and a copy of the data is sent to each sub region. This continues until one node is left in the sub region. GEAR provides energy efficient and location based routing protocols.

2.6.8 ACQUIRE

ACQUIRE [73] is suitable for complex queries that can be divided into sub-queries. ACQUIRE starts from the base station by forwarding the query, each node tries to answer the query using its information and then sends the query on to other nodes. If the

sensor node has no information in its cache, it collects data from its neighbours and forwards the query to other sensor nodes.

This process repeats until a node decides that it has sufficient data to answer the query. The ACQUIRE protocol is advantageous because it can handle complex queries; the queries are answered by the many sensor nodes in the network.

2.6.9 Rumer routing

Rumer routing [74] uses flooding to propagate queries in the network, the data is sent to the base station through multiple paths. When an event occurs, the sensor node adds the event to its event table and generates an agent. Rumer routing finds a few paths in a network by sending out agents; each agent travels from node to node and adds routing information about the event in each node.

When a query is generated, the sensor nodes can reply to a query by checking the event table and forwarding it towards the source node. This protocol is energy saving; however, it has large overheads due to maintaining agents and event tables.

2.6.10   Buddy routing

In a buddy protocol [75], each sensor node attempts to establish a buddy relationship with its neighbours. As a result, a number of buddy groups (clusters) are formed. The cluster has a single node which is representative for all its buddies; this representative

node is responsible for monitoring and answering queries and it allows other nodes to go to sleep.

Communication between the sensor and the representative nodes can be a default or PREMON [76] mode. In the default mode, a sensor node periodically sends data to the representative node. In the PREMON mode, a sensor node generates a prediction of its reading and sends it to the base station with a specific duration for which the prediction model is valid. During the lifetime of predicted reading, the sensor node sends only those readings that differ from the predicted reading; each sensor node decides whether to use a default or PREMON mode based on estimated energy costs.

2.6.11   Energy aware routing for cluster based sensor networks

In energy aware routing for cluster based sensor networks [77], the sensor nodes are divided into clusters, each cluster contains a cluster head, namely the gateway, which is less energy constrained than the sensor nodes. Gateways maintain the states of the sensor nodes and setup paths for collecting sensed data.

The sensor nodes in a cluster have four states: sensing only, relaying only, sensing-relaying, and inactive. In the sensing only state, the sensor node collects data from the environment. In the relaying only state, the node routes the data from other active nodes

and does not sense the environment. In the sensing-relaying state, the node is both sensing and relaying data from other active nodes. In the inactive state, the sensor node can turn off its sensing and communicating circuiting.

The gateway determines the node's state which is based on the current sensor's organisation, the node's energy levels, and the network's performance. The gateway also sets routes for sensor data. The parameters effecting the routing decision are the sensor's state, location, energy, and traffic.

The operation of a network consists of a data cycle and routing cycle. In the data cycle, the sensor nodes send their data to the gateway; while in the routing cycle, the state of the sensor nodes are determined by the gateway and the nodes are informed on how to route the sensed data. Energy aware routing for cluster based sensor networks provide a valuable solution because they minimise energy dissipation; however, this can be complex.

2.6.12   EESH protocol

In EESH [78], all of the sensor nodes send energy statuses and locations to the base station. The base station calculates average energy and divides the sensor nodes into strong nodes and weak nodes. EESH evaluates a cost for every sensor node in the network; cost is determined by the energy of the node, the remaining energy of the neighbouring nodes, the distance from the neighbours, and the number of nodes nearby.

Sensor nodes may have a greater cost if they have more neighbours of lower energy or shorter distances. EESH selects the sensor node which has the greatest cost as the cluster head.

2.6.13   CPEQ protocol

CPEQ [30] is a cluster based routing protocol that groups the sensor nodes to route the sensed data to the base station. It uses a random node to elect the cluster head, instead of using the randomly elected sensor node as the cluster head. In the CPEQ protocol, the sensor nodes with more energy are elected as the cluster heads to route data to the base station by uniformly distributing energy dissipation among the sensor nodes. To build clusters, the CPEQ uses a time to live, to limit the size of the cluster, and calculates the routes from the member nodes to the cluster head. By checking the time to live, the node will join the cluster that is closet to the cluster head.

After receiving data from the sensor nodes within the cluster, the cluster head sends this data to the base station using multihop routes. CPEQ uses the optimised routes among the cluster heads and the base station. It reduces traffic collision and delay by performing data aggregation and selecting the most optimal routes. The disadvantage of CPEQ is that it uses the flooding mechanism which can cause redundancy – a node sends data to its neighbour irrespective of whether it already has it or needs it.

2.6.14 RRCH protocol

RRCH [31] forms clusters in the setup phase. Once the clusters are formed, RRCH keeps the fixed clusters and uses a round robin method to select the cluster heads from the sensor nodes within the clusters. RRCH forms clusters and avoids energy consumption during the setup phase. When a sensor node has been detected as an abnormal node, the RRCH broadcasts information to the entire cluster during frame modification, and then each sensor node deletes the abnormal node from its schedule.

The RRCH protocol is able to implement load balancing among the sensor nodes to enhance energy consumption in sensor networks. Since RRCH keeps the fixed clusters, it cannot handle clusters with poor quality, those which are too small or too big in cluster size or which overlay other clusters.

2.6.15 PEBECS protocol

The PEBECS [32] protocol divides the senor network into several partitions with equal areas and then groups the sensor nodes into unequally sized clusters. A set of sensor nodes, in each partition, are elected as cluster heads. PEBECS can elect the sensor nodes as cluster heads by using a set of metrics with certain weighting factors. This means that a node decides to become a cluster head depending on its combined weight metric. These metrics include: remaining energy, degree difference and the relative location in the network.

The elected cluster heads broadcast messages to advertise their status; upon receiving the message, each sensor node joins a cluster and becomes a cluster member. PEBECS groups the sensor nodes into smaller clusters to save energy within intra cluster communication; thus, prolonging the network's lifetime, reducing the energy consumption and improving the network's scalability.

2.6.16   Energy efficient multihop polling protocol

In proposed energy efficient multihop polling [33], there are two types of sensor node: the basic sensor nodes and the cluster heads. The basic sensor nodes are simple and have limited power supplies, while the cluster head nodes are more powerful because they have greater power supplies. The basic sensor nodes can be deployed randomly; whereas, the cluster heads should be carefully deployed, so that each sensor node can communicate with at least one cluster head.

This protocol divides the network into clusters and selects powerful cluster heads by letting the cluster head know which sensor nodes are in its cluster and by informing the sensor nodes which cluster they belong to. This consumes less energy because it polls data from the sensor nodes, instead of letting the sensor nodes send data randomly. However, the cluster heads need to be very powerful and carefully deployed.

2.6.17 EAD protocol

EAD [34] presents an energy aware protocol – a broadcast tree with leaves. It extends the network's lifetime by turning off the transceivers of all the leaf nodes in the tree and allows only non-leaf nodes to control the data aggregation and the relaying of tasks. Each round comprises an initial phase and a transmit phase. In the initial phase, the objective of EAD is to identify the non-leaf nodes and set up the backbone. Once completed, the sensor nodes proceed to the transmit phase and transmit data to the base station. After each transmit phase, the EAD will rebuild the broadcast tree to identify all of the dead nodes.

The disadvantages of EAD are concerned with the randomly selected cluster heads which may have a high communication cost; if periodic cluster head rotation is used to reduce the communication costs, the selection of the cluster heads uses extra energy to rebuild the clusters. Furthermore, the random selection of cluster heads cannot guarantee good protocol performance.

2.6.18 LEACH-centralised

LEACH-centralised [9] uses a centralised clustering algorithm. In the setup phase, the base station receives all of the information about each node, regarding: their location and energy status. The base station runs local algorithms for the formation of cluster heads and clusters and broadcasts a message that contains the cluster head's ID for each

node. During the steady state phase, the sensor nodes: sense the environment, collect data and send the sensed data to the cluster heads. After receiving all of the data, the cluster heads aggregate the data and send it to the base station. Because the clustering setup is performed each time, a significant amount of energy is consumed and communication latency is increased.

2.6.19   LEACH-F

LEACH with fixed clusters (LEACH-F) [9] uses the following clustering-model: a set of nodes are elected as cluster heads. These cluster heads collect data from other nodes in the clusters, aggregate the data and send it to the base station. It uses fixed clusters that are formed, only once, in the first setup phase by the base station. The cluster head position rotates, and every node can become a head of its cluster. The fixed clusters do not allow new nodes to be added to the network, and the performance of the node is not affected by nodes dying.

2.6.20   HEED

HEED [2] is a clustering protocol that uses the remaining energy and the intra-cluster communication cost. In every cluster period, sensor nodes become cluster heads based on their probability which is proportional to their remaining energy. To prevent sensor nodes from having more than one cluster head, HEED uses intra-cluster communication to determine energy cost. In its initialisation phase, HEED allows the sensor nodes to

compute the probability of becoming the cluster head. Then, during the repetition phase, the sensor nodes seek the best cluster head to join it. If no cluster head is found, the sensor node becomes the cluster head.

HEED provides balanced cluster heads and smaller sized clusters. They use two radio transmission power levels: one for intra-cluster communication and the other for inter-cluster communication. HEED does not select cluster head nodes randomly and the sensor nodes that have a high level of remaining energy can become cluster head nodes. However, to balance the remaining energy of the sensor nodes, HEED requires frequent re-clustering – this has a high overhead cost.

2.7 Conclusion

This chapter has described some of the routing protocols developed for wireless sensor networks; these protocols include many of the important design approaches and techniques.

Sensor networks are different from other networks because they consist of sensor nodes which are powered by batteries; therefore, energy is the most important resource. The typical mode of communication in sensor networks is many-to-one. This provides opportunities for designing special routing protocols. The scalability of the protocol is also very important because the sensor networks have large numbers of sensor nodes.

Wireless sensor networks can be application specific; therefore, it is possible to design routing protocols that are application aware.

Chapter 3

Adaptive Decentralised Re-Clustering Protocol for Wireless Sensor Networks

3.1 Introduction

A wireless sensor network is composed of sensor nodes and a base station. The base station is usually much more powerful than the sensor nodes because it has its own power supply. However, it needs to collect the sensed information from the sensor nodes and send it back to the user. Wireless sensor nodes are low-powered; therefore, the constraint on power consumption is an important issue that needs considering when wireless sensor network protocols are designed.

Clustering is considered an effective method for reducing the energy consumption of a wireless sensor network. It is defined as the process of choosing a set of wireless sensor nodes to be the cluster head within a given wireless sensor network. Therefore, data traffic generated at each sensor node can be sent via cluster heads to the base station [7,

28]. Clustering is also used for data aggregation, where the cluster heads aggregate the information collected by the cluster members.

The adaptive decentralised re-clustering protocol (ADRP), for wireless sensor networks, can be utilised to elect the cluster head and the following heads in a wireless sensor network. The selection of these cluster heads are weighted by the remaining energy of the sensor nodes and the average energy of each cluster. ADRP is an adaptive clustering protocol; the cluster heads rotate over time to balance the energy dissipation of the sensor nodes.

The remainder of this chapter will be organised as follows: the following section, Section 2, will provide an overview of the cluster based routing schemes. Section 3 will define the system model, Section 4 will present the ADRP, Section 5 will provide details of the algorithm, Section 6 will present the simulation setup and results and finally, Section 7 will conclude the chapter.

3.2 System model

In this protocol, the sensor nodes periodically switch on their sensors and transmitters, sense the environment and transmit data. The wireless sensor network consists of (N) sensor nodes, these sensor nodes are deployed randomly in the sensing field. As shown in Figure 3-1, the base station splits the network into clusters and elects some sensor

nodes as cluster heads which collect sensor data from the other nodes in the cluster and transfer the aggregated data to the base station. Each cluster has one cluster head, the next head and a set of sensor nodes. Since the transfer of data to the base station dissipates much energy, the nodes take turns to transmit, by rotating the cluster head; thus, leading to a balanced energy consumption of all nodes and hence to a longer lifetime of the network. In the proposed protocol for this research, the following assumptions are considered:

1- There is a base station located far away from the square sensing field.

2- Each sensor node is assigned a unique identifier (ID).

3- Each sensor node has power control and is able to transmit data to any other sensor node or directly to the base station.

4- Nodes are immobile.

5- All the sensor nodes are location aware; to obtain information the sensor nodes can use GPS or other location detection schemes.
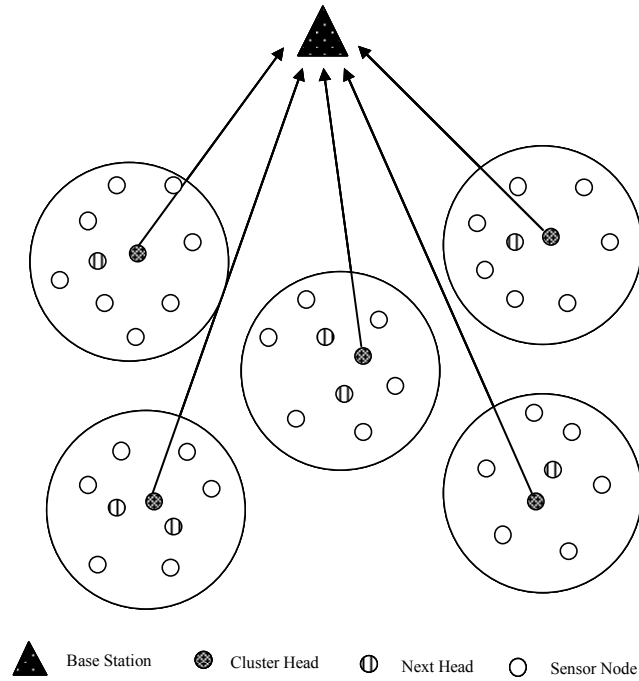
Figure 3-1: Cluster topology.

3.3 ADRP protocol

ADRP is a clustering protocol for wireless sensor networks. It is used to collect data from distributed sensor nodes and transmits the data to a base station. ADRP is designed to support periodic remote monitoring sensor networks.

A wireless sensor network usually contains a large number of sensor nodes over a wide area and the base station is often located far from the sensor nodes. Dividing the entire network into clusters would reduce the energy consumed for data communication. The network activity is organised into rounds, where each round has two phases: initial

phase and cycle phase, as shown in Figure 3-2. The duration of the cycle phase is longer than the duration of the initial phase, this minimises overheads.

Round

| Partition Stage | Selection Stage | Advertis. Stage | Schedule Stage | Transmi. Stage | Recluster Stage |

Initial Phase   Cycle Phase
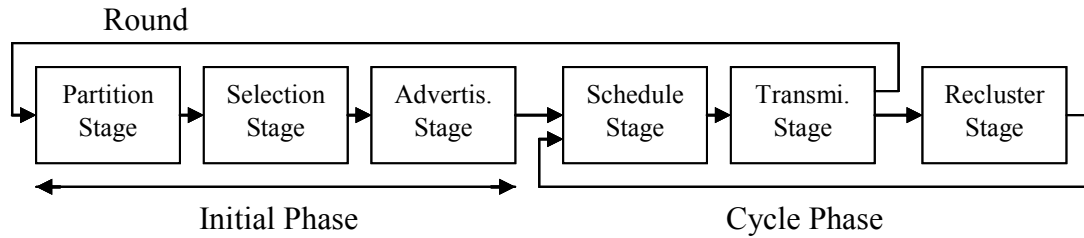
Figure 3-2: ADRP Operations.

During the initial phase, each node sends its energy status and location to the base station. The base station splits the network into clusters and selects a cluster head for each cluster, according to the location information from the sensor nodes.

Once the clusters are formed, the base station selects a set of sensor nodes to be the next heads; this information will be used during the re-cluster stage. The base station sends advertisement messages to all of the nodes in the network which contain the cluster heads ID and next heads for each of the sensor nodes.

During the cycle phase, each cluster head creates and distributes the TDMA schedule, which specifies the time slots allocated for each member of the cluster. The cluster head advertises the schedule to its cluster members through broadcasting. Each node is assigned a unique time slot during which it can transmit its data to the cluster head.

Upon receiving data packets from its cluster nodes, the cluster head aggregates the data before sending them to the base station. At the end of this phase, each node selects the next head as its new cluster head and switches to it. The nodes join the next cluster head and become cluster members in order to complete the forming of the cluster. The old cluster heads switch their status to become member nodes and join the next head.

3.4 ADRP algorithm details

3.4.1 Initial phase

The base station receives information about the current locations and the remaining energy levels from the sensor nodes; it then uses this information to split the network into clusters and to determine the cluster heads. Once the clusters are formed, the base station determines the next heads. In order to do this, the base station computes the average energy for each cluster in the network, any sensor nodes that have energy storage levels that are below this average cannot become the next heads for this round.

Once the cluster heads and next heads are determined, the base station broadcasts the information concerning the cluster heads and next heads to all the sensor nodes. The initial phase consists of three stages: partition stage, selection stage and advertisement stage.

3.4.1.1 Partition stage

During this stage, each sensor node transmits data, to the base station, concerning its position and the amount of energy it has. The sensor nodes obtain their current location by using global positioning system receivers that are activated at the beginning of the initial phase.

On receiving the data, the base station calculates the energy value of all the sensor nodes and then elects the cluster head by minimising the total sum of the distances between the cluster heads and the sensor nodes. Furthermore, the base station ensures that only the nodes with enough energy participate in the cluster head selection. ADRP can distribute the energy between the sensor nodes by positioning cluster heads in the centre of clusters. At end of this stage, ADRP partitions the nodes into sets of clusters and each cluster is managed by a selected cluster head. There are three different kinds of sensors: cluster heads, sensor nodes and next heads. The next stage focuses on electing the next head node.

3.4.1.2 Selection stage

The cluster head is responsible for receiving all the data from the nodes within the cluster, aggregating this data and sending the aggregated data to the base station. If this role was fixed, the cluster head would quickly drain its limited energy and die.

Therefore, ADRP rotates this role among all the sensor nodes in the network to distribute the energy load.

In this stage, the ADRP protocol requires a set of sensor nodes to be elected as the next heads. During the cycle phase, the sensor nodes can switch from the current cluster head to the next head.

Once the clusters have been formed, the ADRP selects a set of sensor nodes as the next heads. To do this, the ADRP computes the threshold (average energy) for each cluster; the nodes which have energy levels below this threshold cannot be the next heads for the current round.

To select the sensor node which will become the next head, the ADRP repeats the following two steps for each cluster.

1- ADRP computes the threshold for each cluster $-j$

$$Tj = \frac{1}{m}\sum_{i=1}^{m} Ei(t) \qquad (3.1)$$

Where m is the number of sensor nodes in cluster j.

$Ei(t)$ is the current energy of node i.

The sensor nodes with higher energies are therefore more likely to become the next heads.

2- If the current energy of node i is greater than or equal to Tj, the threshold of cluster j, then node i is the member of set NHj.

$$Ei(t) \geq Tj \iff i \in NHj \qquad (3.2)$$

Where NHj is the set of nodes that are eligible to be next heads in cluster j.

Once NHj sets have been created, the ADRP elects a group of next heads from the sets and specifies its member nodes.

At end of this stage, there are three different kinds of sensors:

1- Cluster heads collect sensor data from the cluster members, aggregate the data and forward it to the base station.

2- Sensor nodes gather sensor data and forward the data to the cluster head.

3- Next heads act as sensor nodes but during the re-clustering stage each sensor node selects the next head as its new cluster head and switches to it.

