Energy Efficient Routing with Effective Clustering Mechanisms in Wireless Sensor Networks

A Thesis Submitted to

Nirma University

In Partial Fulfillment of the Requirements for

The Degree of

Doctor of Philosophy

in

Technology and Engineering

by

Mr Ankit Thakkar (10EXTPHDE45)

Institute of Technology
Nirma University
Ahmedabad-382481
Gujarat, India

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I dedicate this Thesis to my son Master Maharshi Thakkar, my wife Dr Jignasa Thakkar and my parents.

Nirma University
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Certificate

This is to certify that the thesis entitled **"Energy Efficient Routing with Effective Clustering Mechanisms in Wireless Sensor Networks"** has been prepared by Mr Ankit Thakkar under my supervision and guidance. The thesis is his original work completed after careful research and investigation. The work of the thesis is of the standard expected of a candidate for Ph.D. Programme in Computer Science and Engineering and I recommend that it be sent for evaluation.

Date: 9/5/14

Name and Signature of the Guide

Name and Signature of the
Head of the Department

Name and Signature of the
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Abstract

Recent development in sensor technology and wireless communication has motivated the development of billions of inexpensive sensor nodes, which attracts various applications of Wireless Sensor Networks (WSNs). Because of large application areas, performance metrics for any WSN are strictly application specific. However, energy conservation can be determined as a common metric for any successful application of WSN due to energy constraint of nodes. Also, it is very difficult to replace or recharge batteries of sensor nodes that monitor hostile environments, in which contemporary monitoring schemes requiring human intervention are risky, inefficient and sometimes infeasible. This leads to network longevity as one of the challenging issues of the sensor network.

In the sensor network, energy consumption of the nodes is dominated by two major tasks. First, communication happens between the nodes due to the transmission or reception of the packets; and second, during the time spent by the node to listen or detect any event. Therefore, there are two different approaches for energy conservation. Energy can be conserved either by reducing transmission or reception of packets through load balancing; or reducing idle listening time through proper duty-cycling during event detection. The first approach covers, load balancing during routing, while the second one deals with the duty-cycling technique. Both of these approaches can be managed with effective clustering using cross layer optimization schemes.

In this thesis, initially load balancing through energy efficient clustered routing techniques for static homogeneous wireless sensor network have been studied and investigated. Later, cluster head election techniques for energy efficient routing for static homogeneous clustered wireless sensor network have been developed by considering various parameters that affect the network lifetime. A cluster head election technique for energy and delay constrained applications of wireless sensor networks has been proposed and analyzed using two different types of distances between the communicating nodes. A protocol is proposed for energy efficient routing through Cross-layer Design, wherein, Ant Colony Optimization (ACO) is used to elect the

cluster heads. Later, an approach is proposed to minimize cluster formation overhead by relaxing maximum energy criteria to elect cluster heads along with a scheme that enforces a node to become cluster head, if it has not decided to become cluster head or member node within the stipulated time.

An algorithm is proposed to minimize the standard deviation in the number of cluster heads per round. It also reduces the difference of the relative distances of elected cluster heads from the sink. Both of these help to achieve near optimal load balancing for the cluster heads during each round. Later, a Bollinger Band based cluster head election scheme is proposed. Also, a method is devised to compute optimal cluster (grid) size to prolong the network lifetime. A data forwarding scheme is also proposed that results in the multi-hop routing, in which, elected cluster heads work as the data forwarders. This helps to improve the network lifetime by reducing idle listening time of the nodes, including cluster heads. It also manages proper duty-cycling for all the nodes.

A distributed approach is proposed to minimize the cluster formation overhead. The proposed approach gives a fair chance to each node to become cluster head. This approach allows scheduling of data messages within the cluster along with the proper management of the duty-cycling time of the nodes.

At last, a method is proposed for a heterogeneous network that dynamically computes the number of cluster heads for each round by considering remaining network energy and number of alive nodes in the network. The proposed approaches have been evaluated using extensive simulations.

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Declaration

I, Mr Ankit Thakkar, registered as Research Scholar, bearing Registration Number 10EXTPHDE45 for Doctoral Programme under the Faculty of Technology and Engineering of Nirma University do hereby declare that I have completed the course work, pre-synopsis and my research work as prescribed under R. Ph. D. 3.5.

I do hereby declare that the thesis submitted is original and is the outcome of the independent investigations / research carried out by me and contains no plagiarism. The research is leading to the discovery of new techniques already known. This work has not been submitted by any other University or Body in quest of a degree, diploma or any other kind of academic award.

I do hereby further declare that the text, diagrams or any other material taken from other sources (including but not limited to books, journals and web) have been acknowledged, referred and cited to the best of my knowledge and understanding.

Date: 09/5/14

Signature of Student

Acknowledgments

With immense pleasure, I would like to present this research work related to “Energy Efficient Routing with Effective Clustering Mechanisms in Wireless Sensor Networks” a fruit of labor. They say you need Gurus, Teachers, Mentors, Guides, Friends and Family to achieve success in life. I have all of them and more. My first and foremost thank to Almighty God, without heavenly blessings, it was impossible to complete this research work.

I would like to express my sincere gratitude to my guide, Dr Ketan Kotecha, Director, Institute of Technology, Nirma University for always motivated me forward and inspiring me to explore the unexplored. His guidance, motivation and inspirational words always help to understand things from different aspects that any researcher should know.

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I would also express my sincere thanks to all the staff members of Library specially Ms Hiral Patel and Mr Sujal Soni for providing necessary support by disseminating articles and books as and when I required.

Last but not the least my heartiest thanks to my better half, Dr Jignasa Thakkar, who lived her dream in me. She sacrificed herself and supported me in a way only she can do, so that I can achieve my goals in stipulated time.

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I would like to give my heartfelt thanks to my parents, for their love and grounding they provided along with foundation of knowledge and fundamentals which helped me during this research work.

Mr Ankit Thakkar
10EXTPHDE45

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Abbreviations

ACO	Ant Colony Optimization
ADC	Analog to Digital Convertor
AL-LEACH	Alive Nodes based improved Low Energy Adaptive Clustering Hierarchy for Wireless Sensor Network
ALEACH	Advanced LEACH
BB	Bollinger Band
BFOA	Bacterial Foraging Optimization Algorithm
BS	Base Station
CH	Cluster Head
CI	Convergence Indicator
CLD	Cross-layer Design
CPU	Central Processing Unit
CS	Cluster Setup
CVLEACH	Coverage based energy efficient LEACH algorithm
DEAP	Delay-Energy Aware routing Protocol
DEAR	Delay-bounded Energy constrained Adaptive Routing
EAERP	Energy-Aware Evolutionary Routing Protocol
ECBRP	An Enhanced Cluster Based Routing Algorithm for Wireless Sensor Networks
ED	Event Detection

EDA	Energy for Data Aggregation
EDACH	Energy-Driven Adaptive Clustering Hierarchy
EDIT	Energy Delay Index for Trade-off
EEABR	Energy Efficient Ant Based Routing
EECR	Energy Efficient Clustering Routing algorithm for wireless sensor networks
ESP	An Energy Sorting Protocol with reduced energy and latency for Wireless Sensor Networks
ET	Energy Threshold
FLP	Facility Location Problem
FND	First Node Dies
GA	Genetic Algorithm
GPS	Global Positioning System
HNA	Half of the Nodes Alive
HND	Half of the Nodes Die
IEAL	Improved Energy-efficient Algorithm based on L-DCHS
LDCHS	Low energy adaptive clustering hierarchy with Deterministic Cluster-Head Selection
LEACH	Low Energy Adaptive Clustering Hierarchy
LEICP	A Low Energy Intelligent Clustering Protocol for wireless sensor networks
LND	Last Node Dies
LQI	Link Quality Indicator
MA	Moving Average
MAC	Medium Access Control
MATLAB	MATrix LABoratory

MCH	Master CH
MR-LEACH	Multi-hop Routing with Low Energy Adaptive Clustering Hierarchy
MT-ANT	Modified T-ANT
NEAW	Novel Energy-efficient Algorithm for Wireless Sensor Network
PEGASIS	Power-Efficient Gathering in Sensor Information Systems
PRR	Packet Reception Rate
Q-LEACH	Quadrature-LEACH
QoS	Quality of Service
RBS	Reference Broadcast Synchronization
REEH	Residual Energy Efficient Hetrogeneous Clustered Hierarchy protocol for Wireless Sensor Networks
ROI	Region of Interest
RR	Round Robin
RSSI	Received Signal Strength Indicator
S-LEACH	A Sequential selection approach to elect cluster heads for LEACH protocol
SCH	Second layer of CH
SEP	Stable Election Protocol
SI	Swarm Intelligence
SNR	Signal-to-Noise Ratio
SPE	Spatial Process Estimation
TDMA	Time Division Multiple Access
TDP	Time-Diffusion Protocol
TED	Trade-off Energy with Delay

TL-LEACH	A Two-Levels hierarchy for Low-Energy Adaptive Clustering Hierarchy
TTL	Time To Live
VCH	Vice CH
WALEACH	Weight based Advanced LEACH protocol
WCVALEACH	Weight and Coverage based energy efficient Advanced LEACH protocol
WSN	Wireless Sensor Network

Chapter 1

Introduction

Wireless Sensor Networks (WSNs) consist of a large number of sensor nodes, which are battery operated with a limited amount of memory as well as communication and computation capabilities. The applications for WSN can be classified into two categories: Event Detection (ED) and Spatial Process Estimation (SPE) (Buratti et al.). In ED, sensors are deployed to detect an event such as forest fire detection, earthquake, etc. while in the SPE, WSN aims at monitoring the physical phenomenon like temperature, pressure, etc. for a given Region of Interest (ROI). Because of the variety of applications covered by WSN, performance metrics in the sensor network are strictly application specific. One of the advantages of WSNs is their ability to operate in un-attended harsh environments, where human intervention is risky, inefficient and sometimes infeasible (Abbasi and Younis). This makes "network lifetime" as a common performance metric for almost all applications of the WSN.

The "network lifetime" refers to the time after which network becomes non-functional. In fact, the non-functionality of the underlying WSN is also application dependent. A sensor network is said to be non-functional if (Çetin, Prasad, and Prasad)

- packets are received after the substantial time for delay sensitive applications.
- the desired coverage is not maintained for the coverage preserving applications.
- death of certain nodes due to the energy deficiency results into network partitions.

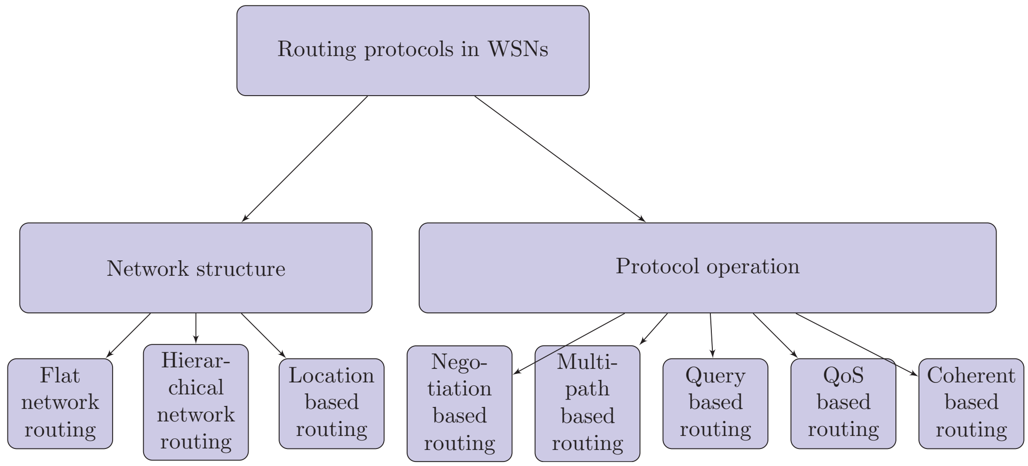


Figure 1.1: Taxonomy of routing protocols in WSN

This research work mainly focuses on improving the functionality of the static homogeneous network due to the energy deficiency.

Energy depletion of the WSN network is dominated by the communication between nodes, which lead to partitioning of the network. This affects the requirements of the application due to unavailability of the data from the certain region. However, the replacement or recharging of the batteries of the nodes is impossible if they are deployed in the harsh environment where human intervention is impossible or risky. Also, it is impractical to replace or recharge batteries of the nodes due to the large number of nodes deployed in the network. Hence, protocols designed for WSN must be energy efficient.

The network lifetime is strictly application specific which depends upon the parameters like topology of the WSNs (Banerjee et al. Santi), the data delivery modes being used (i.e. event driven, query driven or hybrid) (Akkaya and Younis), the data aggregation techniques (such as suppression, min, max or average) (Akkaya and Younis), the MAC algorithms (Ramaraju Kalidindi, Kannan, and Iyengar), routing protocols (Akkaya and Younis) and energy models for communication (Younis, Youssef, and Arisha). This research work focuses on prolonging network lifetime using energy efficient routing protocols with effective clustering mechanisms.

Taxonomy of the routing protocols is shown in the Figure 1.1 (Al-Karaki and Kamal). Based on the network structure, routing protocols can be classified as flat routing protocols, hierarchical network routing protocols and location based routing protocols. Based on operational functionality, routing protocols can be classified as negotiation based routing, multi-path based routing, query based routing, QoS based routing and coherent based routing. This research work focuses on hierarchical network routing protocols, as they are energy efficient, scalable and reduce topology maintenance overhead (Abbasi and Younis).

1.1 Problem Definition

Energy efficient routing for clustered WSNs is an important research area. The parameters used to elect the cluster heads play an important role in improving the network lifetime. In this research work, cluster head election techniques and its effect on energy consumption of individual node is studied that affects the network lifetime. The objective of this research is to design cluster head election techniques and study its effect on the performance of the network from the energy efficiency point of view by varying network parameters that affect the network lifetime.

In order to enhance network lifetime, energy consumption of individual nodes should be reduced under given constraints to meet requirements of the application. The energy spent by a sensor node for communication is very high compared to the energy spent for the computation (Abbasi and Younis Akkaya and Younis). Hence, to prolong network lifetime, communication between the nodes should be minimized, simultaneously requirements of the underlying application should not be compromised. Also, consumption of energy during communication is directly proportional to the square or quad of the communication distance between the sender and receiver (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks"). Hence, long distance communication should be avoided as far as possible. This demands routing of packets from source to sink using multi-hop communication, which is a challenging task in a wireless environment, and it becomes more complex when a large number of nodes are deployed in the ROI, which communicate using broadcast mode of communication (Radi et al.). Clustered routing techniques help to reduce the communication distance as well as network activity. However, the parameters used for the election of cluster head play an important role in providing prolonged network lifetime by load balancing between the nodes. On the other hand, there is large energy consumption by radio, when it is listening to receive possible traffic that is not sent. This phenomenon is called idle listening (Bonny). Energy conservation of a node can also be achieved by setting a radio to the low power mode (sleep state) during an idle listening time, and awaken back at the time of transmission or reception. The process of switching a radio between sleep and awaken modes is called duty-cycling (Boulis, "Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User's manual"). The number of cluster heads in the network significantly affects the network lifetime. Routing protocols discussed in Chapter 2 assumes a fixed number of cluster heads, which is known to the protocol apriori and it does not change with time. For example, it is shown that LEACH gives optimal performance when the total number of cluster heads is 5% of the total number of nodes in the network (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks"). However, once the network is active, the number of alive nodes reduce and their energy gets depleted with time. Hence, the number of cluster heads should also be determined dynamically for the given network as a function of time, alive nodes and their energy. In addition to that, overhearing property of a node can also be used to improve network lifetime by creating non-overlapping clusters. Also, many routing protocols discussed in Chapter 2, always select the highest energy node as a cluster head that incurs overhead of cluster formation and results in non-optimal performance.

To summarize, energy consumption of the nodes can be minimized by four ways: i) by minimizing the number of communications between the nodes; ii) by minimizing long distance communication between the nodes; iii) by minimizing idle listening time of nodes and iv) by properly managing duty-cycling time of nodes. Researchers are working to design a suitable cluster head election method in order to provide energy efficient routing by optimizing all the four parameters mentioned above. Also, dynamically computed number of cluster heads for a given network is to be devised as a function of time.

The following problems are addressed in this research that affects network lifetime:

- How the Cluster Head (CH) election process affected by random numbers?
- How the number of alive nodes helps to improve CH election process?

- How to maintain the desired number of CHs during each round with a simplified CH election approach?
- How overhearing property of nodes helps in the CH election process?
- How CH election technique can be improved by giving importance to the parameters used in the CH election process?
- How to elect CH for delay constraint applications?
- How different types of distances affect the energy consumption of a node and delay experience by the packet?
- How ACO along with cross layer architecture helps in the CH election process?
- How CHs can be elected by avoiding cluster formation overhead?
- How standard deviation in the number of CHs per round affects the network lifetime?
- How grid architecture along with the CH election process helps to reduce idle listening time and to maintain proper duty-cycling of nodes?
- How to compute number of CHs dynamically as a function of time, alive nodes and the remaining energy of the network?

1.2 Scope of the work

The scope of the work is to identify the challenges to prolong the network lifetime for the clustered WSNs and to propose solutions for routing a packet using single-hop or multi-hop communication as per need of the application. The protocol should elect cluster heads to provide energy efficient routing for a static homogeneous network. Also, a solution is proposed to compute number of cluster heads as a function of time for a static heterogeneous network.

1.3 Significant Contribution

The study of this research shows that there are four key points for energy consumption of a node: i) distance between the communicating nodes; ii) amount of communication done between the nodes; iii) idle listening period of a node for detecting any event and iv) proper management of the duty-cycle time of nodes. The first one aimed to reduce the communication distance between the source and sink through effective clustering mechanisms; the second one is to reduce the number of packets exchanged between the nodes and/or the sink; the third one focuses on reducing wait time of a node to receive a packet and last one focuses on proper management of sleep and awake schedule for the radio. The first and second deal with effective selection of cluster heads to reduce the number of packets and communication distance between the nodes, while third and fourth deals with the scheduling of the cluster heads to minimize idle listen period by proper management of the sleep and awake schedule of nodes.

In this research work, scope of improvement is explored for existing routing protocols such as Low Energy Adaptive Clustering Hierarchy (LEACH) (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks") and few of its decedents. Also, techniques for its improvement from the network longevity point of view are proposed. A solution for the energy and delay constraint applications of WSNs is proposed and it is shown that how different types of distances affect the network lifetime. A cluster head election technique inspired from Ant Colony Optimization (ACO) is proposed and results are compared with T-ANT clustering approach (Selvakennedy, Sinnappan, and Shang). An energy threshold based approach is proposed to reduce cluster formation overhead by relaxing the maximum energy constraint to elect CHs. A concentric circle approach is proposed to minimize standard deviation in the number of cluster heads. It helps to improve the network lifetime. The proposed approach is compared with four protocols, including e-LEACH (Randriatsiferana et al.).