Figure 3-3 shows the transition states of a sensor node.
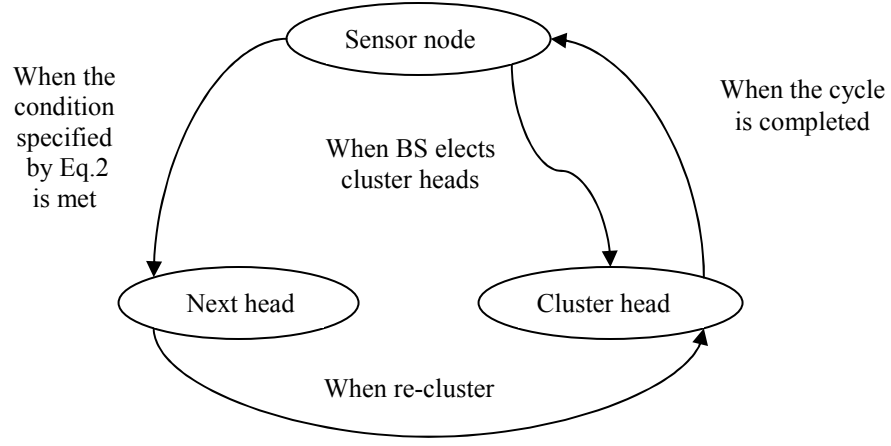
Figure 3-3: State transition diagram of node.

3.4.1.3   Advertisement stage

During this stage, the base station sends a message containing the cluster head's ID and the next heads for each sensor node. If a node's cluster head ID matches its own ID, the node is a cluster head; otherwise, the node is a sensor node.

3.4.2 Cycle phase

Cluster heads create and distribute the TDMA schedule, which specifies the time slots allocated for each member of the cluster. Each sensor node sends its data during its allocated transmission time slot. Upon receiving data packets from its cluster nodes, the cluster head aggregates the data before sending them to the base station. At the end of

this phase each node selects the next head as the new cluster head and switches to it. At this point, the old cluster head switches its role and becomes a normal member. The cycle phase consists of three stages: schedule stage, transmission stage and re-cluster stage.

3.4.2.1 Schedule stage

Once the clusters have been formed, the sensor nodes must send their data to the cluster head. ADRP uses TDMA, which allows the sensor nodes to enter a sleep mode when they are not transmitting data to the cluster head. Furthermore, by using a TDMA approach for intra-cluster communication, this ensures that no collisions of data occur within the cluster.

Based on the number of nodes in the cluster, the cluster head creates a TDMA schedule which informs each node when it can transmit. The TDMA schedule divides time into a set of slots, the number of slots being equal to the number of nodes in the cluster. Each node is assigned a unique time slot during which it can transmit its data to the cluster head. Using TDMA requires that all sensor nodes be time-synchronized and requires guard slots to separate users [29].

3.4.2.2 Transmission stage

The data transmission stage consists of three major activities:

• Data gathering

• Data aggregation

• Data sending

At each sensing period, all of the sensor nodes send their data to their cluster head, when the cluster head receives data from the member nodes, instead of forwarding all the data, the cluster head checks the contents of the incoming data, combines them and eliminates redundant data. Then, the cluster head transmits the aggregated data to the base station using a CSMA MAC protocol. The data aggregation aims to minimise traffic load by eliminating redundancy.

3.4.2.3   Re-cluster stage

The ADRP periodically re-clusters the network in order to distribute the energy consumption among all the sensor nodes in a wireless sensor network.

In the initial phase the base station sends messages containing the cluster head's ID and the next heads for each sensor node in the network. So, the sensor nodes can switch directly to the next heads without communicating with the base station; thus, the ADRP protocol forms new clusters each cycle phase.

During the re-cluster stage, the sensor nodes select the next heads to act as cluster heads in the next cycle and switches to them. When all the sensor nodes in the network select the next heads and switch to them, the re-cluster stage is complete and the schedule stage can begin. If there is no next head available, the initial phase will begin instead.

3.5 Simulation and discussion

In this section, the performance of ADRP will be analysed; simulated using OMNET++ simulator [21] and against the low-energy adaptive clustering hierarchy (LEACH-C) in terms of the following metrics:

1. Network lifetime: this metric shows the number of sensor nodes that die over the time of operation.

2. Received data messages: this metric shows the number of data messages successfully delivered to the base station.

3. Energy dissipation: this metric shows the energy consumption over the time of the activity.

4. Communication overhead: this metric shows the number of messages received at the base station during the initial phase to setup the clusters.

3.5.1 Simulation setup

As shown in Figure 3-4, the simulations were configured with a network size of 100 x 100 meters and with 100 nodes randomly distributed; the base stations were located at positions 50 and 175. All of the sensor nodes periodically sensed the environment and transmitted the data to the cluster heads. Every result shown is an average of 10 experiments, with a 95% confidence interval. Each experiment used a different randomly generated topology.
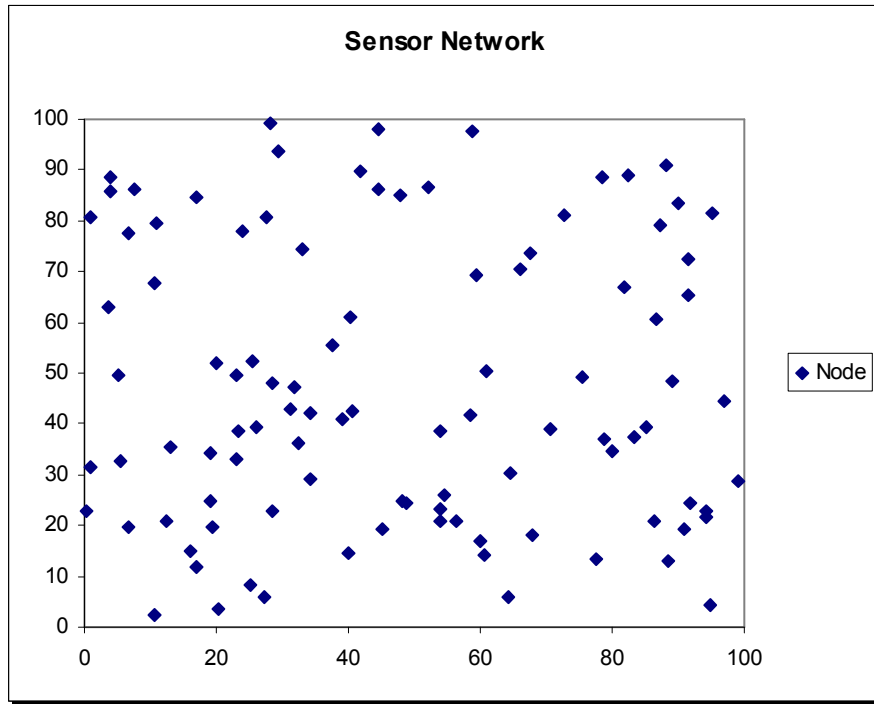
Figure 3-4: Random deployment of sensor nodes in the field.

To compute energy consumption for each sending and receiving, a radio model was used [9]. The energy used to send *n-bit* data, a distance *d*, for each sensor node is:

$$E_{Tx}(n,d) = nE_{elec} + n\varepsilon_{fs}d^2 \qquad (3.3)$$

The energy used to receive *n-bit* data, for each sensor node is:

$$E_{Rx}(n) = nE_{elec} \qquad (3.4)$$

The energy for data aggregation is:

$$E_{DA} = 5nJ / bit / signal \qquad (3.5)$$

Where E_{elec} is the electronics energy, and ε_{fs} is the power loss of free space.

The following table, Table 3-1, summarises the parameters used in this research – the study's simulation.

Parameter	Value
Network size	100 x 100
Number of nodes	100
Base station location	50 x 175
E_{elec}	50nJ/bit
ε_{fs}	10pJ/bit/m^2
Initial energy	1 Joule
Data packet size	500 bytes
Info packet size	25 bytes

Table 3-1: Simulation parameters.

3.5.2 Simulation results

3.5.2.1 Network lifetime

The goal of ADRP is to distribute the energy load among the sensor nodes in the network, in order, to prolong the network's lifetime. Figures 3-5, 3-6 and 3-7 compare the network lifetime of ADRP to LEACH-C [9]. The network lifetime was analysed based on the following three metric definitions: FD (first node dies), HD (half of the nodes alive), and LD (last node dies) [27]. Since more than one node is necessary to perform the clustering algorithm, the LD represents the overall lifetime of a wireless sensor network when 80% of the sensor nodes die.
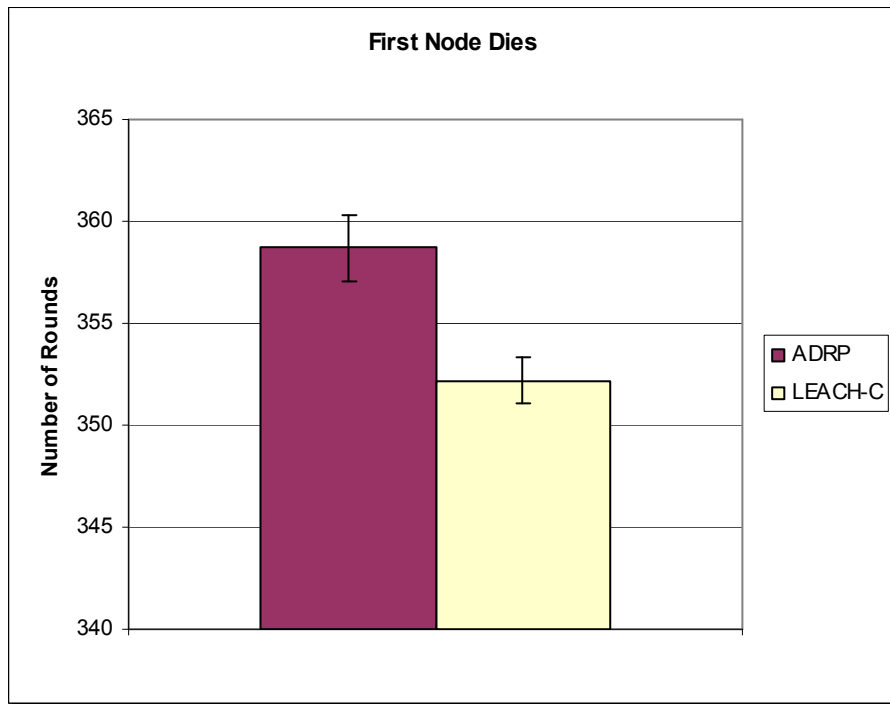
Figure 3-5: Performance comparison of the network lifetime metric FD.

ADRP therefore successfully distributed the energy among all of the sensor nodes in the network. Figure 3-5 shows that the first dead node in LEACH-C appears earlier than in ADRP. The stability period of ADRP is longer because the sensor nodes in LEACH-C need to send the status to the base station each round; whereas, in ADRP, the sensor nodes can switch directly to the next heads without communicating with the base station. The following figures, Figures 3-6 and 3-7, show that the nodes using an ADRP protocol remained alive for longer than those using LEACH-C. The ADRP protocol therefore performs better than LEACH-C in prolonging the network life for all metrics.
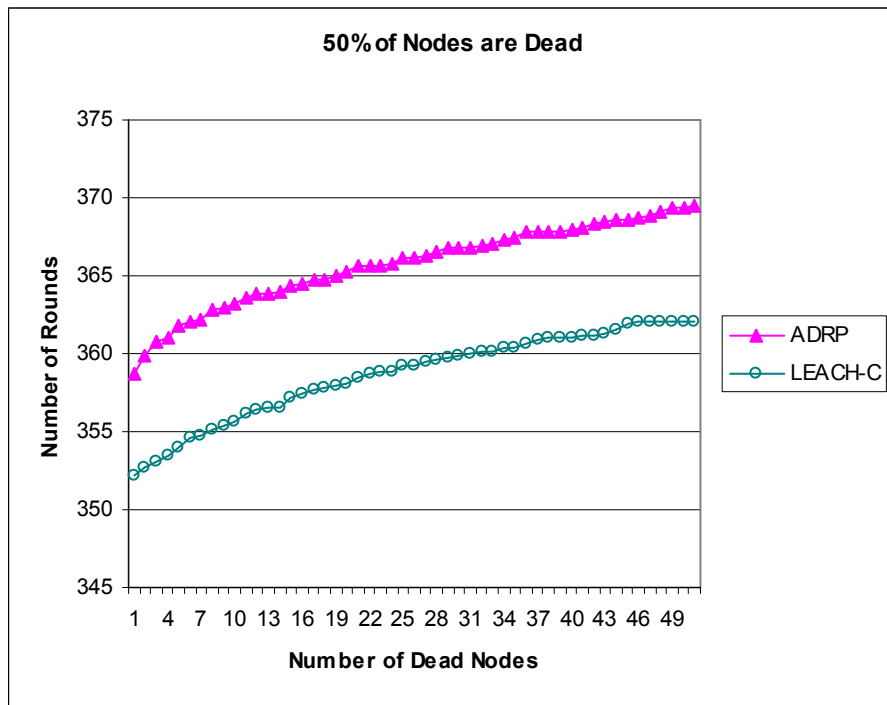
Figure 3-6: Performance comparison of the network lifetime metric HD.
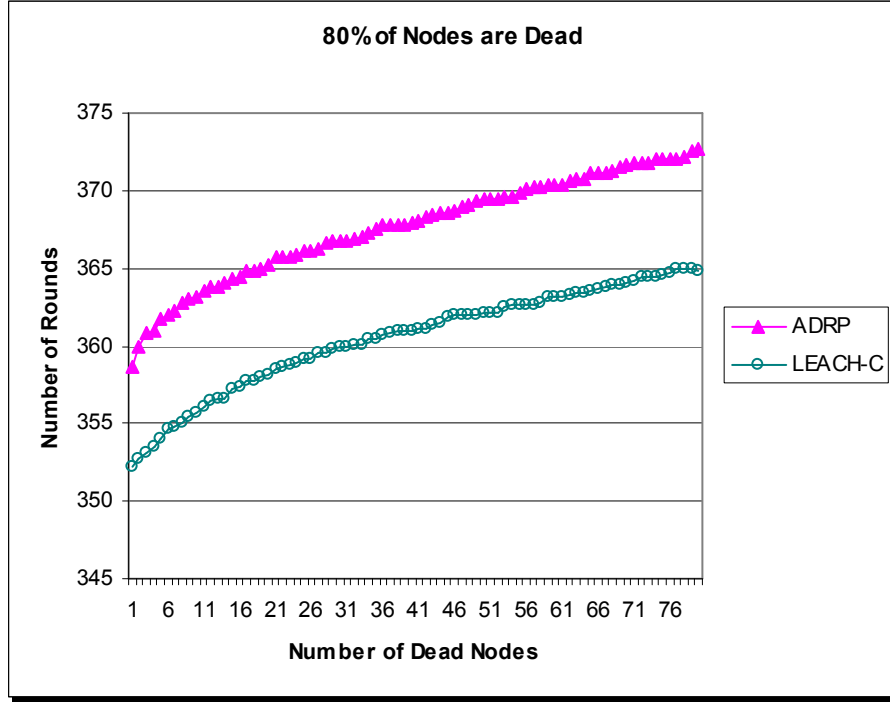
Figure 3-7: Performance comparison of the network lifetime metric LD.

3.5.2.2 Received data messages

The numbers of data messages, received by the base station, were also analysed. Figure 3-8 shows the number of data messages received by the base station during its operating time. In ADRP and LEACH-C, each message was transmitted over a single hop, to the cluster head, where data aggregation occurred. The aggregated data was sent to the base station, greatly reducing the amount of data transmitted. As the sensor nodes death rate in ADRP is less than that in LEACH-C (Figure 3-7), more data messages will be sent to the base station compared with LEACH-C.
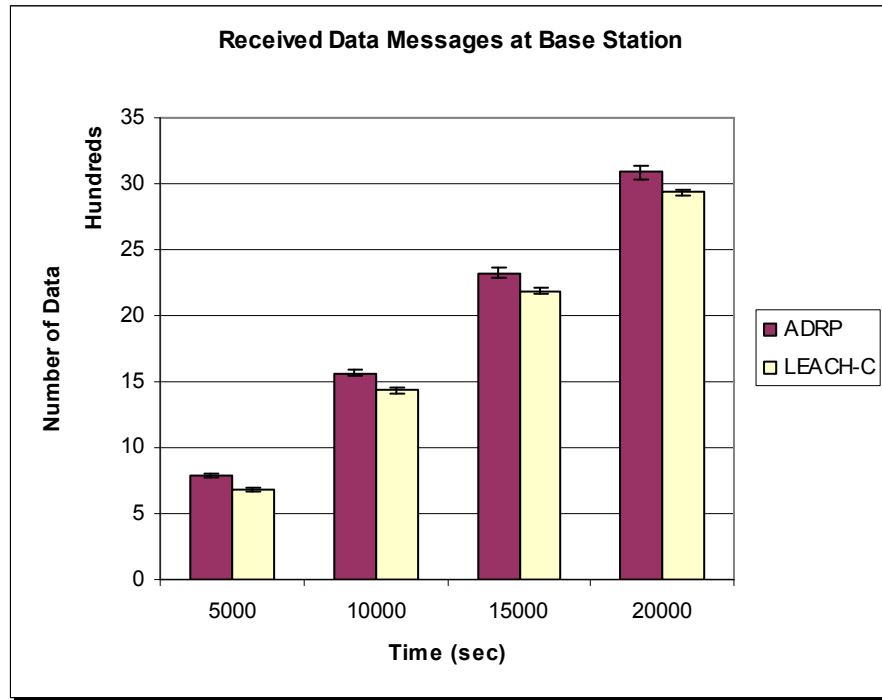
Figure 3-8: Number of data messages received by base station.

3.5.2.3   Energy dissipation

In this section, the ADRP with LEACH-C protocols, in term of energy dissipation, will be compared. The average energy consumed by a sensor node is computed for sensor networks. The energy efficiency of ADRP, in comparison to LEACH-C, can be seen in Figures 3-9 and 3-10. The first columns represent the energy dissipation by ADRP and the second columns represent the energy dissipation by LEACH-C.

Figure 3-9 shows the energy consumed by the sensor nodes. Similarly, Figure 3-10 shows the average energy consumed per round. In both cases, improved energy efficiency can be seen, there is an increase in performance because of the reduction in

energy dissipation by using ADRP. The results show that ADRP performed better than LEACH-C. LEACH-C reforms the clusters and the sensor nodes need to communicate with the base station each round to form the clusters; however, ADRP reduces transmissions to the base station during the re-cluster stage.
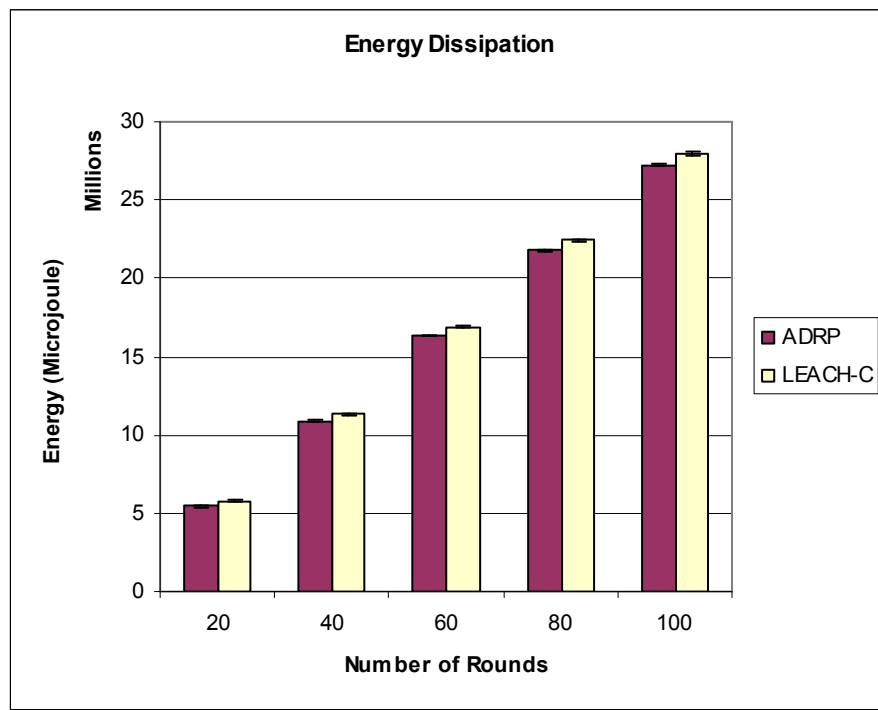
Figure 3-9: Comparison of energy dissipation of ADRP and LEACH-C.
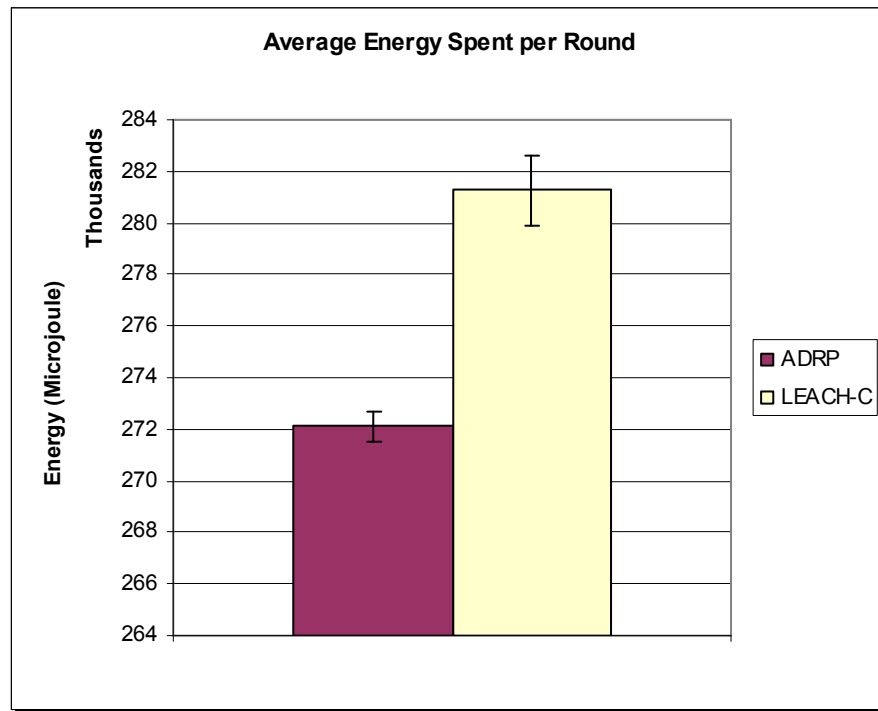
Figure 3-10: Comparison of average energy spent per round.

3.5.2.4 Communication overhead

Communication overheads are defined as the number of additional messages sent by the sensor nodes to form the clusters. In LEACH-C, a sensor node sends one message to the base station each round to form the clusters; while in ADRP, a sensor node sends one message to the base station each set of rounds to form the clusters.

In ADRP the base station sends a message containing the cluster head's ID and the next heads for each sensor node in the network. During the re-cluster stage, the sensor nodes can switch directly to the next heads without communicating with the base station; thus,

reducing a large number of communication overheads. Figure 3-11 shows that the number of messages in the initial phase increased gradually in ADRP, while in LEACH-C the number of messages increased quickly. A large amount of energy was saved during the initial phase due to the reduction in communication overheads.
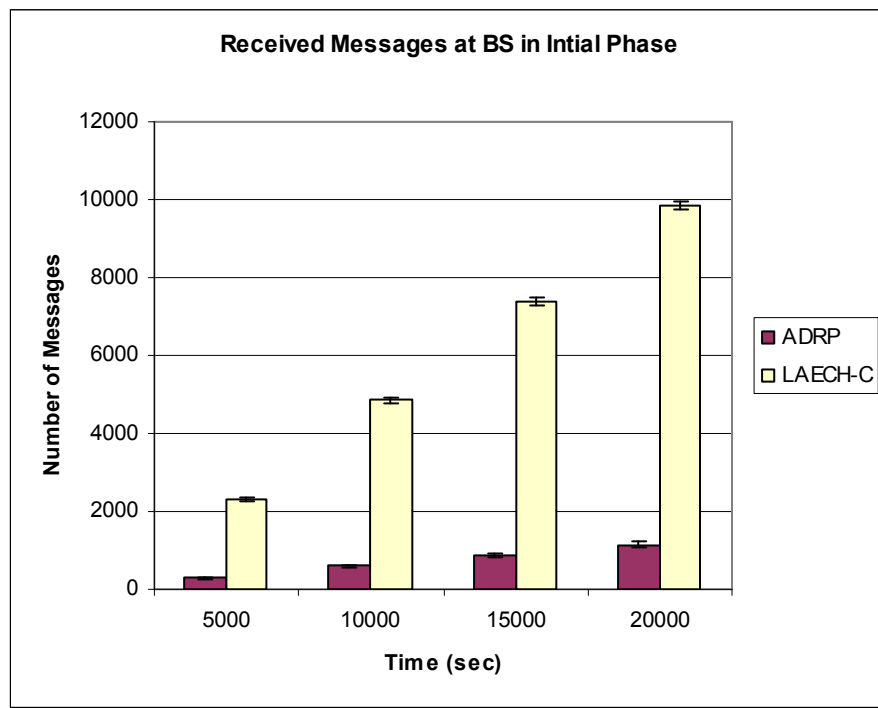
Figure 3-11: Performance comparison of the communication overheads.

3.5.3 Simulation summary

The simulation indicates that the ADRP protocol performs much better than LEACH-C, in prolonging the network's lifetime, for the three metrics: first node dies; half of the nodes alive; and, last node dies. As the sensor nodes death rate in ADRP is less than that

in LEACH-C, more data messages will be sent to the base station than in LEACH-C. In the ADRP protocol, the sensor nodes can switch directly to the next heads without communicating with the base station. Thus, it reduces a large number of communication overheads and consumes the least amount of sensor energy.

3.6 Conclusion

An adaptive clustering scheme, ADRP, was introduced for electing the cluster heads and the next heads in wireless sensor networks. The selection of cluster heads and next heads are weighted by the remaining energy of sensor nodes and the average energy of each cluster. The sensor nodes with the highest energy can become cluster heads at different times in the cycle. By means of the former, the role of the cluster head can be switched dynamically.

The simulation results show that ADRP has extended the lifetime of the network and reduced the communication overheads. Hence, the performance of the proposed protocol is better in terms of: network lifetime, data delivery and communication overheads, when compared with the LEACH-C protocol.

Chapter 4

Energy Efficient Clustering Protocol to Enhance the Lifetime of Wireless Sensor Networks

4.1 Introduction

In wireless sensor networks, the sensor nodes are battery powered; however, it is not convenient to recharge or replace the batteries because the number of sensor nodes are too large or the sensor nodes are in remote areas [28]. While the wireless sensor nodes are low powered, the protocols must be energy efficient, scalable and adaptable. The energy resources of each sensor node must be managed effectively by the protocols. Clustering has been investigated in order to reduce the energy consumption of the wireless sensor network.

In many cluster based schemes [1, 9, 26, 38], the sensor nodes are divided into clusters. The clustering formation procedure involves the selection of a cluster head node that is utilised to control the member nodes. The cluster head is responsible for obtaining data

from its cluster's nodes, aggregating the data and transmitting the aggregated data to the base station. Since the cluster head is responsible for processing the data and sending the data to the base station, the cluster head drains energy much faster than the sensor nodes; consequently, conventional clustering protocols suffer from energy consumption problems.

A number of chain based schemes [22, 40, 41] organised the sensor nodes into large chains where one of the nodes serves as the leader. Each sensor node aggregates its data with its neighbour's data and forwards the aggregated data to the other neighbour. Finally, the leader collects the data from the neighbours and sends it to the base station. The sensor nodes are organised into a chain; however, the delay time for transmissions, in a chain based scheme, would be much larger than in cluster based schemes.

This research presents an energy efficient clustering protocol to enhance the lifetime of wireless sensor networks (EECPL). The main goal of EECPL is to distribute the energy load among all of the sensor nodes in the network, to ultimately increase network lifetime and reduce energy consumption. EECPL aims to form a ring among the sensor nodes within the cluster, so that each sensor node receives data from a previous neighbour and transmits to its next neighbour.

The performance of the EECPL protocol will be evaluated via simulations and it will be compared to the performance of ADRP and LEACH-C [9], in terms the following metrics: the lifetime of the network, the energy consumption of the sensor nodes and the

communication overheads. EECPL aims to provide significant energy savings and balance the energy consumption.

The remainder of this chapter will be organised as follows: Section 2 will provide an overview of the cluster based routing schemes; Section 3 will present the EECPL approach; Section 4 will provide details of the algorithm; Section 5 will present the simulation setup and the results; and finally, Section 6 will conclude the chapter.

4.2 EECPL protocol

Wireless sensor networks consist of hundreds or thousands of low-powered sensor nodes, which operate in unattended environments. The main goal of the energy efficient clustering protocols is to prolong the network's lifetime and balance energy consumption under given energy constraints.

In clustering protocols [26, 35-39, 40, 41], there are two different kinds of sensor nodes, cluster heads and member nodes, as shown in Figure 4-1. The cluster heads manage the member nodes and collect data from them; each cluster head collects data from the member nodes, aggregates the data and then sends the aggregated data to the base station. Since the cluster heads have responsibility for the collecting, aggregating and sending of data to the base station, they drain energy much faster than the member nodes; thus, reducing the network's lifetime.
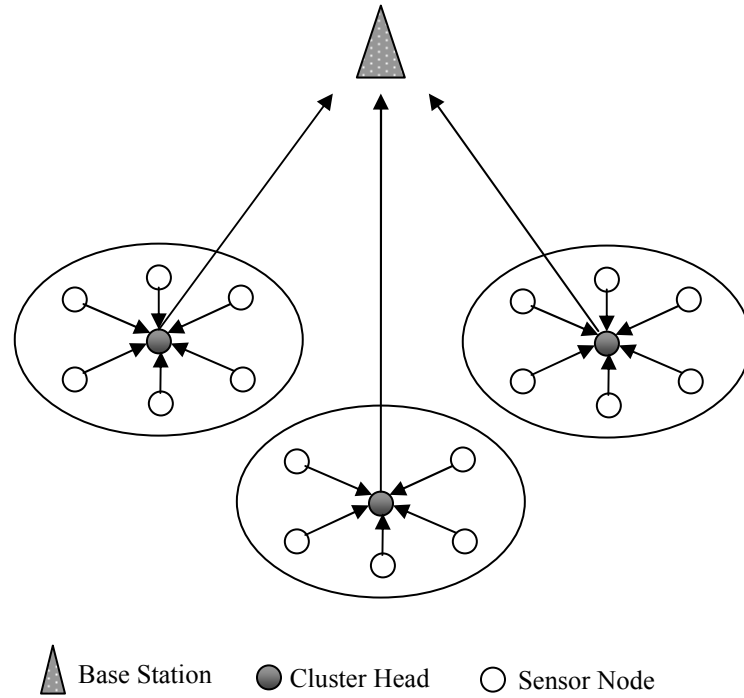
Figure 4-1: Cluster topology.

The clustering protocols periodically re-cluster the network in order to distribute the energy consumption among all of the sensor nodes in the wireless sensor network. These protocols suffer from cluster formation overheads because they consume more energy. Additionally, each sensor node transmits data to its cluster head, even if the cluster head resides at a greater distance from the base station.

In order to avoid this situation, this research proposes the following clustering protocol: energy efficient clustering protocol to enhance the lifetime of wireless sensor networks EECPL. The EECPL protocol is organised into rounds; some rounds begin with a setup phase when the clusters are formed. This is followed by a steady state phase which is divided into several frames, the sensor nodes transmit and receive data at each frame.

4.2.1 Setup phase

In the setup phase, each node sends its energy status and location to the base station. The base station uses this information to find the number of cluster heads and cluster senders as well as making sure that only nodes with enough energy are selected to participate as cluster heads or cluster senders. The cluster head is responsible for creating and distributing the time division multiple access TDMA; while, the cluster senders are responsible for sending the aggregated data to the base station.

When the clusters are formed, the EECPL organises the sensor nodes within the cluster into a ring topology – each sensor node receives data from a previous neighbour and transmits it to the next neighbour. Once the cluster heads and senders are determined, the base station broadcasts this information, concerning the: cluster heads, cluster senders and sensor node's IDs, to all of the sensor nodes within the ring.

4.2.2 Steady state phase

During the steady state phase, the cluster head creates and distributes the TDMA schedule, which specifies the time slots allocated for each member of the cluster to receive and transmit data.

In order to gather data in each frame, the cluster senders sense their environment, collect the sensed data and transmit the data to the next neighbour, in a clockwise direction. Each

sensor node receives data from its previous neighbour, aggregates this with its own data and then transmits it to the next neighbour in the ring, as shown in Figure 4-2. Upon receiving the consolidated aggregated data from the neighbours, the cluster senders transmit it to the base station.

The cluster senders transmit data directly to the base station, consequently, the cluster senders drain energy much faster than the cluster heads and sensor nodes, thus, reducing the network's lifetime. In order to balance the energy consumption among all the sensor nodes in the network, the cluster sender's role should be rotated among the sensor nodes to prevent exhaustion. EECPL uses the remaining energy for cluster sender's rotation. The sensor nodes with the highest remaining energy are selected as cluster senders.

A sensor node is considered dead if it consumes more than 99% of its initial energy level. If any sensor node within a cluster dies, the cluster sender sends messages to the base station to form clusters and repeat the setup phase; otherwise, the sensor nodes would use the remaining energy levels to select new cluster senders with the highest energy for the next round.
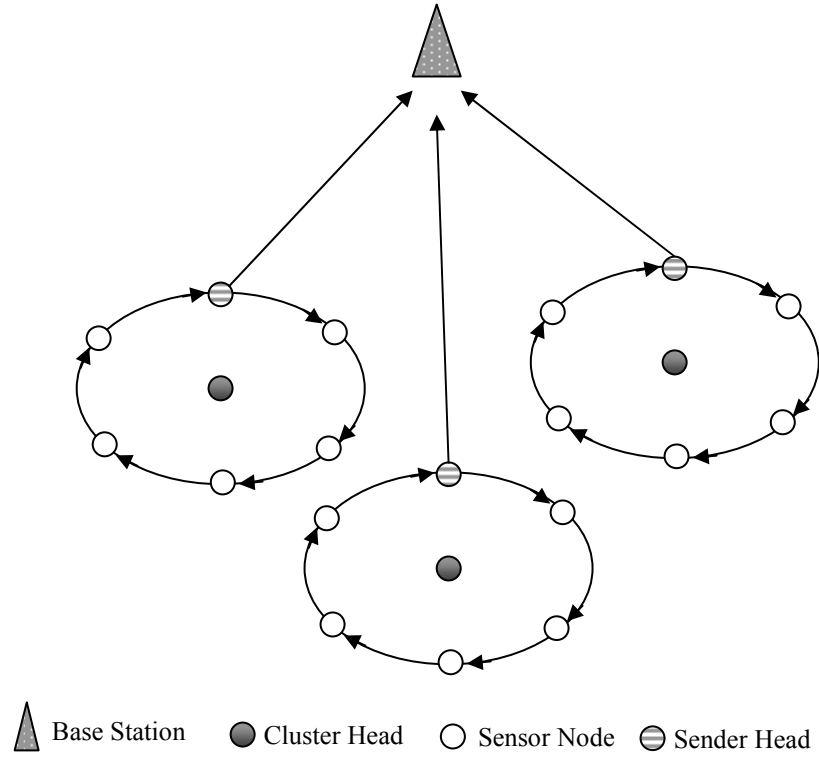
Figure 4-2: An example of our proposed wireless sensor network.

4.3 EECPL algorithm details

4.3.1 Initial configuration

In this stage, each sensor node sends an updated packet with information about its remaining energy and location to the base station. The sensor nodes obtain their current location by using a global positioning system (GPS) receiver that is activated at the beginning of the setup phase.

4.3.2 Cluster configuration

On receiving the energy status and location data, the EECPL calculates the energy value of all the sensor nodes and then selects the cluster heads by minimising the total sum of the distance between the cluster heads and the sensor nodes. Furthermore, the EECPL ensures that only nodes with enough energy participate in the cluster heads selection.

4.3.3 Ring configuration

The idea in EECPL is to form a ring among the sensor nodes within a cluster: each sensor node should receive, from a previous neighbour, and then transmit, to its next neighbour, in a clockwise direction. To build the ring, and since the cluster heads are in the centre of the cluster, EECPL divides the clusters into two parts, upper and lower, as shown in Figure 4-3. Firstly, EECPL starts with the upper part and selects the sensor node that is farthest away from the cluster head as the last node. Then, the sensor node, closet to the last node, is added to the upper part. The sensor nodes are selected in this manner from the remaining nodes until all of the sensor nodes are added to the upper part, as shown in Figure 4-4.

For constructing the lower part, EECPL repeats the steps identified in the upper part, as shown in Figure 4-5. The EECPL creates a ring by linking the upper part with the lower part, as shown in Figure 4-6. If there is only one part within the cluster, EECPL creates a ring by linking the first and the last nodes, as shown in Figure 4-7.

The sensor nodes are assigned identities *1* through *M,* where *M* is the total number of sensor nodes within a ring. Every sensor node knows its previous and next neighbours, based on the identities within the ring.
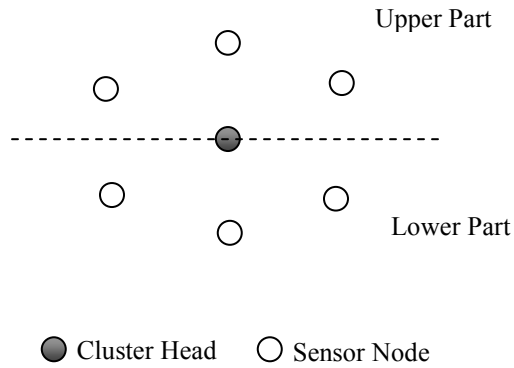
Figure 4-3: Upper and lower parts.
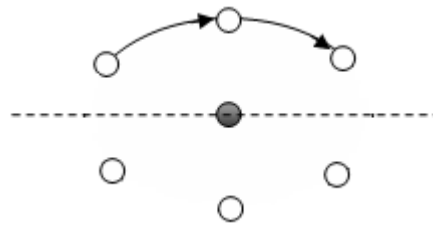
Figure 4-4: Upper part.

Figure 4-5: Lower part.

Cluster Head   Sensor Node
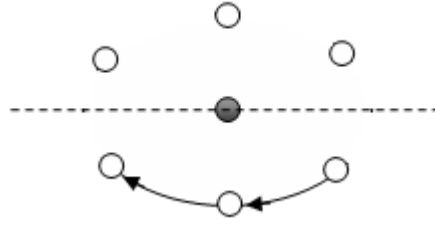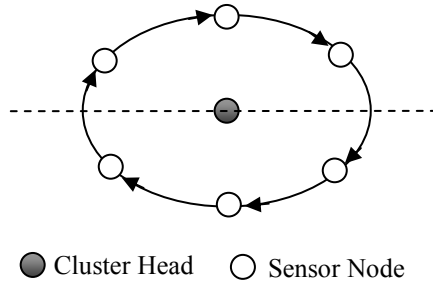
Figure 4-6: An example of a ring configuration.
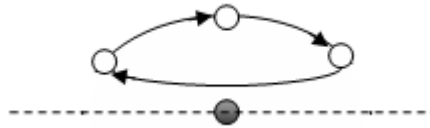
Figure 4-7: An example of a ring configuration with one part.