A virtual grid based architecture along with a cluster head election technique using Bollinger bands is proposed. In that, optimal grid size is identified to get maximum energy conservation. Also, a technique to generate predefined schedule path is proposed that reduces idle listening time and manages proper duty-cycling of both types of sensor nodes: i) CH nodes and ii) non-CH nodes. A Round Robin (RR) schedule based scheme is proposed to elect cluster heads by eliminating cluster formation overhead. In that, a double virtual grid based strategy is proposed to minimize idle listening time and to achieve proper duty-cycling of the nodes. At last, a technique based on a stretched exponential function is proposed that dynamically computes the number of cluster heads over time and the results are compared with the heterogeneous LEACH protocol (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks") and Stable Election Protocol (SEP) (Smaragdakis, Matta, and Bestavros).

1.4 Thesis Organization

The rest of the thesis is organized as follows:

Chapter 2 (*Background*): This chapter begins with the introduction to Wireless Sensor Network (WSNs) that covers distinguish features of WSN and design criteria for WSN routing protocols. Later, energy dissipation in WSN node is explored. This chapter also discusses the effect of routing protocols on the lifetime of the WSN. Issues that make the cluster head election a challenging task is also summarized. Some prominent clustered routing protocols along with the parameters used for the cluster head election have been studied.

Chapter 3 (*Improvements on LEACH and few of its descendants*): This chapter covers improvement areas of LEACH protocol and few of its decedents, and proposes solutions for the identified areas. Two different energy models are also studied as the energy consumption of the WSN node is affected by the energy model being used for the experiments.

Chapter 4 (*Cluster Head Election for Energy and Delay Constraint Applications of Wireless Sensor Network*): This chapter covers Cluster Head Election for Energy and Delay Constraint Applications of Wireless Sensor Network by considering Energy Delay Index for Trade-off (*EDIT*). The protocol, *EDIT*, is examined and derived to analyze energy-delay trade-off by doing extensive simulations. The effect of two types of distances, Euclidean distance and Hop-count, to be used to elect cluster heads using *EDIT* protocol is successfully demonstrated and their effect on delay and energy. In the course of research, the effect of controlling parameters for *EDIT* protocol is also manifested.

Chapter 5 (*Cross-layer Design and Energy Threshold based improved Cluster Head election strategies for Wireless Sensor Networks*): This chapter focuses on two important aspects: i) Use of cross-layer architecture with ACO for CH election, and ii) relaxing maximum energy criteria during the CH election process. A protocol for energy efficient routing using Cross Layer Design (CLD) is proposed, wherein, Ant Colony Optimization (ACO) is used to elect the cluster heads. Later, a solution is proposed by relaxing maximum energy criteria to elect cluster heads to reduce cluster formation overhead.

Chapter 6 (*Concentric Circle Approach for Cluster Head Election in Wireless Sensor Networks*): In this chapter, the concentric circle approach is proposed, to elect the cluster heads for the clustered routing algorithm, that helps to prolong the network lifetime. The proposed approach dynamically selects radius of concentric circles. Also, node density is considered while computing radius of the concentric circles. In addition, the length of the movement of concentric circles is controlled by the maximum distance between alive node and the sink. This approach minimizes the standard deviation in the number of cluster heads. It helps to prolong the network lifetime through near uniform load balancing between the elected CHs.

Chapter 7 (*A new Bollinger Band based Energy Efficient Routing for Clustered Wireless Sensor Network*): This chapter covers a grid based technique to create clusters that help to achieve maximum energy efficiency. Cluster Heads within the clusters are elected using a technique inspired by Bollinger Band, which a technical trading tool developed by John Bollinger in 1980. A data forwarding technique is also proposed to achieve optimal duty-cycling for the energy conservation of the nodes.

Chapter 8 (*Round Robin scheduling approach for Cluster Head election in Wireless Sensor Networks*): In this chapter, an approach based on Round Robin (RR) scheduling is proposed for cluster head election in WSNs, as RR is a fair scheduling scheme. The proposed approach minimizes cluster formation overhead incurred during cluster setup phase by introducing a double virtual grid approach. To achieve load balancing between the WSN nodes, the role of CH should be rotated and each node should be given equal chance to be a cluster head from the set of nodes belongs to the same cluster.

Chapter 9 (*A novel method to compute number of cluster heads in the wireless sensor network using stretched exponential function*): In this chapter, a method is proposed to model percentage of cluster heads during each round as a function of time, current network energy and the number of alive nodes using stretched exponential function. The proposed approach is tested with extensive simulations with heterogeneous networks, wherein, a fraction of total nodes is given more energy. These nodes are called as advanced nodes and others are referred as normal nodes.

Summary and Conclusion: This chapter includes the major conclusions of the research work. Future directions of research in this area are also outlined in this chapter.

A separate section for the *Indexes* used in the Thesis is covered towards the end. The *Works Cited* section consists of related research work cited in the thesis work.

Chapter 2

Background

2.1 Introduction to Wireless Sensor Network

Recent developments in sensor technology and wireless communication make the sensor nodes inexpensive. Researchers across the globe are giving attention to these very attractive cost-effective applications like environmental monitoring, battle field monitoring and structural monitoring to name a few. The applications of WSNs can be classified into two categories: Event Detection (ED) and Spatial Process Estimation (SPE) (Buratti et al.). In ED, sensors are deployed to detect an event such as forest fire detection, earthquake, etc. while in the SPE, WSN aims at monitoring the physical phenomenon like temperature, pressure, etc. for a given Region of Interest (ROI). This thesis focuses on static wireless sensor networks, where nodes do not change their positions after deployment. Node deployment techniques can broadly be classified as deterministic (controlled) or random (Younis and Akkaya). Controlled deployment is generally pursued for indoor applications, while random deployment is observed for harsh environments such as battle field monitoring or disaster monitoring, etc. However, both node deployment techniques may require unattended operations which lead to network longevity as a common optimization problem for static wireless sensor networks (Younis and Akkaya).

Wireless Sensor Networks have the following distinct features compared to other networks:

- Limited resources (i.e. Limited amount of energy, memory, processing and communication capability)

- Random deployment
- Ability to withstand in harsh environmental conditions
- Dynamic network topology due to the communication failure
- Heterogeneity of nodes (i.e. Some nodes are equipped with more resources)
- Large scale of deployment
- Unattended operation
- Difficult network maintenance due to large scale random deployment
- Many to one communication network, i.e. all the sensor nodes send their data to the sink (or Base Station) (see Figure 2.1 taken from (Ibriq and Mahgoub))

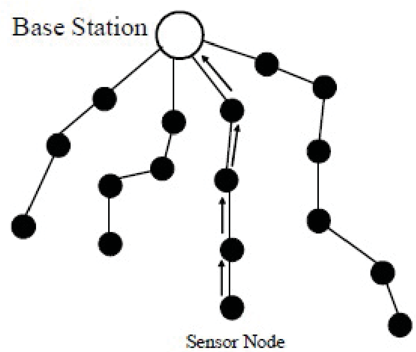


Figure 2.1: Many to one communication network (Ibriq and Mahgoub)

Due to limited resources, the design criteria for WSN routing protocol can be summarized as follows:

- **Energy Efficiency:** Energy is a precious resource in WSNs and therefore the routing protocol must be energy efficient. The term "efficiency" creates many different aspects of a system, which should be carefully distinguished to form actual, measurable figures of merit. The most commonly considered aspects are (Karl and Willig):

  Energy per correctly received bit This refers to the average energy spent to transport one bit of information from the source to the destination. This is often a useful metric for periodic monitoring applications.

Energy per reported unique event This refers to the average energy spent to report a unique event.

Delay/energy trade-offs For delay sensitive applications, it is interesting to find trade-offs between energy and delay.

Network lifetime Possible definitions related to network lifetime are:

- **Time to first node death** It refers to the time when a first node of the network runs out of energy after network deployment.
- **Network half-life** It refers to the time when 50% of the nodes runs out of energy after network deployment. Any other fixed percentile is applicable as well.
- **Time to partition** It refers to the time when the network is partitioned and some nodes are unable to communicate with the sink.

- **Simple Algorithm and Small Footprint:** Sensor nodes are constrained by the limited amount of memory and processing capacity. Hence, the routing protocol for WSNs must be simple to reduce computational overhead and must occupy a small space in a memory.

- **Robust and Fault Tolerant:** Nodes are deployed randomly in a harsh environment and hence they are prone to failure either due to the technical problem with the node (i.e. faulty node) or unable to communicate with other nodes because of communication link failures.

- **Localized Addressing Scheme:** WSNs operate in unattended environments. Hence, sensor nodes must self-organize to form a WSN to meet the requirements of the application. Therefore, the WSN routing protocol should be localized. Each sensor node should be able to discover its own positioning and neighboring nodes in order to make WSNs functional for a given application.

- **Location Awareness:** Many WSN applications such as animal detection would require that sensor nodes should also send the position, where the event is detected. For such applications, sensor nodes should be aware of its position. One approach is to attach Global Positioning System (GPS) with every sensor node. This may not be a good solution as sensor nodes are battery operated.

Received Signal Strength Indicator (RSSI) is one of the methods to find the location of a sensor node (Ibriq and Mahgoub).