4.3.4 Advertisement

The base station sends a message containing the cluster head, the cluster sender and the node ID, within the ring, for each sensor node. If a node's cluster head ID matches its own

ID, the node is a cluster head. Although, if a node's cluster sender ID matches its own ID, the node is a cluster sender; if no ID matches, the node is a sensor node.

4.3.5 TDMA schedule

Once the clusters have been formed, the sensor nodes must send their data to the next neighbour. EECPL uses the TDMA model as the MAC protocol, which allows the sensor nodes to enter a sleep mode when they are not transmitting data to the next neighbour. The TDMA approach, in intra-cluster communication, also ensures that there are no collisions of data within the cluster.

Based on the number of nodes in the cluster, the cluster head node creates a TDMA schedule which advises each node when it can receive and transmit data. The TDMA schedule divides time into a set of slots, the number of slots being equal to the number of nodes within the cluster. Each node is assigned a unique time slot during which it can transmit its data to the next neighbour.

Since the responsibilities of the cluster heads are more distributed among the other sensor nodes, EECPL keeps the cluster heads for a number of rounds; although, the cluster sender's role needs to be rotated to different sensor nodes.

4.3.6 Data transmission

In order to gather data in each frame, the cluster senders sense their environment, collect sensed data and transmit the data to the next neighbour, in a clockwise direction. Each sensor node receives data from the previous neighbour, aggregates this with its own data, and then transmits it to the next neighbour in the ring. Upon receiving the aggregated data from the previous neighbours, the cluster senders transmit the data to the base station.
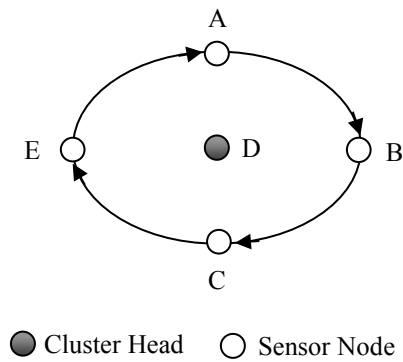
Figure 4-8: An example of cluster.
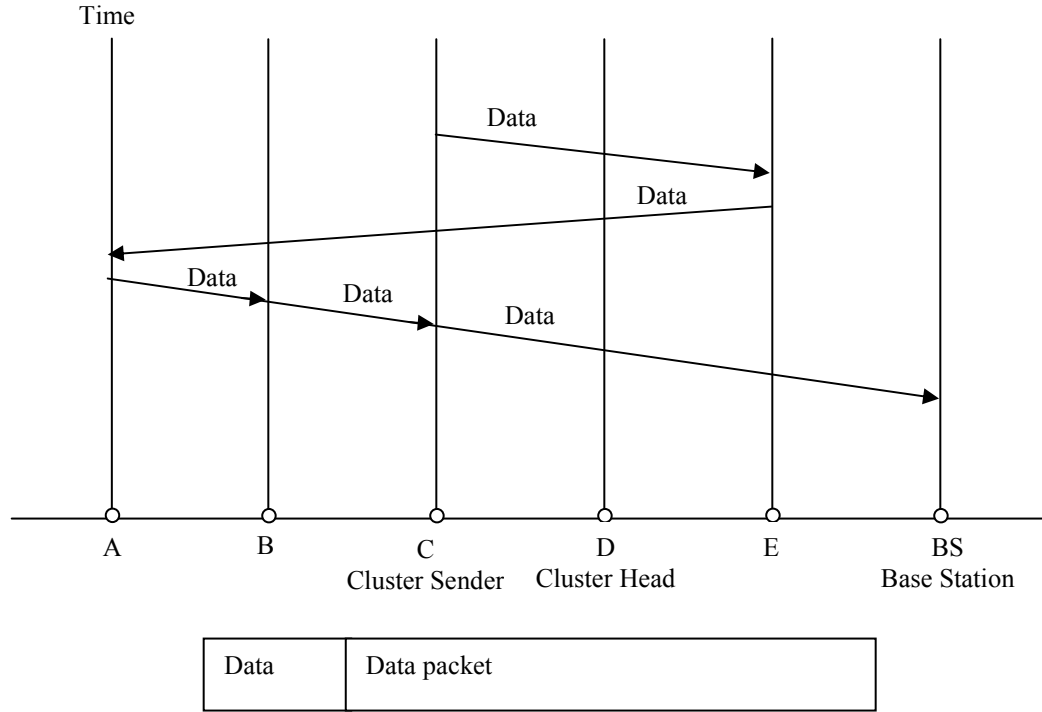
Figure 4-9: Data transmission.

EECPL performs data aggregation at every sensor node in the ring; consequently, each sensor node aggregates its previous neighbour's data with its own data and then transmits the aggregated data to its next neighbour. Figures 4-8 and 4-9, show examples of the data transmissions; the cluster has the following nodes:

- There are five sensor nodes in this cluster A, B, C, D and E.

- D is the cluster head.

- C is the cluster sender.

Therefore, to illustrate, the cluster sender, C, senses the environment, collects sensed data and transmits the data to the next neighbour, E. E aggregates the data with its own data, and then transmits the aggregated data to the next neighbour, A. Upon receiving the aggregated data, from B, the cluster sender, C, transmits it to the base station.

4.3.7 Cluster sender selection

The cluster senders transmit data directly to the base station; therefore, the cluster senders drain energy much faster than the cluster heads and sensor nodes, thus, reducing the network's lifetime. In order to balance the energy consumption among all the sensor nodes in the network, the cluster sender's role should be rotated among the sensor nodes to prevent exhaustion. Sensor nodes with the highest remaining energy are selected as the cluster senders. If there is more than one sensor node with equal remaining energy levels, in the same cluster, one of the sensor nodes is randomly selected.

In frame number $n-1$, the sensor node sends data to the next neighbour; it also sends its remaining energy. Based on the collected information, the sensor node compares the energy levels and selects the highest remaining energy.

The mechanism for selecting the new cluster sender is as follows:

- The sensor node, S_p, sends data and its remaining energy, ES_p, to the next neighbour, S_n.

- Based on the collected information, the sensor node, S_n, compares its energy level, ES_n, with the previous neighbour's energy level, ES_p.

- If $ES_n \geq ES_p$, the sensor node, S_n, selects itself as the provisional cluster sender and sends data with its energy level to the next neighbour.

- If $ES_n < ES_p$, the sensor node, S_n, selects S_p as provisional cluster sender and sends data with ES_p to the next neighbour.

- When a node with the highest remaining energy is selected as the new cluster sender, the current cluster sender informs the cluster head to build a TDMA schedule with a new cluster sender at the beginning.

- Each cluster follows the same procedure to select new cluster senders.

4.4 Simulation and discussion

This section will analyse the performance of EECPL protocol simulations. Simulation experiments were carried out in the network simulator OMNET++ [21]. Three metrics will be used to analyse and compare the experimental simulation results: network lifetime, energy dissipation and communication overhead.

4.4.1 Simulation setup

As shown in Figure 4-10, it was assumed that 100 sensor nodes were randomly scattered into the sensing field with dimensions of 100m x 100m, and a base station would be located at positions 50 and175. All of the sensor nodes would periodically sense the environment

and transmit the data to the next neighbour. Every result shown is an average of 10 experiments, with a 95% confidence interval. Each experiment uses a different randomly generated topology; Table 4-1 summarises the parameters used in this simulation.
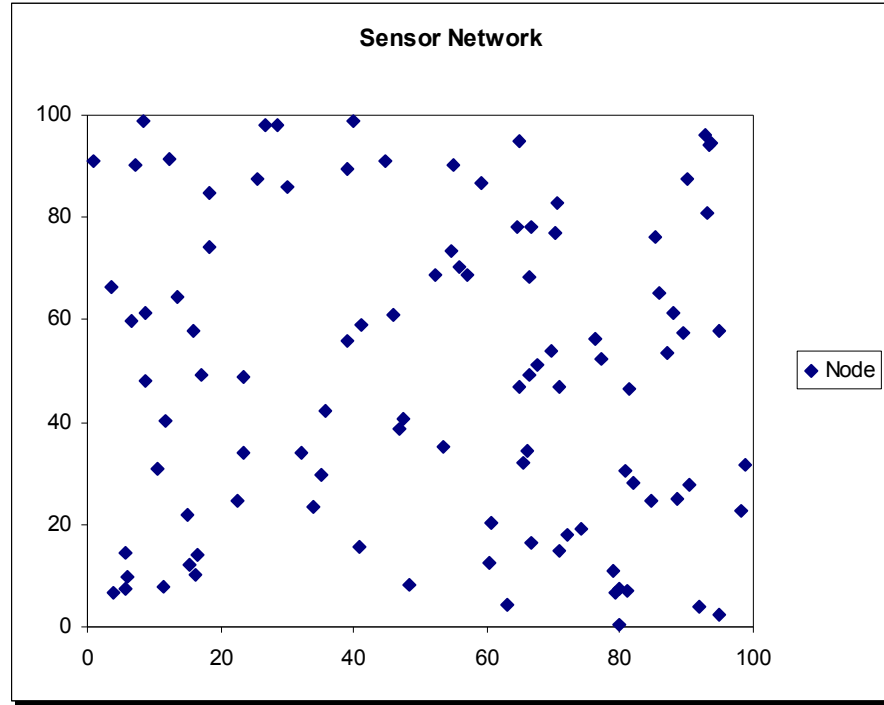
Figure 4-10: Snapshot of random deployment of sensor nodes in the field.

4.4.2 Radio model

This research will use the same radio model to that described in previous research [9]. The initial energy of each sensor node is *1 J*, and the base station has unlimited energy.

Parameter	Value
Network size	100×100
Number of nodes	100
Base station location	50×175
E_{elec}	50nJ/bit
ε_{fs}	10pJ/bit/m^2
Initial energy	1 Joule
Data packet size	500 bytes
Info packet size	25 bytes

Table 4-1: Simulation parameters.

4.4.3 Simulation Results

4.4.3.1 Network lifetime

It is necessary for all sensor nodes to stay alive for as long as possible because the network quality decreases as soon as the sensor nodes die. The goal of EECPL is to increase the lifetime and stability period of the sensor network. The stability period is defined as the time interval prior to the death of the first sensor node. The performance of EECPL will be compared with ADRP and LEACH-C [9] to determine the network's lifetime and stability period. The performance metrics used to evaluate the system's lifetime are: FD (first node dies), HD (half of the nodes alive), and LD (last node dies) [27]. In order for a clustering algorithm to perform, more than one node is necessary; consequently, the LD represents the overall lifetime of the wireless sensor network which is when 80% of the sensor nodes die.

Figure 4-11 compares the FD of EECPL to ADRP and LEACH-C. The EECPL was able to collect data from the whole network until round 379; therefore, the sensor nodes were alive in the whole field. In contrast, in ADRP the FD in round 358, and for LEACH-C the FD in

round 352; hence, the stability period of EECPL is prolonged compared to ADRP and LEACH-C. EECPL performs well and achieves a longer stable period than LEACH-C by about 27 rounds. EECPL is an energy aware protocol, it distributes the responsibilities of the cluster head among the member nodes and also selects a cluster sender based on the remaining energy of the sensor nodes.

As mentioned previously, in Section 4.3, the idea in EECPL is to form a ring among the sensor nodes within the cluster to ensure that each sensor node receives from the previous neighbour and transmits to the next neighbour, in a clockwise direction. In order to gather data in each frame, the cluster senders sense their environment, collect sensed data and transmit the data to the next neighbours. Each sensor node receives data from the previous neighbour, aggregates this with its own data and then transmits it to the next neighbour in the ring. Upon receiving the aggregated data from previous neighbours, the cluster senders transmit it to the base station.

To illustrate the effect of using a ring topology on the lifetime of a sensor network, HD and LD were compared for EECPL, ADRP and LEACH-C. The metric HD denotes an estimated value for the half life period of a sensor network, while the metric LD denotes an estimated value for the overall lifetime of a sensor network. In Figures 4-12 and 4-13, the sensor nodes with EECPL protocol remained alive for longer than those using ADRP and LEACH-C. It was apparent that the lifetime of the sensor network was increased from 364 rounds to 396 rounds. In ADRP and LEACH-C, the cluster heads collect data from the

sensor nodes, aggregate the data and transmit the aggregated data to the base station. Thus,

EECPL can spread energy consumption across all nodes over the whole network.
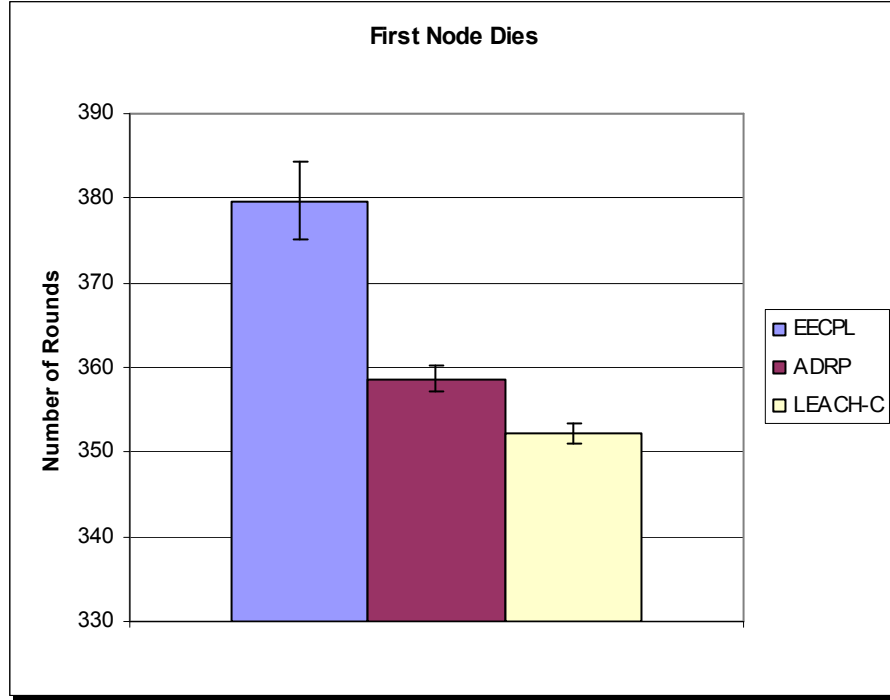
Figure 4-11: Performance comparison of the network lifetime metric FD.
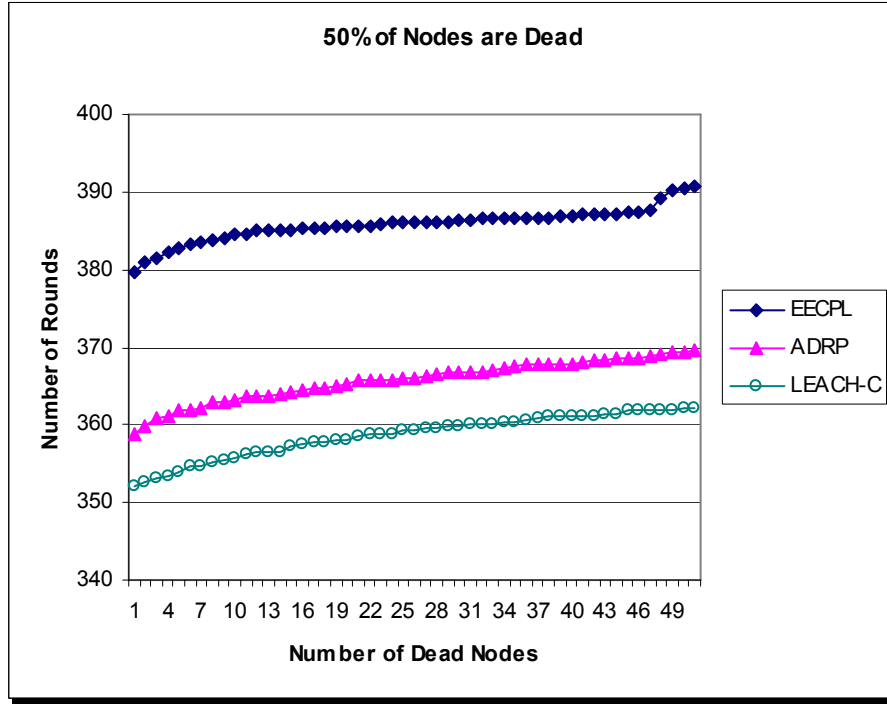
Figure 4-12: Performance comparison of the network lifetime metric HD.
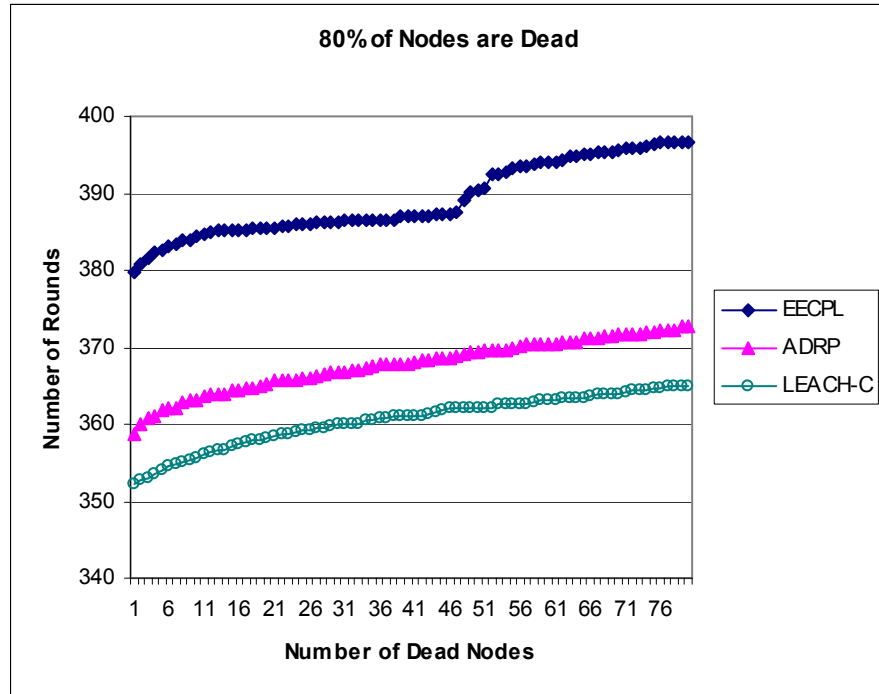
Figure 4-13: Performance comparison of the network lifetime metric LD.