2.2 Energy dissipation in WSN node

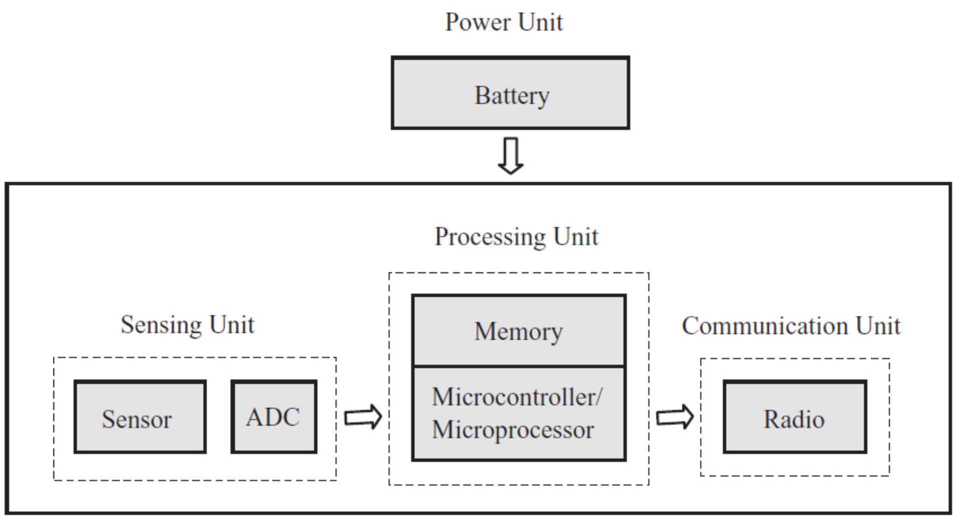


Figure 2.2: Sensor Node Structure (Karl and Willig)

A sensor node typically consists of four basic components: a sensing unit, a processing unit, a communication unit, and a power unit, which is shown in Figure 2.2. This figure is taken from (Karl and Willig). The energy dissipation in a sensor node is due to the following components of the sensor node:

- Sensing Unit (Sensors+ADC)
- Processing Unit (Microprocessor/Microcontroller + Memory)
- Communication Unit (Radio)

However, energy dissipated by the communication unit, i.e. radio, is very high compared to energy dissipated by Sensing Unit or Processing Unit (Abbasi and Younis Akkaya and Younis). Hence, to enhance the network lifetime of WSNs, radio should be kept in low power mode, i.e. sleep state as and when possible. Also, energy expenditure is directly proportional to the square or quad of the distance. Thus, to achieve maximum network longevity, long distance communication should be avoided as far as possible. In addition to that, energy expenditure is proportional to the number of packets transmitted or received by radio. Hence, data aggregation techniques (such as Min, Max or Avg) should be used to reduce energy consumption of radio.

2.3 Effect of routing on the lifetime of Wireless Sensor Network

Routing is the process to select a path between communicating nodes, i.e. between the source and the destination, along which packets are to be sent (Tuteja, Gujral, and Thalia). Direct communication results in higher energy depletion for WSN nodes, as the energy consumption of a node is proportionate to the square or quad of the communication distance. Thus, the lifetime of a network can be improved by reducing long distance communication as far as possible.

Clustering is one of the techniques that helps to reduce long distance communication, in which one of the nodes from a set of reachable nodes act as Cluster Head (CH). The node, elected as CH, is responsible to collect data from the neighboring nodes. Energy consumption of a WSN node is also affected by the number of bits communicated i.e. transmitted or received. Hence, data aggregation technique(s) (e.g. min, max or average) can be used by CHs before sending packets to the BS or sink. This helps to conserve energy of CHs.

Clustering process helps to save energy of non-CH nodes at the cost of higher energy depletion for the CH nodes. This is because CHs are required to perform many tasks, including reception of packets from the neighboring nodes, aggregating and sending packets to the sink node. This demands selection of CHs on a rotation basis with the use of effective clustering mechanisms. This thesis focuses on effective clustering mechanisms that provides energy efficient routing and thus improves the lifetime of Wireless Sensor Network.

2.4 Hierarchical Routing protocols for Wireless Sensor Networks

As discussed in Chapter 1, based on the network structure, routing protocols can be classified as flat, hierarchical or location based routing protocols. This research work is aimed at improving network lifetime through the effective clustering mechanism from the routing point of view. The formation of the cluster for the cluster based routing protocols is a challenging task due to the following issues (Ibriq and Mahgoub):

- How clusters are to be formed?
- Is the clustering process centralized or distributed?
- Is the number of clusters known to the algorithm apriori or computed dynamically?

After cluster formation, Cluster Head (CH) receives data from its member nodes (to avoid long distance communication by the member nodes), performs data aggregation (to reduce the number of bits required to be transmitted by CH) and sends it to the Base Station (BS). Hence, energy utilization for CHs is higher than the non-CH nodes. So, the CH must be selected on a rotation basis to achieve uniform energy depletion.

Low Energy Adaptive Clustering Hierarchy (LEACH) (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks") is one of the prominent cluster based protocol that works in rounds. Round is the time duration for which a node elects itself as CH and serves to other nodes. Each round is divided into two phases: i) Cluster Setup Phase and ii) Steady State Phase. Cluster heads are elected during Cluster Setup Phase. During this phase, a node assumes a random number between 0 and 1; and it elects itself as cluster head if the generated random number is less than $T(n)$, where $T(n)$ is given by Equation 2.1.

$$T(n) = \begin{cases} \frac{p}{1 - p * (r \ mod \ \frac{1}{p})} & \text{if } n \ \in \ G, \\ 0 & \text{otherwise} \end{cases} \tag{2.1}$$

In Equation 2.1, p is the desired percentage of the Cluster Heads (CHs) during each round and it is known to the algorithm in advance; G is the set of nodes that had not been Cluster Heads since last $\frac{1}{p}$ rounds, where p is given by Equation 2.2.

$$p = \frac{k}{N} \tag{2.2}$$

Here, N is the number of nodes and k is the number of Cluster Heads. After Cluster Heads (CHs) are elected, they inform their status to other nodes. Non-Cluster Head nodes associate with one of the CHs, for which minimum communication energy is required. After receiving join messages, CHs prepare TDMA schedule and inform to the member nodes. During Steady State Phase, member nodes transmit data as per TDMA schedule. CHs perform data aggregation and send it to BS after receiving data from the member nodes.

Low energy adaptive clustering hierarchy with Deterministic Cluster-Head Selection (LDCHS) (Handy, Haase, and Timmermann) improves LEACH algorithm by including the remaining energy level available in each node, and it is given by Equation 2.3, where $E_{current}$ and E_{max} denote the current and initial energy of the nodes respectively.

$$T(n) = \begin{cases} \frac{p}{1 - p * (r \ mod \ \frac{1}{p})} * \frac{E_{current}}{E_{max}} & \text{if } n \in G, \\ 0 & \text{otherwise} \end{cases} \tag{2.3}$$

The network does not progress after a certain number of rounds with this threshold value, and hence, the threshold value $T(n)$ is further modified which is given by Equation 2.4.

$$T(n) = \begin{cases} \frac{p}{1 - p * (r \ mod \ \frac{1}{p})} [\frac{E_{current}}{E_{max}} + (r_s \ div \ \frac{1}{p})(1 - \frac{E_{current}}{E_{max}})] & \text{if } n \in G, \\ 0 & \text{otherwise} \end{cases} \tag{2.4}$$

where r_s denotes a number of consecutive rounds for which the node is not elected as CH. The Quadrature-LEACH (Q-LEACH) (Manzoor et al.) divides network area into quadrants, and cluster head is elected from each quadrant using Equation 2.1. Advanced LEACH routing protocol for wireless microsensor networks (ALEACH) (Ali, Dey, and Biswas) improves the LEACH protocol by modifying the threshold equation $T(n)$, given by Equation 2.5.

$$T(n) = G_p + CS_p \tag{2.5}$$

where G_p and CS_p are the general probability and the current state probability respectively, given by Equation 2.1 and 2.6.

$$CS_p = \frac{E_{current}}{E_{nmax}} * \frac{k}{N} \tag{2.6}$$

where k is the desired number of Cluster Heads, N is the number of nodes, $E_{current}$ and E_{nmax} denote the current and initial energy of a node.

To reduce long distance communication, TL-LEACH (A Two-Levels hierarchy for Low-Energy Adaptive Clustering Hierarchy) (Loscri, Morabito, and Marano) was proposed. A further improvement is shown in MR-LEACH (Multi-hop Routing with Low Energy Adaptive Clustering Hierarchy) (Farooq, Dogar, and Shah) that uses multi-hop communication technique to reduce communication distance between a transmitter and the intended receiver. T-ANT algorithm (Selvakennedy, Sinnappan, and Shang) inspired from the ACO, incorporates the TCCA clustering with the ANT election scheme. CH election is dynamically controlled by ant swarms in T-ANT algorithm. PEGASIS (Lindsey and Raghavendra) forms the chain of nodes to avoid long distance communication and thus provides network longevity.

"An Enhanced Cluster Based Routing Algorithm for Wireless Sensor Networks (ECBRP)" (Han et al.) has modified the threshold value $T(n)$ of the LEACH algorithm, given by Equation 2.7.

$$T(n) = \begin{cases} \frac{p}{1 - p * (r \ mod \ \frac{1}{p})} * \frac{E_{current}}{E_{max}} & \text{if } n \ \in \ G, \\ 0 & \text{otherwise} \end{cases} \tag{2.7}$$

where $E_{current}$ and E_{max} denote residual energy of a node and maximum energy of the entire network respectively.

W. Guifeng et al. has proposed "An Ant Colony Clustering Routing Algorithm for Wireless Sensor Networks" (Guifeng, Yong, and Xiaoling), which differs from LEACH algorithm by two ways: i) Threshold value $T(n)$ is calculated using Equation 2.8

$$T(n) = \begin{cases} \frac{p}{1 - p * (r \ mod \ \frac{1}{p})} * \frac{E_{current}}{E_{max}} & \text{if } n \ \in \ G, \\ 0 & \text{otherwise} \end{cases} \tag{2.8}$$

where $E_{current}$ denotes the current energy of the node and E_{max} denotes the initial energy of the node and ii) ACO approach is used to communicate data from CH to sink using multi-hop communication if required, and a next hop selection is done using Equation 2.9

$$p_{ij} = \frac{(\tau_{ij})^{\beta_1} * (\eta_{ij})^{\beta_2}}{\sum_{k \in N_i} (\tau_{ik})^{\beta_1} * (\eta_{ik})^{\beta_2}} \tag{2.9}$$

where a set of neighbor nodes for CH_i is denoted by N_i, β_1 and β_2 is used to show the relative importance of distance between two CHs and energy of the CH to be selected as the next hop.