4.4.3.2 Energy dissipation

The EECPL was also compared with the ADRP and LEACH-C protocols to determine energy dissipation. The average energy consumed by the sensor nodes is computed for sensor networks. The energy efficiency of EECPL, in comparison to ADRP and LEACH-C, can be seen in Figures 4-14 and 4-15. The first columns represent the energy dissipated by EECPL, the second and third columns represent the energy dissipated by ADRP and LEACH-C, respectively. During the operations, ADRP and LEACH-C consumed more energy because of the responsibilities of the cluster heads to collect data from the sensor nodes, aggregate the data and then send the data directly towards the base station; whereas, EECPL alleviated this problem by distributing the responsibilities of the cluster heads among the member nodes. Since the responsibilities of the cluster head were more distributed among the sensor nodes, EECPL could keep the cluster heads for sets of rounds and the cluster sender's role was rotated to different sensor nodes. Furthermore, EECPL performed data aggregation at every sensor node in the ring; each sensor node aggregated its previous neighbour's data with its own and then transmitted this aggregated data to its next neighbour.
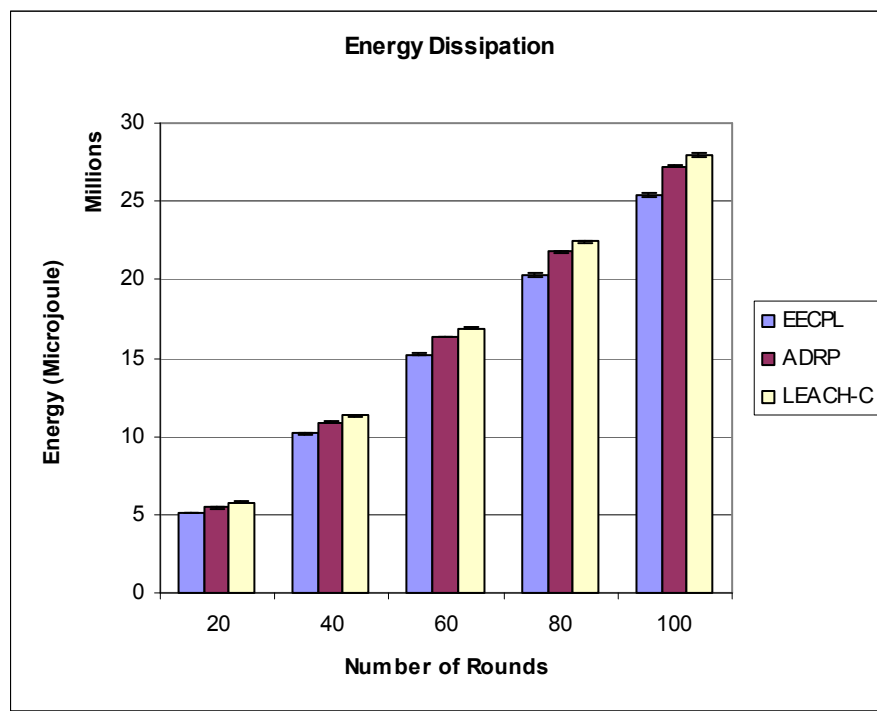
Figure 4-14: Energy dissipation comparison of EECPL, ADRP and LEACH-C.
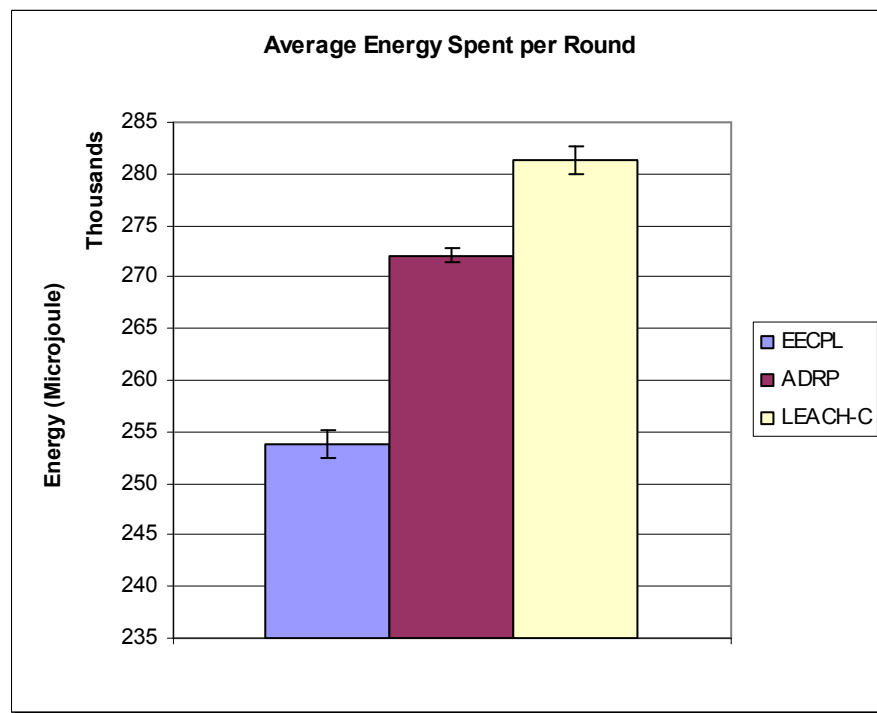
Figure 4-15: Average energy dissipation.

4.4.3.3   Communication overhead

LEACH-C suffers from cluster formation overheads; it consumes more energy due to the cluster formation overheads. Additionally, each sensor node transmits data to its cluster head even if the cluster head resides at a greater distance from the base station.

Since EECPL uses the remaining energy for cluster sender's rotation, sensor nodes with the highest remaining energy are selected as the cluster senders without the need to communicate with the base station; thus, reducing a large number of communication overheads. Furthermore, ADRP reduces communication overheads during the re-cluster stage, the sensor nodes can switch directly to the next heads without communicating with the base station. As shown in Figure 4-16, EECPL can reduce communication overheads during the initial phase by 93%.
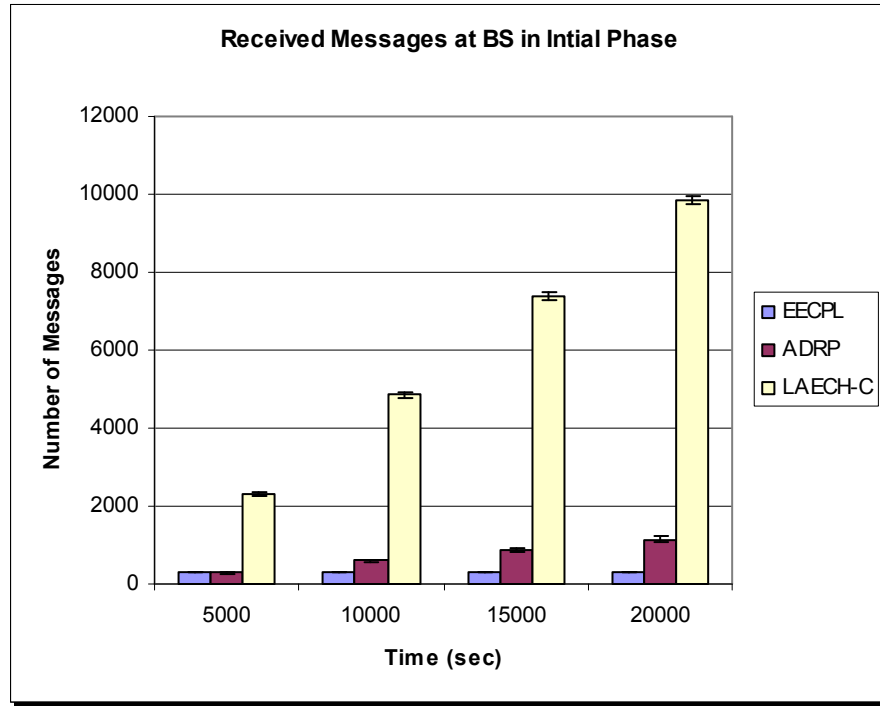
Figure 4-16: Performance comparison of the communication overhead.

In summary, the above results indicate that EECPL can: balance energy, reduce energy consumption, reduce communication overheads and extend the network's lifetime.

4.4.4 Simulation summary

Sensor networks should be able to achieve energy balances and energy efficiency in order to prolong the lifetime of the sensor networks. The lifetime of sensor networks is one of the most popular measurements for evaluating clustering protocols. The lifetime of a sensor network is defined by: the first node dying, half of nodes dying and the last node dying. It is necessary for all sensor nodes to stay alive for as long as possible, to increase the network quality. The stability period of EECPL is longer than that of ADRP and LEACH-

C; furthermore, the sensor nodes in the EECPL protocol remain alive for longer periods than those using ADRP and LEACH-C. In summary, the proposed protocol has several advantages: first, it is simple and has a supporting scalability; second, the protocol maintains energy efficiency for the network and keeps its energy balance; and, third, it reduces communication overheads.

4.5 Conclusion

This research proposed EECPL, an energy efficient clustering protocol for wireless sensor networks that aims to maximise the network's lifetime and minimise the energy consumption. EECPL organises the sensor nodes into clusters and uses ring topology to send data packets, so that each sensor node receives data from the previous neighbour and transmits data to the next neighbour. Upon receiving the aggregated data from the previous neighbours, cluster senders transmit the aggregated data to the base station.

This research has evaluated the performance of the EECPL protocol using simulations and has then compared it to the performance of the ADRP and LEACH-C protocols. EECPL is shown to achieve significant energy savings, balance the energy consumption among the sensor nodes and also reduce the communication overheads.

Chapter 5

Bidirectional Data Gathering

Protocol for Wireless Sensor

Networks

5.1 Introduction

The proposed applications for wireless sensor networks include: environmental monitoring, natural disaster prediction, healthcare, manufacturing and transportation. Wireless sensor networks consist of inexpensive devices that are networked via wireless communication subsystems. The architecture of a wireless sensor network is shown in Figure 5-1, the sensor nodes are usually deployed randomly inside the region of interest, known as the sensor field [19, 20, 25]. The base station connected to the internet is usually more powerful than the sensor nodes because it has power supplied. It needs to collect the sensed data from the sensor nodes and send it to users.

Sensor Field

△ Base Station   ○ Sensor Node
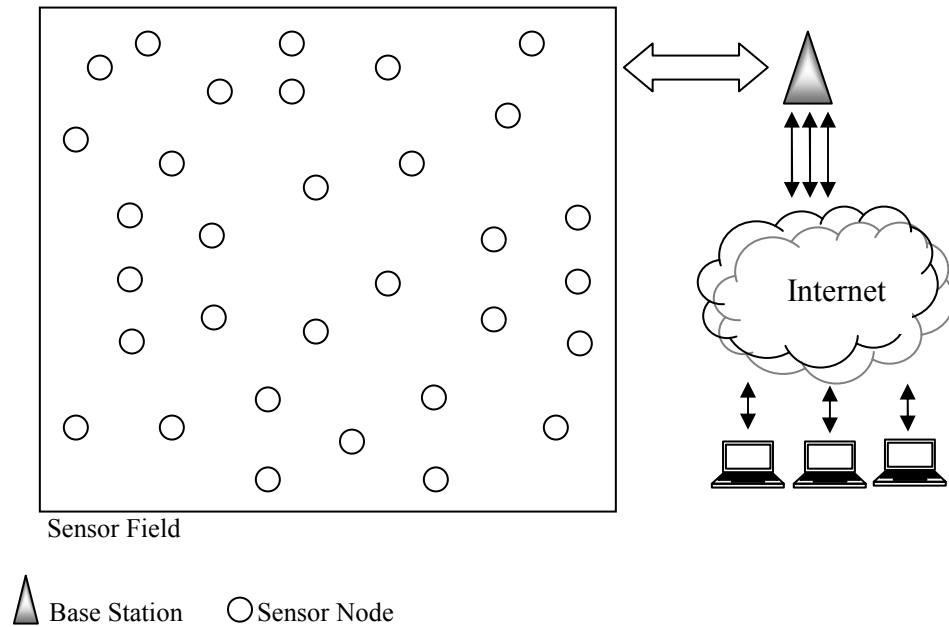
Figure 5-1: The architecture of a wireless sensor network in which sensor nodes are deployed randomly into the sensor field.

When the sensor nodes are organised in clusters, they could use either single hop or multihop modes of communication to send their data to the base station. Since the sensor nodes send their data to the base station or cluster heads for processing, the many-to-one communication paradigm is common.

The sensor nodes also have limited energy because it is not convenient to recharge or replace the batteries. This is a major limitation of wireless sensor networks because it affects the network's lifetime. Energy efficient protocols, in wireless sensor networks, are essential because the sensor nodes always utilise a certain amount of energy while sending sensed data to the cluster head or the base station. In order to address this limitation, several

protocols have been proposed for wireless sensor networks. They can be classified into direct communication, conventional clustering protocols, dynamic clustering protocols and multihop clustering protocols [1, 5, 7, 11].

Using direct communication [1-4], all the sensor nodes directly communicate with the base station, as shown in Figure 5-2. Consequently, the sensor nodes located far away from the base station consume large amounts of energy when transmitting the data to the base station. This quickly drains their energy and reduces the network's lifetime.

Base Station   ◯ Sensor Node
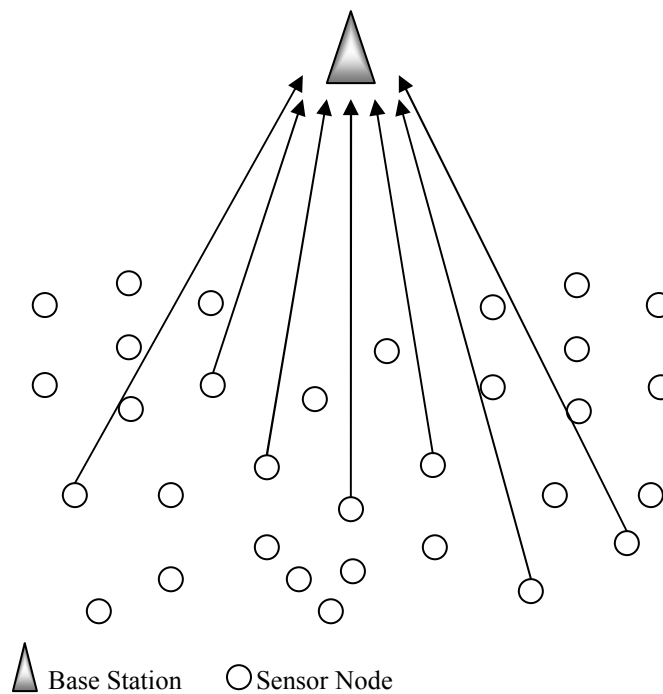
Figure 5-2: An example of direct communication in which all sensor nodes can communicate with the base station directly.

In terms of conventional clustering protocols [1, 5, 6], the sensor nodes are organised into clusters that communicate with the cluster heads. Each cluster head collects sensed data from the member nodes, aggregates the sensed data and then sends the aggregated data to the base station, as shown in Figure 5-3. Since the cluster heads have responsibility for collecting, aggregating and sending data to the base station, they drain energy much faster than the member nodes; thus, reducing the network's lifetime.

Dynamic clustering protocols [7-10] have been proposed to solve a problem in conventional clustering protocols. Sensor nodes are organised into clusters that communicate with the cluster heads. During data gathering, each sensor node senses the environment and sends its sensed data to the cluster head. Each cluster head collects the sensed data from the member nodes, aggregates the sensed data and then sends the aggregated data to the base station. The cluster head nodes act as a local control centre to coordinate the data transmission in their clusters. The cluster head will setup a time division multiple access TDMA schedule, and then sends this schedule to the sensor nodes within the cluster.

These protocols rotate the role of being cluster head among the sensor nodes to balance the energy dissipation of the sensor nodes. Consequently, they periodically re-cluster the network in order to select new cluster heads and distribute the energy consumption among all of the sensor nodes in a wireless sensor network. These protocols suffer from consuming more energy due to the cluster formation overheads. Additionally, each sensor

node transmits data to its cluster head, even when the cluster head resides at a greater distance from the base station.
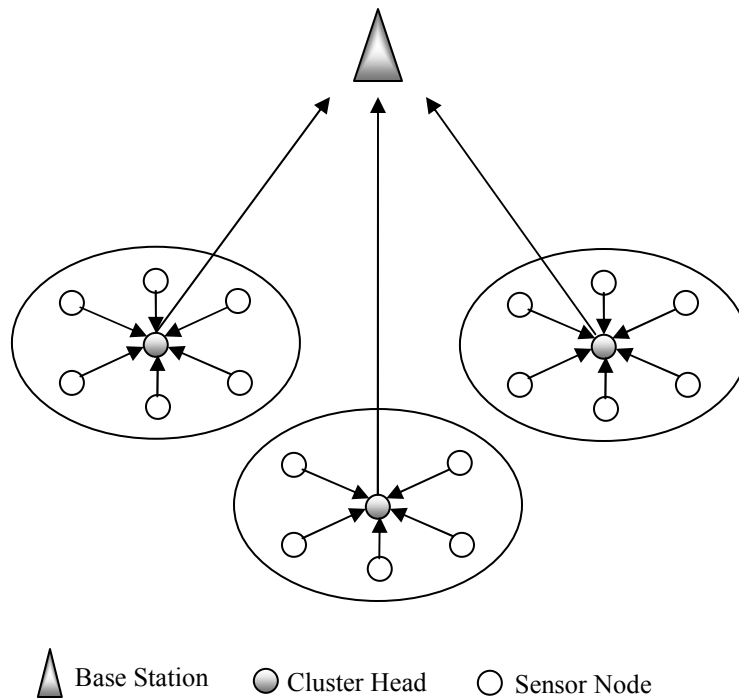
Figure 5-3: An example of conventional clustering.

In terms of multihop clustering protocols [11-18], the sensor nodes are organised into clusters. Each cluster has one cluster head and other sensor nodes; the sensor node sends its sensed data to the cluster head within the cluster and the cluster head collects sensed data from the member nodes and aggregates the data. Consequently, the cluster head also acts as a router, they route data received, from their peer cluster heads, towards the base station, as shown in Figure 5-4. The data routing from the cluster heads to the base station is done

over multihop paths. Since the cluster heads have responsibilities for collecting, aggregating and routing data to the base station, they drain energy much faster than the sensor nodes; thus, reducing the network's lifetime.
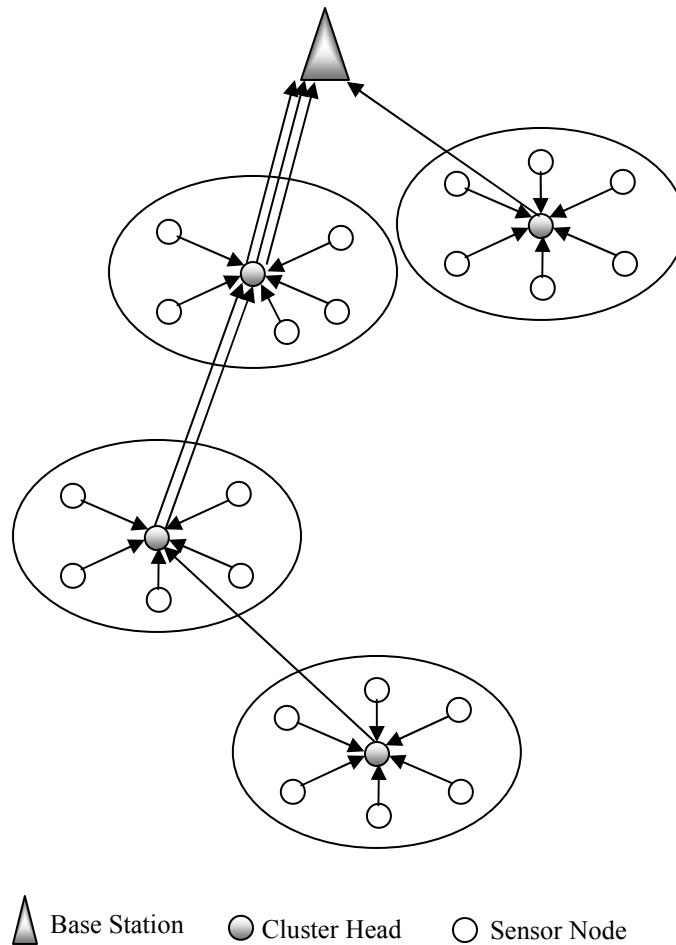
Figure 5-4: An example of multihop clustering.

In order to avoid these situations, this study proposes a protocol for forming clusters, selecting cluster heads, selecting cluster senders and determining the appropriate routings,

in order to reduce the overall energy consumption and enhance the network's lifetime. This clustering protocol is called bidirectional data gathering protocol for wireless sensor networks (BDGP).