A-LEACH (Abdellah et al.) uses heterogeneous architecture by providing α times more energy to the m fraction of nodes called the CAG i.e. nodes selected as cluster heads or gateways, and the rest of $(1-m)*n$ will be the normal nodes. A-LEACH uses the similar approach proposed in LEACH to select CH. CAG nodes will be working as gateway nodes, except those are selected as a CH for the current round. It helps to increase the stability period.

The authors have proposed EDACH algorithm (Kim and Youn), in which each node calculates the threshold value $T(n)$ as per Equation 2.1, but the value of p differs for each node, depending upon its location from BS. p can take one of three segment values termed as near, medium and far; and it is represented by $(1-x)p$, p and $(1+x)p$ respectively, where $0 < x < 1$.

REEH (Sehgal and Choudhary) uses the similar concept as described in (Handy, Haase, and Timmermann) to calculate threshold value $T(n)$ for each node, but it differs from (Handy, Haase, and Timmermann) in terms of heterogeneity. REEH assigns more energy to 10% of total node to increase the lifetime of WSN.

Double CH election strategy is used in IEAL (Wang et al., "An Improved Energy-efficient Algorithm based on L-DCHS in WSN") by introducing Master CH (MCH) and Vice CH (VCH). MCHs are elected as per Equation 2.4. After announcement of MCHs, other nodes calculate the node factor and send it with the join message given to MCH; where the node factor is given by Equation 2.10.

$$D(i) = \frac{E_{i\_current}}{D_{i\_bs}} \tag{2.10}$$

Here, $E_{i\_currnet}$ and D_{i_bs} denote current energy of the node and the distance between node and BS, respectively. A node having maximum node factor will be elected as VCH by MCH.

The Authors have proposed "NEAW: A Novel Energy-efficient Algorithm for Wireless Sensor Network" that divides ROI in three parts based on the distance of each node i from BS called as d_i (Wang et al., "A novel energy-efficient algorithm for wireless sensor networks"). Each node will be assigned a region I, II or III by Equation 2.11.

$$Region(i) = \begin{cases} I & \text{if } d_i < \frac{d_0}{2}, \\ II & \text{if } \frac{d_0}{2} < d_i < d_0, \\ III & \text{if } d_i > d_0. \end{cases} \tag{2.11}$$

If a particular node has been assigned region II or III, it transmits data directly to BS or through multi-hop communication by considering CH factor, which is given by Equation 2.12.

$$CF_{ij} = a * \frac{D_{js}}{E_j} + b * D_{ij} \tag{2.12}$$

where a and b are the weight factors for the corresponding parameters; D_{ij} is the distance between node i and node j; D_{js} is the distance between node j and BS. CH always selects a node with the lowest CF_{ij} as its next hop. MCH available in Region I can directly transmit data to BS without getting the help of VCH. MCH available in Regions II and III can transmit data to BS by taking help of VCH available in Regions I and II.

In (Ran, Zhang, and Gong), authors have proposed LEACH-FL algorithm, in which, CHs are selected based on probability, which is given by Equation 2.13.

$$Probability = battery\ level\ *\ 2 + node\ density + (2\ -\ distance) \tag{2.13}$$

A node with the highest battery level, the lowest node density and nearest to BS have the highest probability to be elected as CH and a node with the lowest battery level, the lowest node density and farthest from the BS have the lowest probability to be elected as CH. A total 27 rules are defined to get probability value, details of which can be found at (Ran, Zhang, and Gong). To get the crisp value of probability, centroid based defuzzyfication is used. To get the value of probability, authors have used a formula of $G(i)$ shown in Equation 2.14.

$$G(i) = \frac{\sum_{j=1}^{n} x_j * u(x_j)}{\sum_{j=1}^{n} u(x_j)} \tag{2.14}$$

To translate the value of $G(i)$ to $F(i)$ linear method is used, where $F(i)$ is given by Equation 2.15.

$$F(i) = 1 - \frac{G(i) - 0.665}{12.2335 - 0.665} \tag{2.15}$$

Each node calculates $F(i)$ in each round, and if $F(i)$ is less than the threshold value, the node will be elected as CH, where the threshold is given by Equation 2.1.

Like ALEACH, in EC-LEACH (Chen, Lu, and Wang), authors have extended LEACH algorithm by modifying the threshold value $T(n)$, given by Equation 2.16.

$$T(n) = \begin{cases} \frac{p}{1 - p * (r \ mod \ \frac{1}{p})} * \frac{E_{r\_e} - E_{r\_c}}{E_{r\_e}} & \text{if } n \ \in \ G, \\ 0 & \text{otherwise} \end{cases} \tag{2.16}$$

where E_{r_e} and E_{r_c} represent the remaining energy of nodes after r round ending and energy consumption of data transfers of nodes respectively.

LEACH-C (Heinzelman, Chandrakasan, and Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks"), uses centralized clustering approach. In LEACH-C, each node sends its energy and location information to the Base Station (BS). After receiving energy information, BS calculates average node energy. Nodes having lesser energy cannot become cluster head for the current round. For the remaining nodes, simulated annealing algorithm is used to find out k optimal Cluster Heads.

LEACH-F (Heinzelman) is not adaptive for dynamic systems. In such systems, either new nodes may be added to the system or existing nodes may die at any point of time.

In (Okdem and Karaboga), the authors have proposed a novel approach for WSN routing operations to prolong the network lifetime by discovering the shortest path from a source to BS using ACO approach. In the paper, the next hop is chosen by a node from the set of neighboring nodes by considering the ratio of the energy level of each node with respect to the sum of energy levels of all neighboring nodes.

In (Camilo et al.), the authors have proposed Energy Efficient Ant Based Routing (EEABR), which uses lightweight ants to optimize routing paths in terms of energy and distance.

In (Selvakennedy, Sinnappan, and Shang), the authors have proposed ACO based CH election scheme for uniform distribution of CHs to prolong the network lifetime.

In (Behboudi and Abhari), the authors have proposed algorithm to elect CH according to its distance to BS. A node which is nearer to BS have more probability to be elected as CH, compared to the nodes which are far away from the BS. However, this algorithm does not consider the current energy level of a node while electing it as CH.

Quio Li et al. has proposed LEICP (Li et al.), which makes use of Bacterial Foraging Optimization Algorithm (BFOA) technique to enhance the lifetime of WSN.

I-Hui Li et al. has proposed “An Energy-efficient Three-layer Clustering Hierarchy for Wireless Sensor Networks” (Li, Wu, and Liao) by introducing a second layer of CH called SCH. Like LEACH-C, CHs and SCH are selected by BS, and then BS sends TDMA schedule to CHs and SCHs. BS ensures that each CH is connected to only one of the SCHs. The selection of SCH is based on Facility Location Problem (FLP) (Li, Dong, and Wen) and Facility Cost function of SCHs is given by Equation 2.17.

$$CostSCH_j = \frac{e_{jBS}}{e_j} \tag{2.17}$$

where e_{jBS} and e_j denote transmission energy from SCH_j to BS and the remaining energy of SCH_j respectively.

Enan Khalil et al. has proposed Energy-Aware Evolutionary Routing Protocol (EAERP) (Khalil and Attea), in which CHs are elected using centralized evolutionary algorithm based on Genetic Algorithm (GA).

Li et al. has proposed EECR (Li, Dong, and Wen), in which, first round cluster heads are selected by BS by splitting network repeatedly until the desired number of clusters is formed. After forming clusters, BS will select one of the nodes within the cluster as CH, which is generally located in the center of the cluster. CH will send invitation to other nodes within the cluster to join it as soon as it will be informed by the BS to work as CH. Nodes will send join messages to CH with current weight value W, given by Equation 2.18. After the first round, CH will calculate its own value of W, and if it is higher than the maximum value W that it has received, then it will continue to work as a CH for the next round; otherwise it will inform the node with the maximum value of W to work as a CH for the next round.

$$W = C_1 E_{re} + C_2 N + C_3 T \tag{2.18}$$

where $C_1 + C_2 + C_3 = 1$, E_{re}, N and T denote the remaining energy of node, total neighboring nodes and time taken to become CH in the former round respectively.

In "An Energy Sorting Protocol with Reduced Energy and Latency for Wireless Sensor Networks" (ESP) (Allirani and Suganthi), energy of individual nodes is compared with all other nodes to select top 5 nodes with the maximum energy.

In (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks"), authors have shown performance of LEACH protocol with a homogeneous network, i.e. all nodes are equipped with the same amount of energy. In Stable Election Protocol (SEP) (Smaragdakis, Matta, and Bestavros), the authors have shown that the classical protocol like LEACH cannot take advantage of network heterogeneity. Network heterogeneity is attained by assigning more energy to the fraction of total nodes. These nodes are called as advanced nodes, while the remaining nodes are the normal nodes. The study of optimal probability of being cluster head as a function of spatial density, has been studied through simulations (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks") or analytically (Bandyopadhyay and Coyle, "An energy efficient hierarchical clustering algorithm for wireless sensor networks" "Minimizing communication costs in hierarchically-clustered networks of wireless sensors") under the constraint that nodes are uniformly distributed over the sensor field. Such clustering scheme is optimal when energy consumption is well distributed over all sensors and total energy consumption is minimum.

In SEP, a node assumes a random number between 0 and 1 and a node is elected as CH, if the selected random number is less than the threshold. As SEP uses the heterogeneous network, threshold values are different for normal nodes and advanced nodes. The threshold value for normal nodes is given by Equation 2.19

$$T(S_{nrm}) = \begin{cases} \frac{p_{nrm}}{1 - p_{nrm} * (r \ mod \ \frac{1}{p_{nrm}})} & \text{if } S_{nrm} \in G', \\ 0 & \text{otherwise} \end{cases} \tag{2.19}$$

where r is the current round, G' is the set of nodes that have not become Cluster Heads within the last $\frac{1}{p_{nrm}}$ rounds, $T(S_{nrm})$ is the threshold applied to a population of N nodes, p_{nrm} is the probability of the normal nodes to become Cluster Heads, given by Equation 2.20.

$$p_{nrm} = \frac{p_{opt}}{1 + \alpha * m} \tag{2.20}$$

where m is the percentage of total nodes, which are advanced nodes, α is the percentage of more energy given to the advanced nodes, and p_{opt} is given by Equation 2.21.

$$p_{opt} = \frac{k_{opt}}{N} \tag{2.21}$$

where N is the total number of nodes in the network and k_{opt} is the optimal number of Cluster Heads. The threshold value for advanced nodes is given by Equation 2.22.

$$T(S_{adv}) = \begin{cases} \frac{p_{adv}}{1 - p_{adv} * (r \ mod \ \frac{1}{p_{adv}})} & \text{if } S_{adv} \in G'', \\ 0 & \text{otherwise} \end{cases} \tag{2.22}$$

where r is the current round, G'' is the set of nodes that have not become Cluster Heads within the last $\frac{1}{p_{adv}}$ rounds, $T(S_{adv})$ is the threshold applied to a population of $N * m$ nodes, p_{adv} is the probability of the advanced nodes to become Cluster Heads and it is given by Equation 2.23.

$$p_{adv} = \frac{p_{opt}}{1 + \alpha * m} * (1 + \alpha) \tag{2.23}$$

In (Randriatsiferana et al.), authors have proposed Low Energy Adaptive Clustering Hierarchy with deterministic cluster head selection by introducing new parameters for electing a cluster head: the remaining energy and its meaningful variance. Nodes with the highest remaining energy and lower energy variance are having more probability to become CHs. A node participating in the CH election process generates a random number between 0 and 1, which is compared with the threshold value $T(n)$, given by Equation 2.24.

$$T(n) = \begin{cases} \frac{p}{1 - p * (r \ mod \ \frac{1}{p})} * \frac{\gamma_i(r) * E_i(r)}{E_o} & \text{if } n \ \in \ G, \\ 0 & \text{otherwise} \end{cases} \tag{2.24}$$

where $E_i(r)$ is the node energy during round r, E_o is the initial energy of the nodes, p is the desired percentage of CH given by Equation 2.25 and $\gamma_i(r)$ is the convex function to ensure convergence of the algorithm given by Equation 2.27.

$$p = \frac{K_{opt}}{n} = \frac{\sqrt{\frac{n}{2*\pi}} * d_0 * \frac{M}{d_{toBS}^2}}{n} \tag{2.25}$$

Here, n is the number of nodes deployed in a square region of M x M $meter^2$, $d_0 = \sqrt{\frac{\epsilon_{fs}}{\epsilon_{mp}}}$, ϵ_{fs} and ϵ_{mp} depend on the transmitter amplifier models used for the experiments and d_{toBS} is the distance between cluster head and the BS given by Equation 2.26.

$$d_{toBS} = 0.765 * \frac{M}{2} \tag{2.26}$$

$$\gamma_i(r) = \frac{\mu_i(r)}{\sqrt{\mu_i^2(r) + v_i(r)}} \tag{2.27}$$

In Equation 2.27, $v_i(r)$ represents the variance of the energy level and $\mu_i(r)$ represents the average energy of a node at round r. $v_i(r)$ and $\mu_i(r)$ is given by Equations 2.28 and 2.29 respectively.

$$v_i(r) = \frac{1}{r} \sum_{r=1}^{r} (E_i(r) - \mu_i(r))^2 \tag{2.28}$$

$$\mu_i(r) = \frac{1}{r} \sum_{r=1}^{r} E_i(r) \tag{2.29}$$

2.5 Summary

Energy efficiency is one of the important issues in Wireless Sensor Networks and cluster based routing techniques help to improve the network lifetime. Also, distributed clustering scheme is more preferable as it provides scalability. Clustered routing protocols discussed in this chapter can be optimized further, even though they are energy efficient. The techniques to prolong the network lifetime of Wireless Sensor Networks are identified and considered for the implementation.

Chapter 3

Improvements on LEACH and few of its descendants

LEACH (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks") is one of the energy efficient cluster based routing protocols. LEACH has not only put the foundation for the cluster based routing protocols to improve network lifetime, but also inspires researchers across the globe to work in this direction. Many protocols are developed as an extension of the LEACH protocols, while others are inspired and developed separately as described in Chapter 2.

The following assumptions are made about the sensor nodes and underlying network for the LEACH protocol (Chen et al. Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks").

- Base Station (BS) is located in the center of the node deployment area, and it is having infinite amount of energy.
- BS and sensor nodes are stationary once they are deployed in the Region of Interest (ROI).
- All sensor nodes are homogeneous and are assigned unique identifier.
- All sensor nodes are having limited amount of energy.
- All sensor nodes are capable of transmitting with different power levels depending upon the distance from the desired recipient.

- All sensor nodes are capable to communicate with each other and BS.
- All sensor nodes are always having some data to be sent.
- Communication links are symmetric.
- Cluster Heads always receive highly correlated data from the member nodes. Thus, data aggregation is possible.
- Energy consumption for Cluster Head is uniform (Aslam et al.).
- Cluster Heads are uniformly distributed (Kim and Youn).

Following improvement areas for the LEACH protocol have been identified and solutions are proposed for the same.

- Extensions of LEACH algorithm give better performance by improving threshold value $T(n)$, given by Equation 2.1. However, it is also possible to improve the clustering process of the LEACH algorithm by either incorporating some method along with the uniform random number generation scheme or using a method other than uniform random number generation. This modified random number is compared with threshold $T(n)$ to make the decision of a node to be worked as CH or not.
- LEACH gives optimal performance when number of CHs is 5% of total nodes (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks"). However, maintaining maximum 5% of total nodes as CHs during each round, along with the constraint that each node becomes CH exactly once within every $\frac{1}{p}$ rounds, is a challenging task as sensor nodes require simple algorithm and smaller footprint.
- LEACH uses a stochastic approach to elect the CHs, and hence it is possible that during a particular round more than one CHs sit nearby. This results in non-optimal energy conservation.

3.1 Energy Models

Network lifetime is affected by the energy model being used for the experimentation. Two types of energy models are available for WSN (Banerjee, Mitra, and Naskar): i) First order radio energy model and ii) Realistic radio model.

3.1.1 First order radio energy model

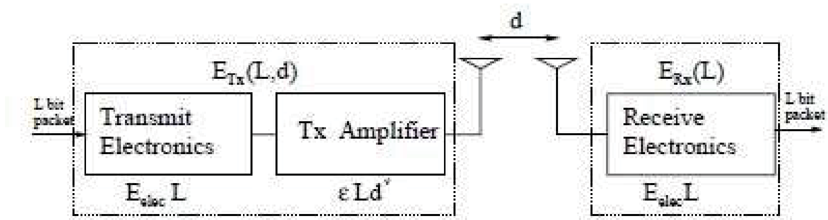


Figure 3.1: First Order Radio Energy Dissipation Model (Smaragdakis, Matta, and Bestavros)

Network lifetime is affected by the energy model being used for the simulation purpose. The energy model discussed in this section is widely accepted to study network lifetime. This energy model is referred as first order radio energy model. This model is used in this thesis to simulate protocols using MATLAB and it is as follows:

First order radio energy model is shown in Figure 3.1. This figure is taken from (Smaragdakis, Matta, and Bestavros). As shown in the Figure 3.1, the energy expenditure of a radio to transmit an L-bit message over a distance d with an acceptable Signal-to-Noise Ratio (SNR) is given by Equation 3.1 (Smaragdakis, Matta, and Bestavros)

$$E_{Tx}(L,d) = \begin{cases} L * E_{elec} + L * \epsilon_{fs} * d^2 & if\ d < d_0 \\ L * E_{elec} + L * \epsilon_{mp} * d^4 & if\ d \geq d_0 \end{cases} \tag{3.1}$$

where E_{elec} is the energy dissipated per bit to run the transmitter or the receiver circuit, ϵ_{fs} and ϵ_{mp} depend on the transmitter amplifier models used for the experiments, and d is the distance between the communicating nodes. By equating two expressions, at $d = d_0$, $d_0 = \sqrt{\frac{\epsilon_{fs}}{\epsilon_{mp}}}$. To receive an L-bit message, the radio expends $E_{Rx} = L * E_{elec}$.

3.1.2 Realistic radio energy model

An energy consumption of a sensor node (with realistic radio energy model) is due to the following reasons:

- Energy required to run the node.
- Energy required to run the sensor mounted on the node.
- Energy required for communication, i.e a radio module of a node.

In such realistic node behavior, communication energy is very high compared to other two components. Hence, to enhance the network lifetime, radio module should be kept in the low power mode as and when possible by reducing idle listening time and proper duty-cycling.

Castalia is a simulator for Wireless Sensor Network that supports testing of distributed algorithms and/or protocols with a realistic wireless channel, radio models and node behavior (Boulis, "Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User's manual"). Castalia uses realistic radio energy model. In (Stetsko, Stehlik, and Matyas), authors have performed experiments to compare energy consumption of sensor nodes obtained with open-source simulators – Castalia, MiXim, TOSSIM and WSNet, and compared them with the real test bed experiment for the MICAz motes. The results show that the energy consumption of a sensor node obtained with Castalia simulator is closest to real measurement compared to other three.