The remainder of this chapter is structured as follows: Section 2 will present the BDGP; Section 3 will provide details of the algorithm; Section 4 presents the simulation setup and the results; and finally, Section 5 will conclude the chapter.

5.2 BDGP protocol

The BDGP protocol is organised into rounds; some rounds begin with a setup phase when the clusters are formed, this is followed by a steady state phase which is divided into several frames and sensor nodes which transmit and receive data at each frame.

5.2.1 Setup phase

The setup phase allows the sensor nodes to exchange necessary information with the base station, such as: node ID, location and remaining energy. The base station uses this information to identify the number of cluster heads and cluster senders, whilst ensuring that only the sensor nodes with enough energy participate in the cluster head and cluster sender selection. The sensor nodes are organised into clusters, each cluster has the following: one sensor node which is promoted as the cluster head; one sensor node promoted which is the cluster sender; and the other sensor nodes.

The cluster heads are responsible for creating and distributing the time division multiple access (TDMA) schedule to the sensor nodes. They send the data over the multihop paths, to the base station; therefore, they act as routers since they route data received from the cluster senders or the peer cluster heads toward the base station, through the neighbouring cluster heads.

The cluster senders are responsible for sending the aggregated data to the base station using multihop or single hop communication. The formation of clusters allows the BDGP to organise the sensor nodes within the cluster into a ring topology, to ensure that each sensor node receives data from a previous neighbour and then transmits data to a next neighbour.

The sensor node has two connections which point to the clockwise neighbour and the counter-clockwise neighbour, on the ring, respectively. They form a bidirectional ring structure. Once the cluster heads and cluster senders are determined, the base station broadcasts to all sensor nodes the information including cluster heads, cluster senders, neighbour cluster heads and the sensor node's IDs within the ring.

5.2.2 Steady state phase

During the steady state phase, the cluster head creates and distributes the TDMA schedule, which specifies the time slots allocated for each member sensor node of the cluster, to receive and transmit data. Since the sensor node has two connections which point to the clockwise neighbour and its counter-clockwise neighbour, in the ring, respectively; the sensor node can therefore transmit the sensed data in a bidirectional way.

In order to gather data in the first round, the cluster senders sense their environment, collect sensed data and transmit the data to the next neighbour, in a clockwise direction. Each sensor node receives data from the previous neighbour, aggregates this with its own data and then transmits it to the next neighbour on the ring. Upon receiving the aggregated data, from the previous neighbours, the cluster senders transmit it to the base station using multihop or single hop communication.

In next round, the cluster senders sense their environment, collect sensed data and transmit the data to the next neighbour, in a counter-clockwise direction. Each sensor node receives data from the previous neighbour, aggregates this with its own data and then transmits it to the next neighbour on the ring. Upon receiving the aggregated data, from the previous neighbours, the cluster senders transmit it to the base station using multihop or single hop communication, as shown in Figure 5-5.

In order to distribute energy consumption over the sensor nodes, the cluster sender's role should be rotated among the sensor nodes to prevent their exhaustion. BDGP uses the remaining energy for the cluster sender's rotation. The sensor nodes with the highest remaining energy are selected as cluster senders. A sensor node is considered dead if it consumes more than 99% of its initial energy level. If any sensor nodes die, within the cluster, the cluster sender sends a message to base station to instigate the cluster's setup phase; thus, ensuring that the sensor nodes use the remaining energy levels to select new cluster senders with the highest energy for the next round.
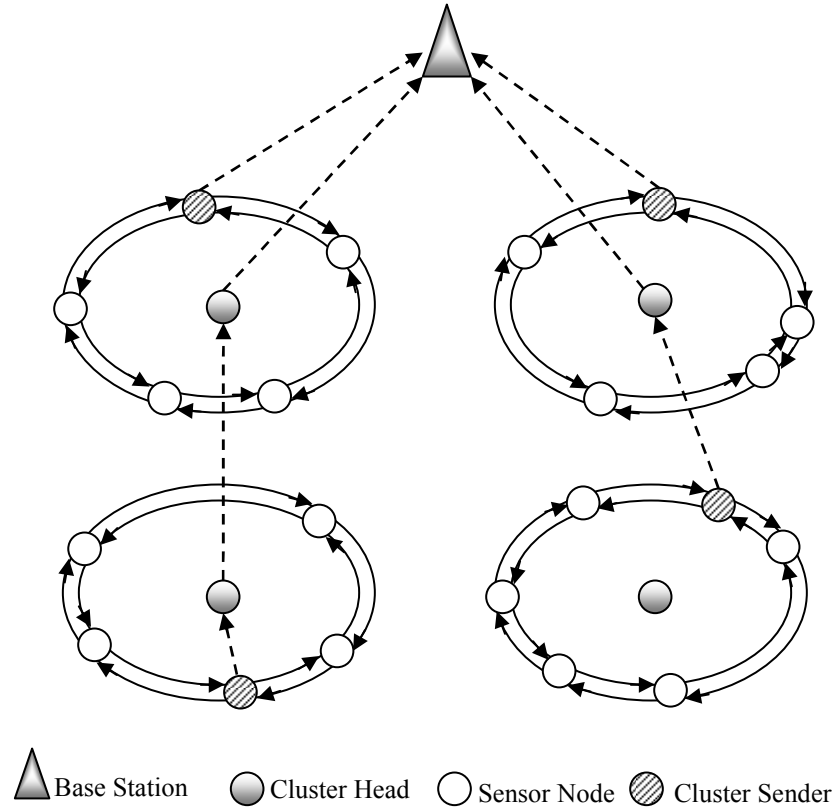
Figure 5-5: An example of multihop clustering in which cluster senders transmit data to the base station.

5.3 BDGP algorithm details

5.3.1 Initial configuration

In this stage, the sensor nodes send an updated information packet concerning the remaining energies and locations to the base station. The sensor nodes gather their current location by using global positioning system (GPS) receivers that are activated in the initial setup phase.

5.3.2 Cluster configuration

On receiving the energy status and location data, the BDGP calculates the energy value of all the sensor nodes and then selects the cluster heads by minimising the total sum of the distance between the cluster heads and the sensor nodes. Furthermore, the BDGP ensures that only the nodes with enough energy participate in the cluster heads selection.

5.3.3 Ring configuration

The BDGP aims to form a bidirectional ring structure among the sensor nodes; within these clusters, each sensor node will receive from a previous neighbour and transmit to the next neighbour clockwise and then counter-clockwise. The cluster heads are in the centre of the clusters; therefore, to build the ring, the BDGP divides the cluster into two parts, the upper and the lower parts, as shown in Figure 5-6. The BDGP initially starts with the upper part: first, the BDGP selects the sensor node that is farthest away from the cluster head as the last node; second, the sensor node closet to the last node is added to the upper part; finally, all of the sensor nodes are selected in this manner, from the remaining nodes, until all the sensor nodes are added to the upper part, see Figure 5-7.

To construct the lower part, the BDGP repeats the steps described for the upper part, as shown in Figure 5-8. Consequently, the BDGP creates a ring by linking the upper part with the lower part, see Figure 5-9. If there is only one part within the cluster, the BDGP creates a ring by linking the first and the last nodes, as shown in Figure 5-10.

The sensor nodes are assigned identities, *1* through *M*, where *M* is the total number of sensor nodes within the ring. Every sensor node knows its previous and next neighbours based on the identities within the ring.
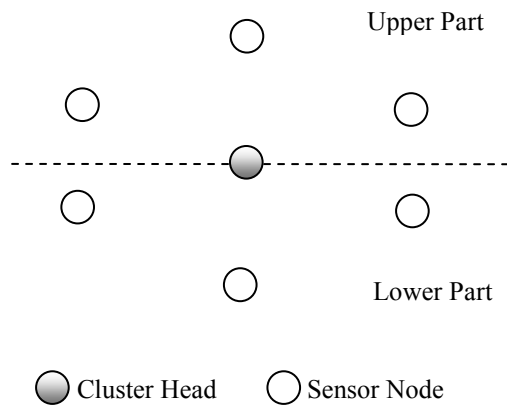
Figure 5-6: Upper and lower parts.
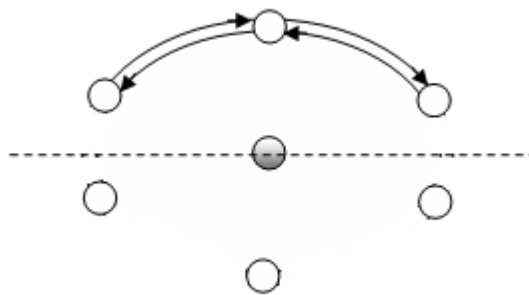
Figure 5-7: Upper part.
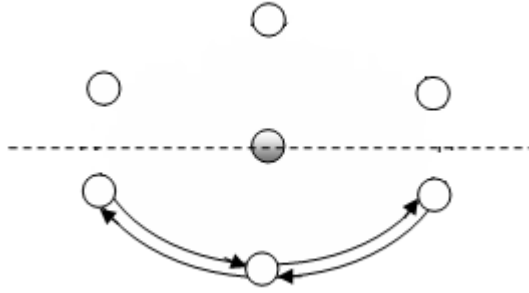
Figure 5-8: Lower part.
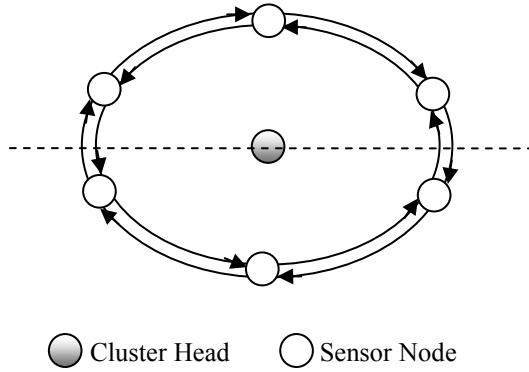
Figure 5-9: An example of the ring configuration.
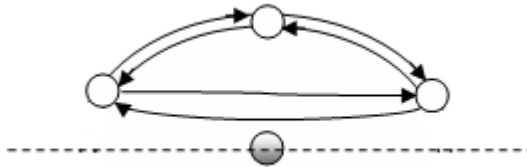
Figure 5-10: An example of the ring configuration with one part.

5.3.4 Advertisement

During the advertisement stage, the base station broadcasts setup information to the sensor nodes. This setup information includes the: cluster heads, cluster senders, neighbour cluster heads, the distance to the base station and the node's ID within the ring. Every sensor node receives this broadcasted information, it initialises its distance and cost. If a node's cluster head ID matches its own ID, the node is a cluster head; although, if a node's cluster sender ID matches its own ID, the node is a cluster sender. Consequently, if no ID matches, the node is a sensor node.

5.3.5 Balanced routing

The sensor node's energy is a major concern in wireless senor networks. BDGP therefore forms clusters, within each cluster there is: one sensor node which is promoted as a cluster head; one sensor node which is promoted as a cluster sender; and, a set of member nodes. The cluster heads also act as routers because they route data, received from the cluster senders or the peer cluster heads, towards the base station through the neighbour cluster heads.

Within this research, the routing task to cluster heads were restricted since the cluster heads were more eligible than the other sensor nodes because of their remaining energy and because they had less responsibilities than the other dynamic cluster based protocols [1, 12, 28].

The BDGP uses cluster senders to transmit data to the base station; the data from the cluster senders are routed among the neighbouring cluster heads (one or multiple) until it reaches the base station. The proposed protocol sends data through energy efficient paths to ensure that the total energy needed to route the data are kept to a minimum.

The definition of energy cost, *EC*, for transmission from cluster sender, *CS*, to the cluster head, *CH*, and the base station, *BS*, is:

$$EC_{CS-BS} = E_{CS-CH} + E_{CH-BS} \qquad (5.1)$$

Where E_{CS-CH} is the energy cost from the *CS* to the neighbour *CH*, and E_{CH-BS} is the energy cost from the *CH* to the base station.

The energy used to send *n-bit* data, a distance, *d*, for each sensor node is:

$$E_{TX}(n,d) = n * E_{elec} + n * \varepsilon_{fs} * d^2 \qquad (5.2)$$

Where E_{elec} is the electronic energy, and ε_{fs} is the power loss of free space.

The idea of BDGP is to save energy by using a path with the minimum distance. When the cluster sender sends data to the base station, it can transmit data to the base station directly or route the data to the neighbour cluster heads. To evaluate these alternatives, a cluster sender (*CS*) that wants to send data to the base station (*BS*) could calculate the sum of the distance from the cluster sender (*CS*) to the neighbour cluster head (*I*) and from the neighbour cluster head (*I*) to the base station (*BS*) which is defined as:

$$D(I) = d_{CS-I}^2 + d_{I-BS}^2 \qquad I \in \{neighbor\ cluster\ heads\} \quad (5.3)$$

Based on this third equation, the cluster sender can select the best neighbour cluster head node, in terms of the minimum distance for an intermediate node. The intermediate node would then be compared with the distance from the cluster sender to the base station (direct communication).

$$Min(D(I)) < d_{CS-BS}^2 \quad (5.4)$$

If the distance of the intermediate node is less than the distance of direct communication, the cluster sender would select the intermediate node as the next hop; otherwise, the cluster sender would transmit the data to the base station directly.

When the data arrives at the intermediate node, the above steps would be repeated to determine whether the intermediate node should select another intermediate node or choose to transmit the data to the base station directly. The process would be repeated until the data arrives at the base station.

Figure 5-11 shows an example of balanced routing. The cluster sender (*CS1*) has three alternative paths to the base station: one is direct to the base station; and two are indirect, via neighbouring cluster heads. The cluster sender (*CS1*) calculates the *D(I)* value using the third equation, for each alternative route, as shown in Table 5-1.

Route	d^2_{CS-I}	d^2_{I-BS}	D(I)	Detail
Route1	30	70	100	d^2_{CS-I} represents distance from CS1→CH2 d^2_{I-BS} represents distance from CH2→CH3→BS
Route2	20	120	140	d^2_{CS-I} represents distance from CS1→CH1 d^2_{I-BS} represents distance from CH1→CH2→CH3→BS
Route3	-	210	210	d^2_{I-BS} represents distance from CS1→BS

Table 5-1: Alternative routes for transmission are available.

The second column shows the distance from the cluster sender (*CS1*) to the neighbour cluster heads, and the third column shows the distance from the neighbour cluster heads to the base station. By totalling the second and third column, a total distance for each route can be calculated, as shown in the fourth column. The computational results indicate that *route1* is the minimum distance; thus, it is the most energy efficient, in terms of cost. The cluster sender (*CS1*) chooses the cluster head as the intermediate node and sends the data to (*CH2*). After receiving this data from the cluster sender (*CS1*), cluster head (*CH2*) repeats the routing process until the base station receives the data.
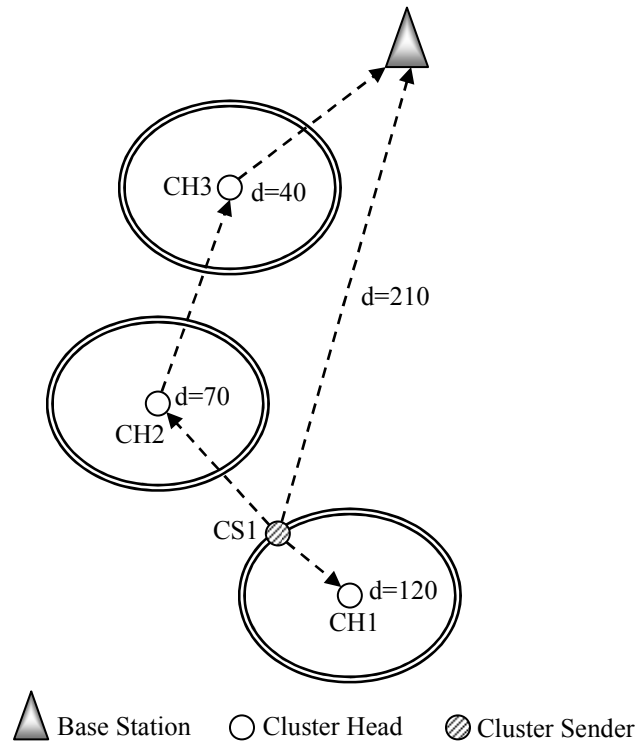
Figure 5-11: An example scenario: node *CS1* needs to send data to the base station.

5.3.6 TDMA schedule

Once the clusters have been formed, the sensor nodes must send their data to the next neighbour. The sensor node has two connections which point to its clockwise neighbour and its counter-clockwise neighbour, on the bidirectional ring, respectively. However, the BDGP uses the TDMA model as the MAC protocol; thus, allowing the sensor nodes to enter a sleep mode when they are not transmitting data to the next neighbour. The TDMA approach, for intra-cluster communication, ensures that no collisions of data occur within the cluster.

Based on the number of nodes within the cluster, the cluster head node creates a TDMA schedule telling each node when it can receive and transmit data to the next neighbour. The TDMA schedule divides time into a set of slots; the number of slots are equal to the number of nodes within the cluster.

The responsibilities of the cluster head are distributed more evenly among the sensor nodes when compared with other dynamic cluster based protocols [1, 9, 26]; thus, the BDGP keeps the cluster heads for sets of rounds and the cluster sender's role is rotated to different sensor nodes.

5.3.7 Data transmission

The senor nodes are distributed over the cluster area; these sensor nodes, within the cluster, form a bidirectional ring structure. Each sensor node has two connections which point to its clockwise neighbour and its counter-clockwise neighbour, on the bidirectional ring, respectively.

In first round, the cluster senders sense their environment, collect sensed data and transmit the data to the next neighbours, in a clockwise direction. In the following round, the cluster senders sense their environment, collect sensed data and transmit the data to the next neighbours, in a counter-clockwise direction, in order to distribute the energy consumption evenly among the sensor nodes.

During the data gathering process, the cluster heads do not need to receive any sensed data from the member nodes; therefore, the cluster heads save their energy for receiving data. Each sensor node receives data from the previous neighbour, aggregates this with its own data and then transmits it to the next neighbour on the ring. Upon receiving the aggregated data from the previous neighbours, the cluster senders transmit it to the base station either directly or through neighbour cluster heads. The BDGP performs data aggregation at every sensor node in the bidirectional ring. Each sensor node aggregates its previous neighbour's data with its own data and then transmits aggregated data to its next neighbour.
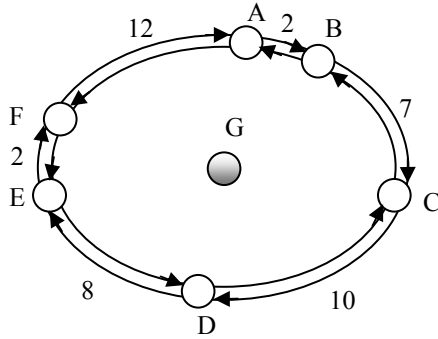
| **Figure 5-12:** Bidirectional ring. | **Figure 5-13:** Unidirectional ring. |
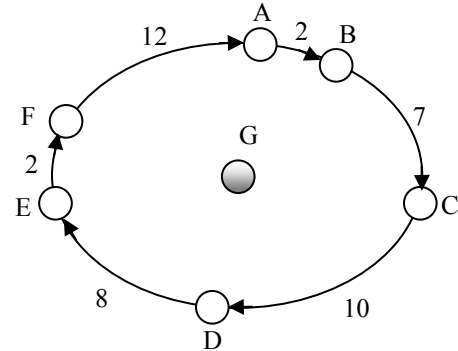
Figures 5-12 and 5-13 illustrate data transmission in bidirectional and unidirectional rings, respectively. The cluster has the following sensor nodes:

- There are seven sensor nodes in this cluster: A, B, C, D, E, F and G.

- G is the cluster head.

- A is the cluster sender.