In this research work, during the simulations, nodes are equipped with CC2420 transceivers to test the protocols using Castalia simulator. Each node constantly draws $6mW$ and sensing device within the node draws $0.02mW$.

A transceiver of a node can be in one of the three states: RX (receive), TX (transmit) or $SLEEP$. Transceiver takes the 194μsec to change from $SLEEP$ state to either RX or TX, 10μsec to change between TX and RX states and 50μsec to enter the $SLEEP$ state (Boulis, "Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User's manual" Instruments). Transition to $SLEEP$ state from RX or TX consumes $1.4mW$ while any other transition consumes

$62mW$ (Boulis, "Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User's manual" Instruments).

3.2 LEACH improvements based on random numbers

In this section, protocols are proposed to improve LEACH algorithm either by modifying random numbers or generating random numbers other than uniform random number generation scheme. These random numbers are compared with the threshold $T(n)$, given by Equation 2.1, to decide that a node can work as a CH or not for the current round.

3.2.1 Improved LEACH based on the Gaussian distribution of random numbers

In (Hasbullah et al.), the authors have mitigated energy holes around the sink by deploying nodes in Gaussian fashion. In this section, the LEACH protocol is extended to see effects of random numbers on the CH election scheme. These random numbers are generated using the Gaussian distribution function. The protocol works as follows:

At the beginning of each round, a node selects a random number between 0 and 1. Unlike LEACH, this random number is generated using Gaussian distribution. The random number must be between 0 and 1; otherwise a new random number is selected by the node. This process is repeated by the node until it finds a random number between 0 and 1. After generation of random number, it is compared with the threshold $T(n)$, given by Equation 2.1. A node elects itself as a CH, if the random number is less than $T(n)$, otherwise it works as a member node (non-CH node) for the current round. CH nodes inform their status to other nodes within the network. Non-CH node selects one of the CH nodes for which minimum communication energy is required, and sends a join message to the selected CH. After receiving join messages from the non-CH nodes, CH nodes prepare TDMA schedule and inform to the member nodes of their own cluster.

3.2.1.1 Simulation Strategy, Performance Parameters and Result Discussion

Simulations are carried out in MATLAB, and code for the LEACH protocol is obtained from csr.bu.edu (Smaragdakis, Matta, and Bestavros). First order radio energy model (see page 28) is used for the simulation (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks"). Total 18 simulation runs were executed, including 9 simulation runs for the LEACH protocol (initial energy/node $*$ number of nodes = 3 *3) and 9 simulation runs for the proposed approach (initial energy/node $*$ number of nodes = 3 *3). This helps to verify the robustness of the proposed approach. Simulation parameters are shown in Table 3.1.

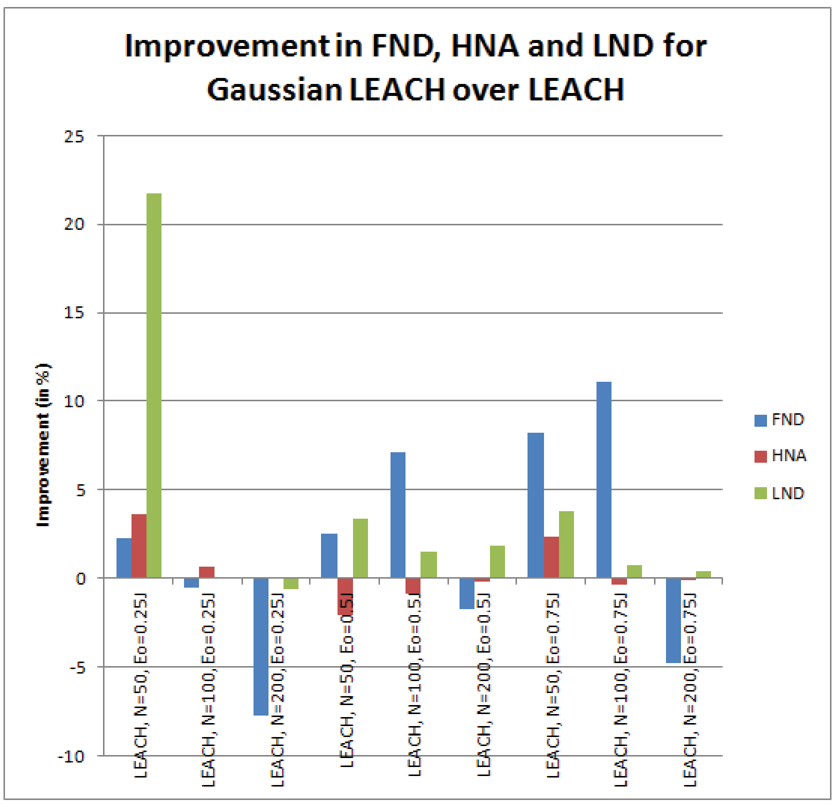


Figure 3.2: Improvement in FND, HNA and LND for the Gaussian LEACH protocol

The improvement in the network lifetime is measured using the following performance parameters: i) First Node Dies (FND), Half of the Nodes Alive (HNA) (or Half of the Nodes Die (HND)) and Last Node Dies (LND). Here, LND refers to the time when 90% of the total nodes die, as the network is not useful after the death

Parameter Name	**Value**
Node Deployment Area	100m X 100m
Number of Nodes (Excluding BS)	1) 50 2) 100 3) 200
Relative Position of BS	(50,50)
Initial Energy/Node (in Joules)	1) 0.25 2) 0.50 3) 0.75
Simulation Stopping Criteria	5000 Rounds
Transmitter Electronics ($E_{Tx-elec}$) Receiver Electronics ($E_{Rx-elec}$) ($E_{Tx-elec} = E_{Rx-elec} = E_{elec}$)	50 nJ/bit
Energy for Data Aggregation (EDA)	5 nJ/bit/message
Free Space (ϵ_{fs})	10 pJ/bit/m^2
Multi-path Fading (ϵ_{mp})	0.0013 pJ/bit/m^4
Packet Size	4000 bits
Percentage of Cluster Heads	5% [1]
Proposed Approach Compared with	LEACH [1]

[1] (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks")

Table 3.1: Parameters used for the simulation of the Gaussian LEACH protocol

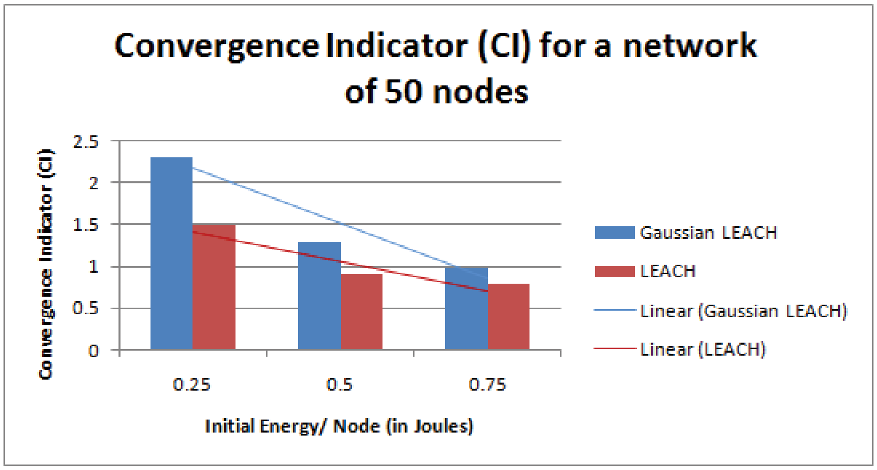


Figure 3.3: Convergence Indicator (CI) for a network of 50 nodes for the Gaussian LEACH protocol

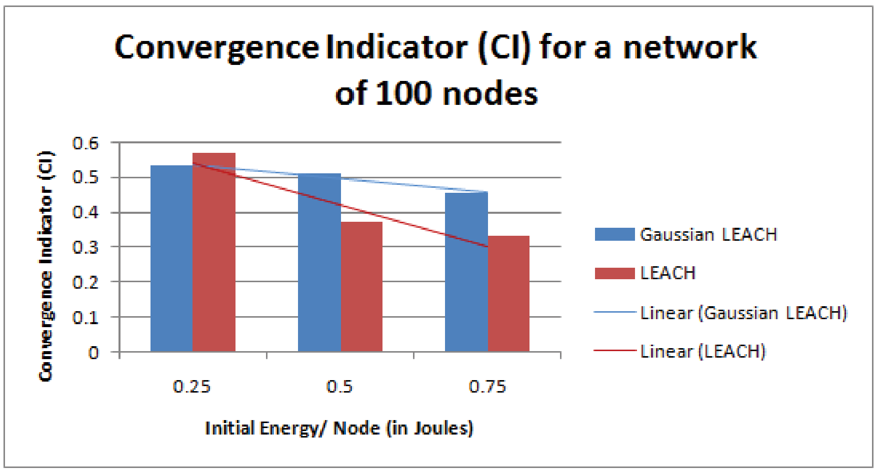


Figure 3.4: Convergence Indicator (CI) for a network of 100 nodes for the Gaussian LEACH protocol