In round i, the cluster sender, A, senses the environment, collects the sensed data and transmits the data to the next neighbour, B, in a clockwise direction. B aggregates the data with its own data and transmits the aggregated data to the next neighbour, C, in a clockwise direction. Upon receiving the aggregated data from F, the cluster sender, A, transmits it to the base station.

In round $i+1$, the cluster sender, A, senses the environment, collects sensed data and transmits the data to the next neighbour, F, this time in a counter-clockwise direction. F aggregates the data with its own data and transmits the aggregated data to the next neighbour, E, again counter-clockwise. Upon receiving the aggregated data from B, the cluster sender, A, transmits it to the base station.

Direction	Round i (clockwise)
A→B	2
B→C	7
C→D	10
D→E	8
E→F	2
F→A	12

Table 5-2: Distance of each transmission in the bidirectional ring (clockwise).

Direction	Round $i+1$ (counter-clockwise)
A→F	12
F→E	2
E→D	8
D→C	10
C→B	7
B→A	2

Table 5-3: Distance of each transmission in the bidirectional ring (counter-clockwise).

Direction	Distance	Total of distance
A→B	2	14
A→F	12	
B→C	7	9
B→A	2	
C→D	10	17
C→B	7	
D→E	8	18
D→C	10	
E→F	2	10
E→D	8	
F→A	12	14
F→E	2	
Variance		13.06

Table 5-4: Total distance in the bidirectional ring.

Table 5-2 shows the distance for each transmission in round i (clockwise), while Table 5-3 shows the distance for each transmission in round $i+1$ (counter-clockwise) and Table 5-4 shows the total distance for round i and round $i+1$ in the bidirectional ring.

In the unidirectional ring, the sensor node collects the sensed data and transmits the data to the next neighbour, in a clockwise direction for all of the rounds.

Direction	Round i (clockwise)	Round $i+1$ (clockwise)	Total of distance
A→B	2	2	4
B→C	7	7	14
C→D	10	10	20
D→E	8	8	16
E→F	2	2	4
F→A	12	12	24
Variance			67.87

Table 5-5: Distance of each transmission in the unidirectional ring.

Table 5-5 shows the distance for each transmission in the unidirectional ring. The second column shows the distances for round i (clockwise) and the third column shows the distances for round $i+1$ (clockwise). By totalling these two columns, the total distance for each transmission is show in the last column. In Table 5-4, the third column shows the total distance for the bidirectional ring with a variance of 13.06 and the fourth column in Table 5-5 shows the total distance for the unidirectional ring with a variance of 67.87. In this example, a significant decrease in variance of the transmission distance in the bidirectional ring was observed.

5.3.8 Cluster sender selection

Since the cluster senders transmit data to the base station using multihop or single hop communication, the cluster senders drain energy much faster; thus, reducing the network's lifetime. In order to balance the energy consumption among all of the sensor nodes in the network, the cluster sender's role should be rotated among the sensor nodes to prevent their

exhaustion. Sensor nodes with the highest remaining energy are selected as the cluster senders. In case where there is more than one sensor node, with equally high remaining energy levels, one of these sensor nodes is randomly selected from this cluster.

In frame number $n-1$, the sensor node sends data to the next neighbour, including its remaining energy. Based on the collected information, the sensor node compares the energy levels and selects the highest remaining energy.

The mechanism for selecting the new cluster sender is as follows:

- The sensor node, S_p, sends data and its remaining energy, ES_p, to the next neighbour, S_n.

- Based on the collected information, the sensor node, S_n, compares its energy level, ES_n, with the previous neighbour's energy level, ES_p.

- If $ES_n \geq ES_p$, the sensor node, S_n, selects itself as the provisional cluster sender and sends data with its energy level to the next neighbour.

- If $ES_n < ES_p$, the sensor node, S_n, selects S_p as the provisional cluster sender and sends data with ES_p to the next neighbour.

- When the node with the highest remaining energy is selected as the new cluster sender, the current cluster sender informs the cluster head to build a TDMA schedule with a new cluster sender at the beginning.

- Each cluster follows the same procedure for selecting a new cluster sender.

5.4 Simulation and discussion

This section will analyse the performance of the BDGP protocol using simulations. Simulation experiments were conducted in the network simulator OMNET++ [21]. Three metrics were used to analyse and compare the experimental simulation results: network lifetime, energy dissipation and communication overhead.

5.4.1 Simulation setup

As shown in Figure 5-14, it was assumed that 100 sensor nodes were randomly scattered into the sensing field, with dimensions of 100m x 100m, and the base stations were located at positions 50 and 350. All of the sensor nodes periodically sense the environment and transmit the data to the next neighbours. Every result shown is an average of 10 experiments, with a 95% confidence interval and each experiment uses a different randomly generated topology. Table 5-6 summarises the parameters used in this study's simulation.
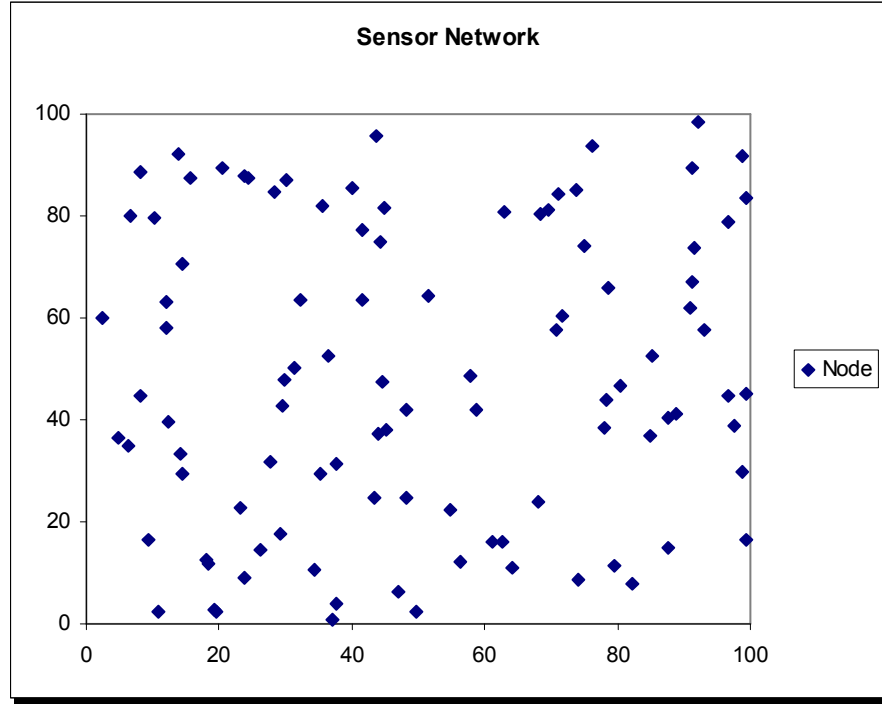
Figure 5-14: Snapshot of random deployment of the sensor nodes in the field.

5.4.2 Radio model

This research will use the same radio model to that described in previous research [9]. The initial energy of each sensor node is *1 J*, and the base station has unlimited energy.

Parameter	Value
Network size	100×100
Number of nodes	100
Base station location	50×350
E_{elec}	50nJ/bit
ε_{fs}	10pJ/bit/m^2
Initial energy	1 Joule
Data packet size	500 bytes
Info packet size	25 bytes

Table 5-6: Simulation parameters.

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5.4.3 Simulation Results

5.4.3.1 Network lifetime

The effectiveness of the proposed BDGP protocol will be validated based on the sensor network's lifetime, as the performance measure. To evaluate the network's lifetime, BDGP, EECPL and LEACH-C [9] will be compared. The performance metrics used to evaluate the system's lifetime are FD (first node dies), HD (half of the nodes alive) and LD (last node dies) [27]. More than one node is necessary to perform the clustering algorithm; thus, the LD represents the overall lifetime of a wireless sensor network, when 80% of the sensor nodes die.

The first column, in Figure 5-15, corresponds to the BDGP, the second column corresponds to EECPL and the third column corresponds to LEACH-C. This figure shows the round in which the first note dies: it is apparent that until round 349, the BDGP is able to collect data from the whole network with live sensor nodes in the network; whereas, LEACH-C operates for 254 rounds before the FD; and, in EECPL, the FD at round 326. The stability period of BDGP is much longer than that of EECPL and LEACH-C, this is because the BDGP is an energy aware protocol and, as such, obtains 27% more rounds than LEACH-C.
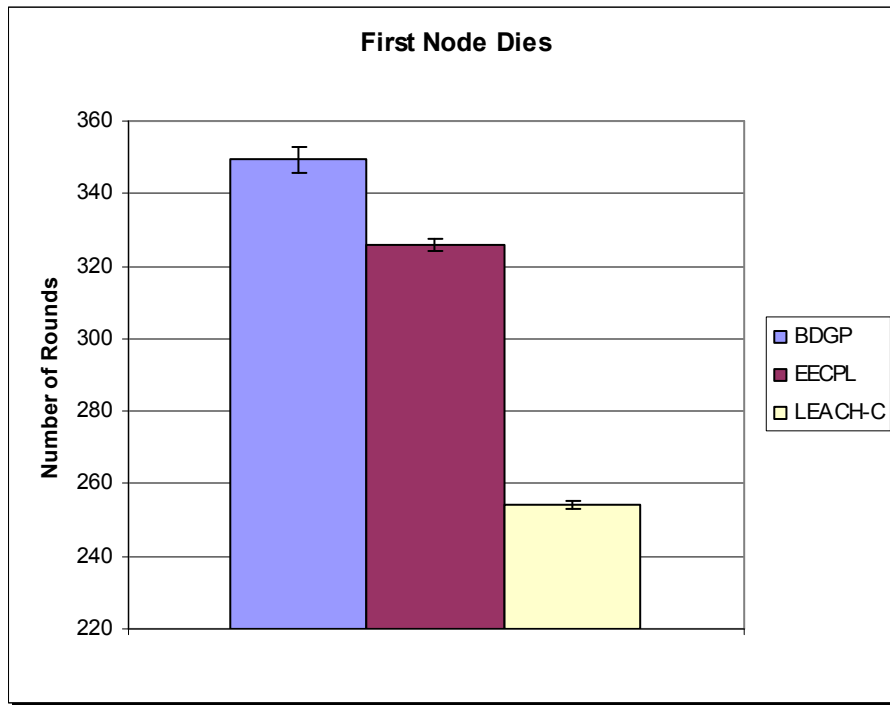
Figure 5-15: Performance comparison of the network lifetime metric FD.

To illustrate the effect of using a bidirectional ring topology on the lifetime of a sensor network, it is important to compare the HD and the LD of BDGP, EECPL and LEACH-C. Figure 5-16 and 5-17 show the round in which the HD and the LD. The sensor nodes within the BDGP protocol remain alive for longer than those in EECPL and LEACH-C. The network lifetime in LEACH-C is only 267 rounds because the majority of the sensor nodes have dissipated all of their energy; the BDGP protocol runs longer, than the EECPL and LEACH-C, with a network lifetime up to 394 rounds. Consequently, the BDGP obtains 12% more rounds than EECPL and 32% more than LEACH-C.

In LEACH-C, a cluster head is responsible for the inter-cluster and intra-cluster communication. Intra-cluster communication involves the cluster head being an aggregation point where the sensor nodes transmit their data to the cluster head. The sensor nodes located farthest from the cluster head expel the maximum amount of energy. The cluster head aggregates the data – this is performed only at the cluster head. Inter-cluster communication involves the cluster head forwarding the aggregated data to the base station directly. In contrast, in the BDGP protocol, each sensor node receives data from the previous neighbour, aggregates this with its own data and then transmits the data to the next neighbour, on the bidirectional ring. The cluster senders transmit the aggregated data to the base station using multihop or single hop communication. Thus, the BDGP protocol successfully distributes the energy among all of the sensor nodes, across the whole sensor network.
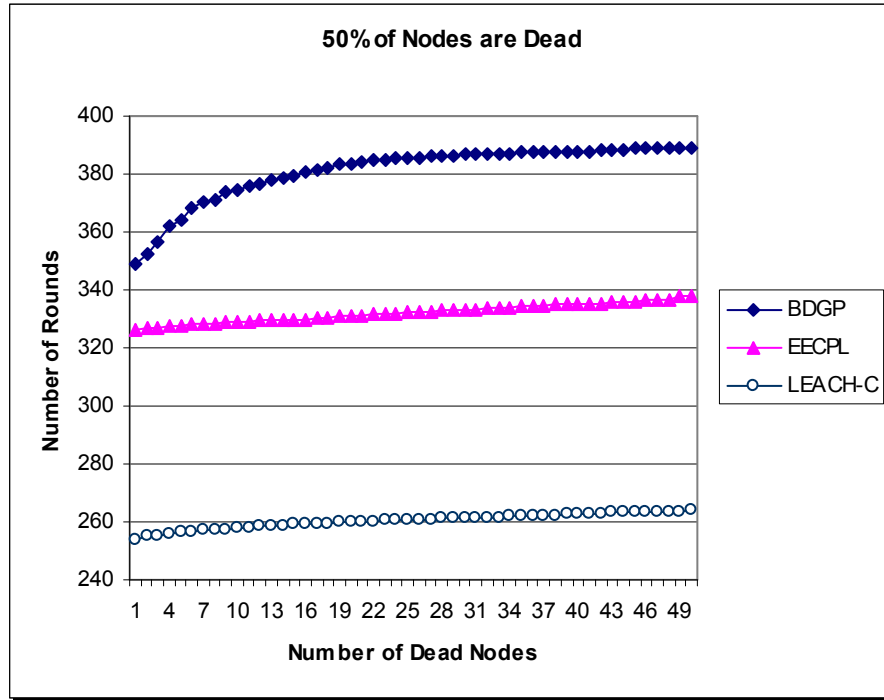
Figure 5-16: Performance comparison of the network lifetime metric HD.
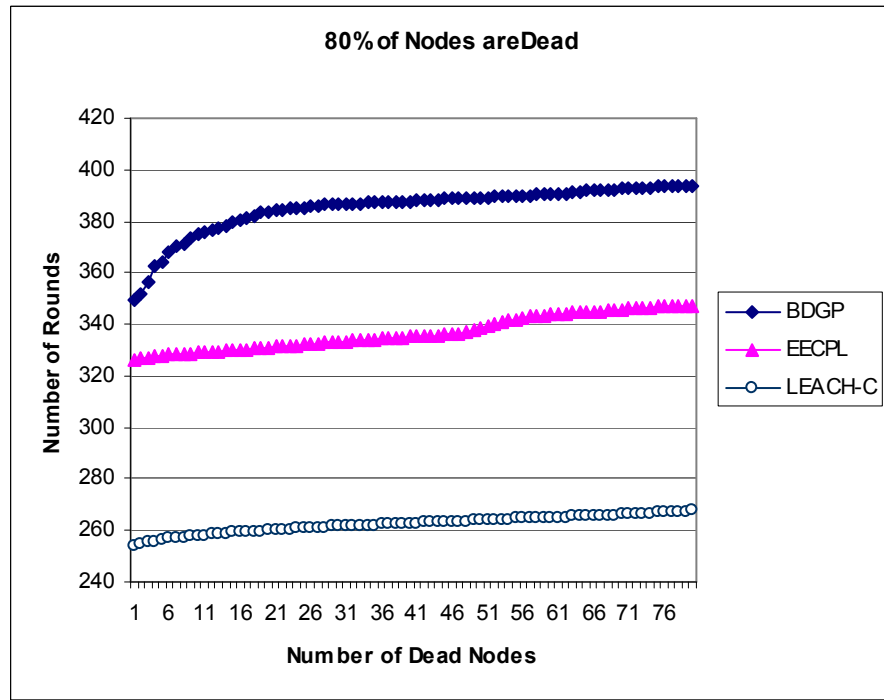
Figure 5-17: Performance comparison of the network lifetime metric LD.

5.4.3.2   Energy dissipation

This section compares the BDGP, EECPL and LEACH-C protocols in terms of energy dissipation. The average energy consumed by the sensor nodes is computed for the sensor network. The energy efficiency of BDGP, when compared to EECPL and LEACH-C, can be seen in Figures 5-18 and 5-19. The first column corresponds to the BDGP and the second and third columns correspond to EECPL and LEACH-C, respectively. LEACH-C consumes more energy because the sensor nodes, located far from the cluster heads, send their data to the cluster heads. The cluster heads collect data from the sensor nodes in their clusters, aggregate the data and send it to the base station. The cluster heads, located far from the base station send their data directly toward the base station. Due to this communication scheme, the cluster heads and the sensor nodes dissipate more energy transmitting over longer distances. The EECPL uses a single hop mechanism for routing data to the base station, each cluster head directly transmits its data to the base station; hence, the cluster heads located farthest from the base station consume more energy.

This is avoided in the BDGP because each sensor node consumes a small amount of transmitting energy in order to reach the neighbours sensor node in the bidirectional ring and the cluster heads do not need to receive any sensed data from the member nodes. The communication between the cluster senders and the base station is multihop or single hop and the cluster sender sends its data through the shortest possible path to the base station.
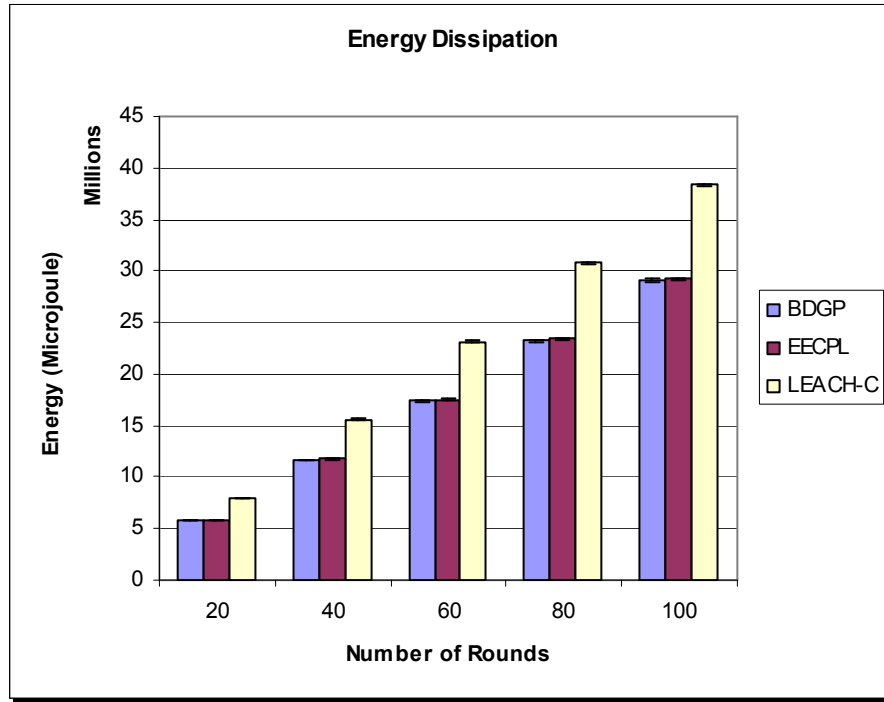
Figure 5-18: Energy dissipation comparison of BDGP, EECPL and LEACH-C.
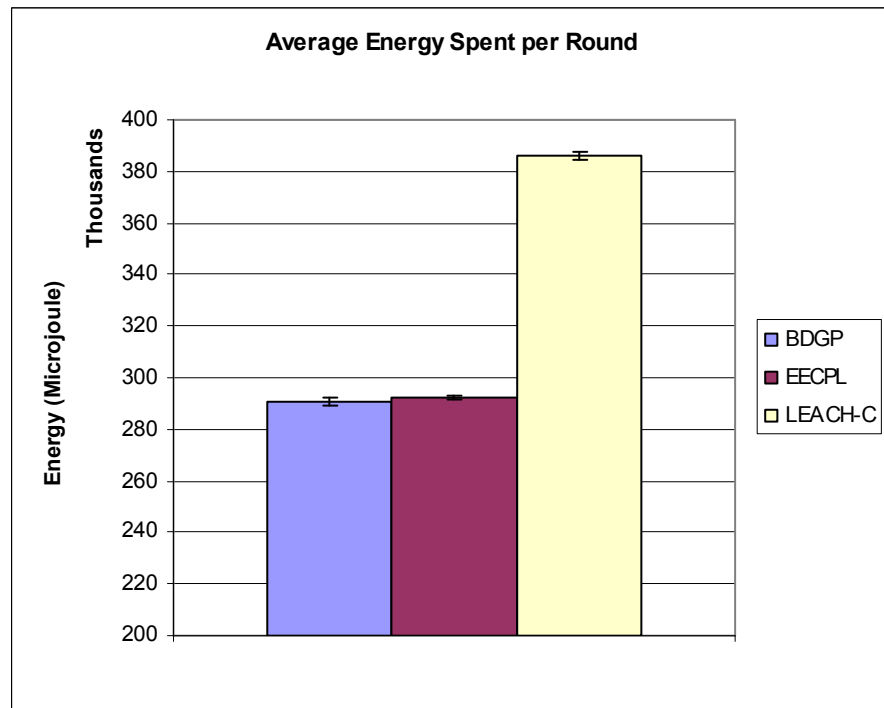
Figure 5-19: Average energy dissipation.

5.4.3.3   Communication overhead

Different protocols often rotate the cluster head's functionality among the sensor nodes to distribute the energy among them. Clustering protocols need to obtain a balance between the frequency of reforming the clusters and the energy saving from cluster reformation. LEACH-C suffers from consuming more energy due to the cluster formation overheads. Additionally, each sensor node transmits data to its cluster head, even if the cluster head resides at a greater distance from the base station.

The BDGP uses the remaining energy for the cluster sender's rotation; thus, the sensor nodes with the highest remaining energy are selected as cluster senders without needing to communicate with the base station. Thus, it reduces a large number of communication overheads. As shown in Figure 5-20, BDGP can reduce communication overheads, during the initial phase, by 97%.
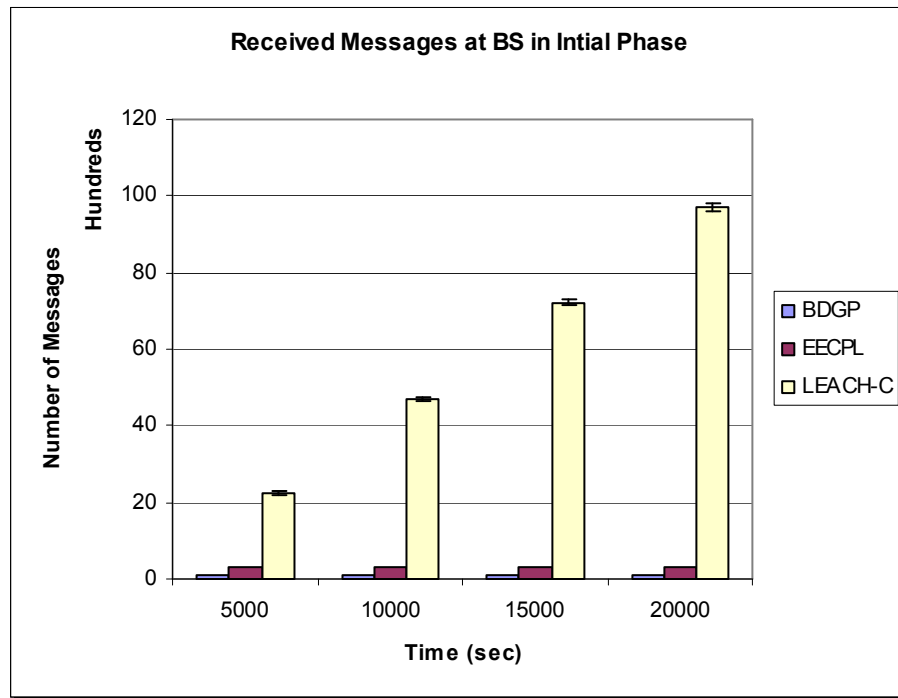
Figure 5-20: Performance comparison of the communication overhead.

5.4.3.4 Transmission distance

It is important to study the effect of the transmission distance between the sensor nodes and the base station; this will determine performance and whether the distance between the nodes effects the energy consumption in the data transmission. The total transmission distance is computed from the sensor node to other sensor nodes and from the sensor node to the base station.

The following figures, Figures 5-21 and 5-22, show the simulation results of the transmission distance. LEACH-C obtained a very large total transmission distance because the distance between the nodes and their cluster heads increased, and the rate of energy

consumption in the sensor network also increased; the energy consumption is therefore related to the distance from the source to the destination, as shown in Figure 5-18.

BDGP and EECPL outperform LEACH-C because they have lower transmission distances. The ring topology identified in BDGP and EECPL contributes to them attaining increased performance over LEACH-C.
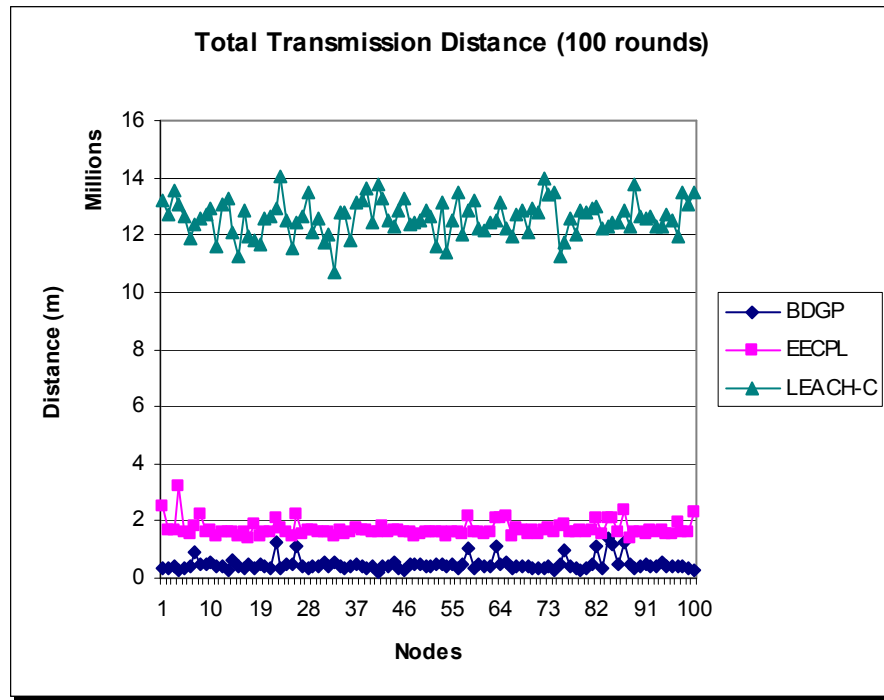
Figure 5-21: Performance comparison of the total transmission distance.
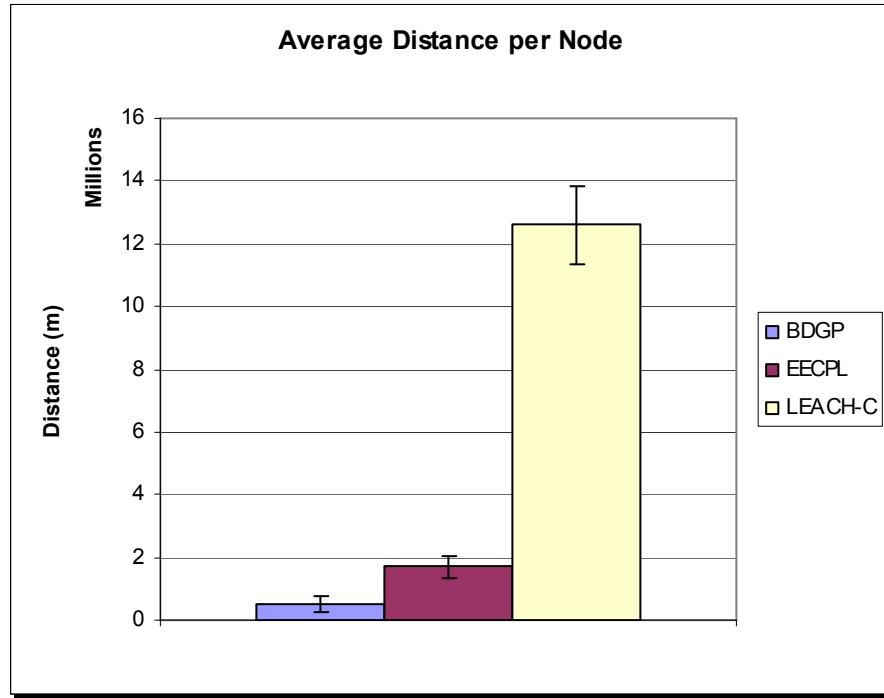
Figure 5-22: Average transmission distance.

5.4.3.5   Increasing the network area

The performance of the clustering protocols was evaluated when the area of the network was increased from 100 x 100m to 200 x 200m. For this study, 100 sensor nodes were randomly scattered in the sensing field, other parameters remained the same as in the network size of 100 x 100m.

Figures 5-23 and 5-24 show the energy dissipated by BDGP, EECPL, and LEACH-C. Clearly, BDGP and EECPL outperformed LEACH-C; they had very similar average energy dissipations as the network area increased, see Figures 5-18 and 5-19. This is likely to be because LEACH-C always sends its data directly towards the cluster heads and the base

station; whereas, BDGP and EECPL send their data using the ring topology. Despite, BDGP using a multihop routing mechanism for sending its data, Figures 5-23 and 5-24 illustrate the effectiveness of both BDGP and EECPL for wireless sensor applications that cover large network areas.
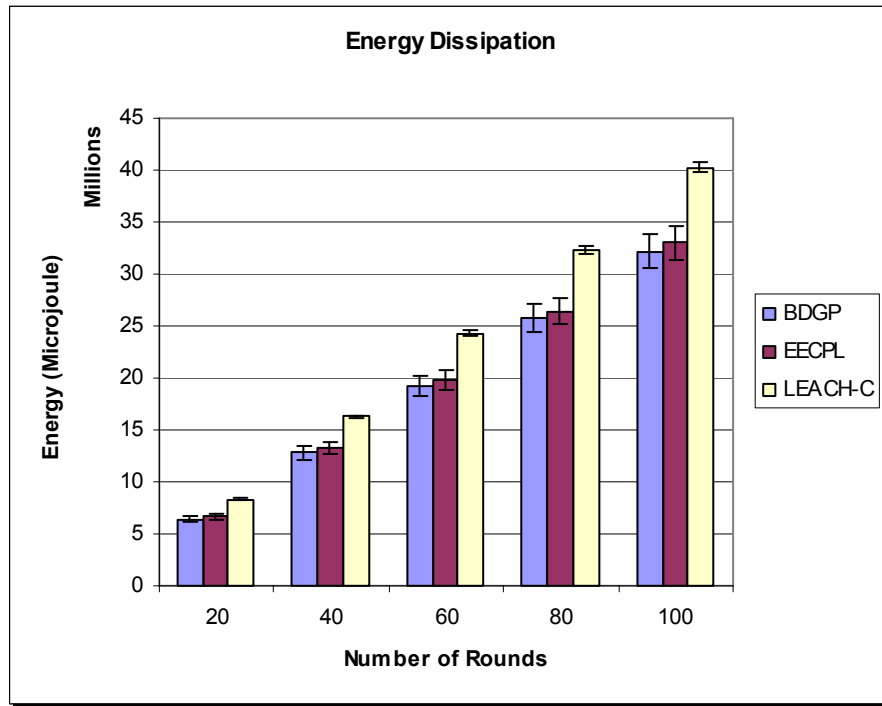
Figure 5-23: Energy dissipation comparison of BDGP, EECPL and LEACH-C 200 x 200m network.
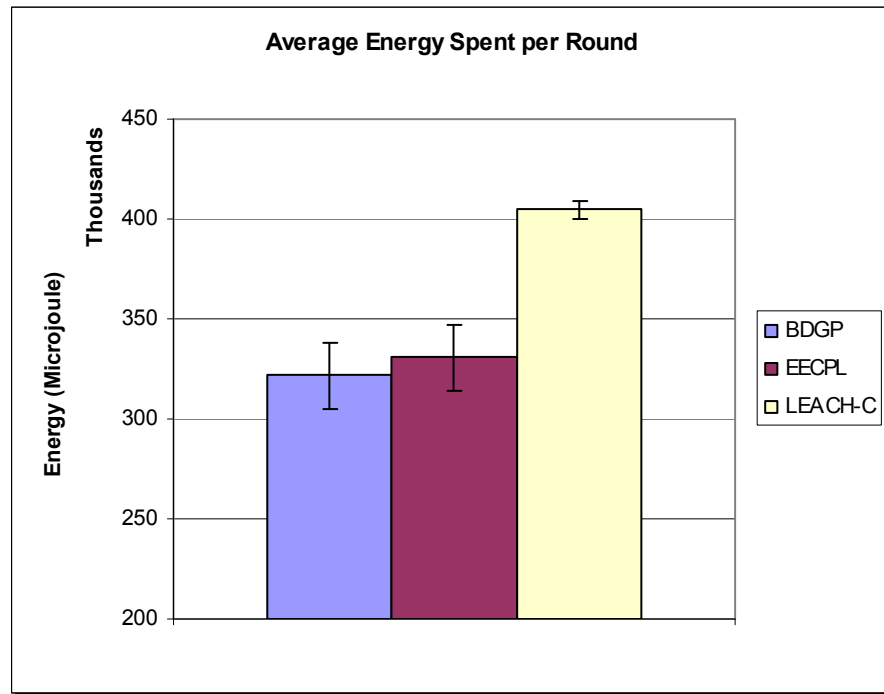
Figure 5-24: Average energy dissipation.

5.5 Conclusion

Since wireless sensor nodes are low powered, the constraint on the power consumption is an important issue when designing wireless sensor network protocols. Many clustering protocols have been proposed, with different clustering criteria, to reduce the energy consumption of a wireless sensor network. This research has introduced a protocol which can form clusters, select cluster heads, select cluster senders and determine appropriate routings in order to reduce the overall energy consumption and enhance the network's lifetime. Our proposed clustering protocol is called: bidirectional data gathering protocol for wireless sensor networks (BDGP).

A set of senor nodes are distributed over the cluster area, these sensor nodes, within the cluster, form a bidirectional ring structure. Each sensor node has two connections which point to its clockwise neighbour and its counter-clockwise neighbour, on the bidirectional ring, respectively. During the data gathering process, the cluster heads do not need to receive any sensed data from the member nodes; therefore, the cluster heads save the energy for receiving the data. Each sensor node receives data from the previous neighbour, aggregates this with its own data and then transmits it to the next neighbour on the ring.

The performance of the BDGP protocol, via simulation, needs evaluating. Our simulation model uses a sensor network with a number of sensor nodes that were randomly distributed in the sensor field. The BDGP was compared to the well known protocols: EECPL and LEACH-C, and was measured against the following three metrics: the network's lifetime, the energy dissipation and the communication overheads. The results show that BDGP outperformed EECPL and LEACH-C across all of the metrics. The simulation results confirm that the BDGP provides a higher energy efficiency which meets the constraints of the wireless sensor networks.

Chapter 6

Conclusions and Future Work

6.1 Conclusion

This thesis has investigated the design and development of clustering protocols which would enhance the lifetime of wireless sensor networks. Different clustering protocols were presented which utilise less energy when gathering data in the sensor network. The proposed mechanisms can achieve better performance, in terms of the: network's lifetime, received data messages, energy dissipation, and the communication overheads.

Three clustering protocols: ADRP, EECPL, and BDGP, were proposed for wireless sensor networks. These protocols were implemented and verified using the OMNET simulator. A comparative study of the proposed protocols was presented and discussed through a number of experiments, in order, to demonstrate their merits and capabilities.

In a wireless sensor network, it is important to prolong the network's lifetime so that more data can be sent to the base station; consequently, the efficient use of energy is critical for the network's lifetime. In terms of dynamic clustering protocols [7-10], the cluster heads are responsible for collecting, aggregating and sending data to the base station. These protocols rotate the role of the cluster head, among the sensor nodes, which balances the

energy dissipation of the sensor nodes. However, they suffer from cluster formation overheads and consume more energy which shortens the lifetime of the sensor network.

The proposed protocol, ADRP, can improve the network's lifetime while expending energy more efficiently by identifying a set of sensor nodes which will become the next heads, during the re-cluster stage. The sensor nodes can switch directly to the next heads; therefore, the role of a cluster head can be switched dynamically.

The experimental results show that, under ADRP, it is possible to achieve a better network lifetime and expand energy more efficiently; furthermore, this research reveals that the network's lifetime could be expanded by combining the remaining energy of the sensor nodes and the average energy of the cluster.

The energy efficient clustering protocol (EECPL) was proposed, its main goal was to distribute the energy load among all of the sensor nodes in the sensor network to increase the network's lifetime and reduce the energy consumption. The EECPL organises sensor nodes into clusters and uses ring topology among the sensor nodes, within the clusters; consequently, each sensor node receives data from a previous neighbour and then transmits the data to the next neighbour.

This thesis has also evaluated the performance of the EECPL, using simulations. ADRP and LEACH-C consume more energy because the cluster heads are responsible for collecting data from the sensor nodes, aggregating the data and then sending the data directly towards the base station. The EECPL alleviates this problem by distributing the

responsibilities of the cluster heads among the member nodes; since the responsibilities of the cluster heads are more distributed among the sensor nodes, EECPL can keep cluster heads for sets of rounds.

BDGP is a bidirectional data gathering protocol that can be used in wireless sensor networks. BDGP forms a bidirectional ring structure among the sensor nodes, within a cluster, so that each sensor node has two connections which point to its clockwise neighbour and its counter-clockwise neighbour, in the ring, respectively. BDGP creates a cluster sender that transmits data to the base station via one or multiple intermediate cluster heads. The data from the cluster senders are routed among the neighbour cluster heads, until it reaches the base station. During the data gathering process, the cluster heads do not need to receive any sensed data from the member nodes. Therefore, the cluster heads save their energy for receiving data. Each sensor node receives data from the previous neighbour, aggregates this with its own data and then transmits it to the next neighbour on the ring.

The BDGP was designed to incorporate the following features which would meet the challenges of the wireless sensor networks. As the sensor nodes are battery operated, any reduction in energy consumption will help to extend the network's lifetime. BDGP uses multihop and single hop communication to reduce the energy consumption and balance the energy load among the sensor nodes.

In addition, the BDGP reduces the energy consumption by exploiting the data gathering aspect of the sensor networks. The nodes within a cluster are located close to each other

and are likely to have correlated data; therefore, performing local data aggregation in a bidirectional ring could greatly reduce the energy consumption. Thus, the BDGP successfully distributed the energy among all of the sensor nodes, over the whole sensor network.

6.2 Future work

An intuitive and directive suggestion for future work could include the following:

- Cooperation between multiple cluster heads to overcome high data rate.

- In heterogeneous networks, where some sensors are more powerful and more reliable, these powerful sensor nodes could be chosen as the base station or cluster head. Several base stations could be kept to communicate with each other and use the proposed protocols.

- The development of secure data aggregation protocols; users need to be able to ensure that unauthorised users can not access the data from the sensor networks.

- Investigation into the sequence of the base station's movement and the schemes to handle the changing network topologies, while the base station moves.

- The mobility of nodes indicates that they can improve a network.

- The proposed protocols could be evaluated in the presence of node mobility.

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