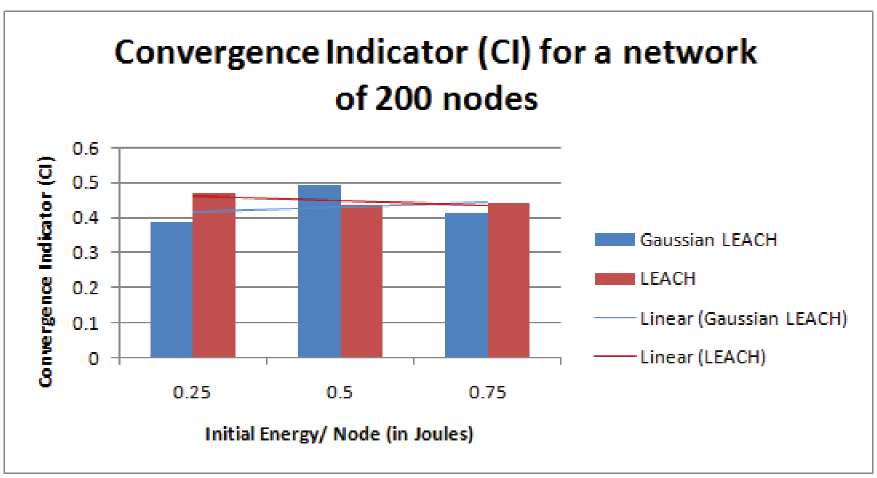


Figure 3.5: Convergence Indicator (CI) for a network of 200 nodes for the Gaussian LEACH protocol

of 90% nodes (Qiu et al.). It can be seen from the Figure 3.2 that improvement in FND, HNA and LND varies between -7.77% and 11.13%, -2.08 % and 3.64% and -0.59% and 21.7% respectively. ii) Convergence Indicator (CI) is given by Equation 3.2 (Qiu et al.), where FND, HND and LND refer to the time when First Node Dies, Half of the Nodes Die and 90% of the total node die. It is used to measure network convergence. As the value of CI increases, energy consumption of the network is considered to be balanced. It can be seen from the Figures 3.3-3.5 that Gaussian LEACH is preferable over the LEACH protocol. It is also observed from the results that CI value decreases for the Gaussian LEACH with the increase in node density.

$$CI = \frac{\text{LND - HND}}{\text{HND - FND}} \tag{3.2}$$

iii) An average energy reduction per round for the Gaussian LEACH over LEACH protocol is shown in the Figure 3.6. It can be seen from the figure that energy reduction per round varies between -0.55% and 21.8%. It can also be concluded from the figure that Gaussian LEACH is preferred one over LEACH protocol.

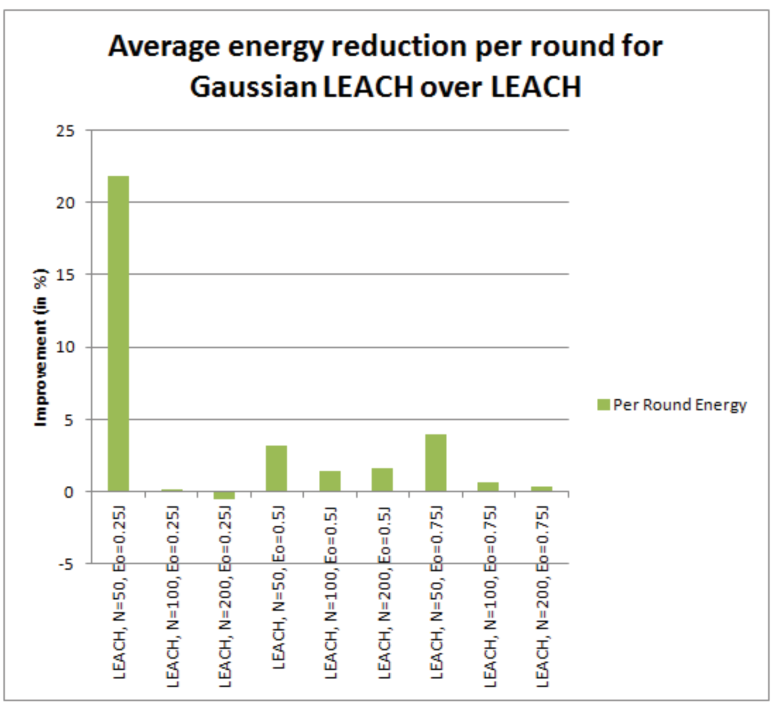


Figure 3.6: Improvement in the average energy reduction per round for the Gaussian LEACH protocol

3.2.2 AL-LEACH: Alive Nodes based improved Low Energy Adaptive Clustering Hierarchy for Wireless Sensor Network

To enhance the network lifetime, the authors in (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks" Manzoor et al. Handy, Haase, and Timmermann Ali, Dey, and Biswas Randriatsiferana et al. Xu et al. Abdellah et al.), have optimized threshold equation $T(n)$ by considering different parameters that affect network lifetime. During cluster setup phase, a node selects a random number between 0 and 1 and compares it with $T(n)$. A node elects itself as CH, if the selected random number is less than $T(n)$; otherwise it works as member node for the current round. These algorithms also ensure that each node elects as a CH exactly once within every $\frac{1}{p}$ rounds.

The approach, described above, works well when dead nodes are very less or zero. However, as the dead nodes increase in the network, the CH election probability for the nodes decreases, because these protocols use fixed span for random numbers. This can be improved by assigning weight (importance factor) to the random numbers. Thus, in this section, a new method is proposed to calculate weighted random numbers that are compared with $T(n)$ to elect CHs, where $T(n)$ is given by Equation 2.1

3.2.2.1 Proposed Approach

The proposed approach is derived from the LEACH protocol. Like LEACH, the proposed approach also runs in rounds. During Cluster Setup Phase, each node assumes a random number, *rnd*, between 0 and 1, and it is weighted as per the Equation 3.3; where N is the total nodes deployed in the network and *Dead* is the number of dead nodes during a particular round. A node becomes CH, if RND is less than $T(n)$, where $T(n)$ is given by Equation 2.1.

$$RND = rnd * \frac{(N - Dead)}{N} \tag{3.3}$$

Equation 3.3 reduces the span of RND as the dead nodes increase in the network. This helps to increase the probability of alive nodes to become CH. This protocol works similar to the LEACH till the death of the first node.

3.2.2.2 Simulation Environment

Simulations are carried out in MATLAB and the code for LEACH protocol is obtained from csr.bu.edu (Smaragdakis, Matta, and Bestavros). The parameters used for simulations are shown in Table 3.2. First order radio energy model is used for the simulation (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks"). To verify robustness of the proposed approach, total 36 simulation runs were executed, including four protocols, three different energy levels and three node densities.

3.2.2.3 Performance Metrics

- **Network Lifetime:** Network lifetime is measured using three metrics: First Node Dies (FND), Half of the Nodes Alive (HNA) (or Half of the Nodes Die (HND)) and Last Node Dies (LND). LND refers to the time when 90% of the total nodes die (Qiu et al.).

- **Number of Packets:** It indicates the number of packets received by BS from the network. More number of packets received indicates less die rate of nodes as well as less expense of energy (Wang, Yang, and Sun).

- **Convergence Indicator (CI):** It is given by Equation 3.2 (Qiu et al.). It is used to measure network convergence. As the value of CI increases, energy consumption of the network is considered to be balanced.

Simulation results are given in Table 3.3. AL-LEACH attains the highest value of FND, HNA and LND for 11.11%, 16.66% and 100% times respectively. It can be seen from the results that for CI metric, AL-LEACH is preferable as the node density increases. The same is evident through Figures 3.7-3.9. It can also be concluded from these figures that CI value decreases with an increase in the initial energy. However, the CI value may increase or decrease with the increase in the node density with the given initial energy. Also, it can be concluded from the results that more number of packets are received by BS for the proposed approach compared to LEACH, LDCHS and ALEACH.

Parameter Name	**Value**
Node Deployment Area	100m X 100m
Number of Nodes (Excluding BS)	1) 50 2) 100 3) 200
Relative Position of BS	(50,50)
Initial Energy/Node (in Joules)	1) 0.25 2) 0.50 3) 0.75
Simulation Stopping Criteria	5000 Rounds
Transmitter Electronics ($E_{Tx-elec}$) Receiver Electronics ($E_{Rx-elec}$) ($E_{Tx-elec} = E_{Rx-elec} = E_{elec}$)	50 nJ/bit
Energy for Data Aggregation (EDA)	5 nJ/bit/message
Free Space (ϵ_{fs})	10 pJ/bit/m^2
Multi-path Fading (ϵ_{mp})	0.0013 pJ/bit/m^4
Packet Size	4000 bits
Percentage of Cluster Heads	5% [1]
Proposed Approach Compared with	1) LEACH [1] 2) LDCHS[2] 3) ALEACH[3]

[1] (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks")
[2] (Handy, Haase, and Timmermann)
[3] (Ali, Dey, and Biswas)

Table 3.2: Parameters used for the simulation of the AL-LEACH protocol

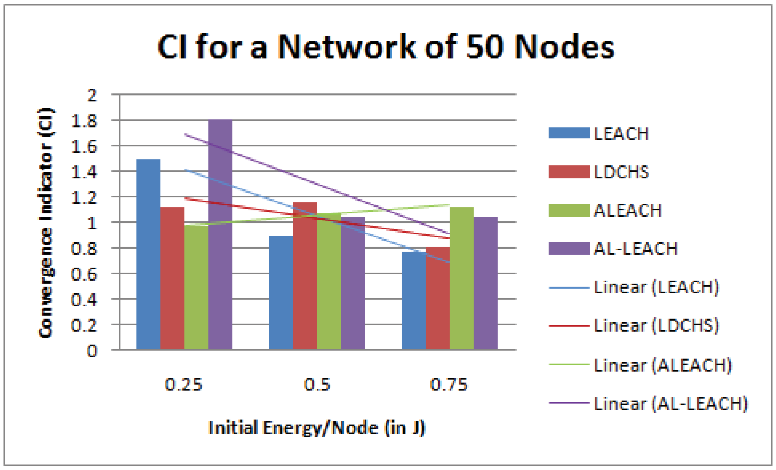


Figure 3.7: Convergence Indicator (CI) for a network of 50 nodes for the AL-LEACH protocol

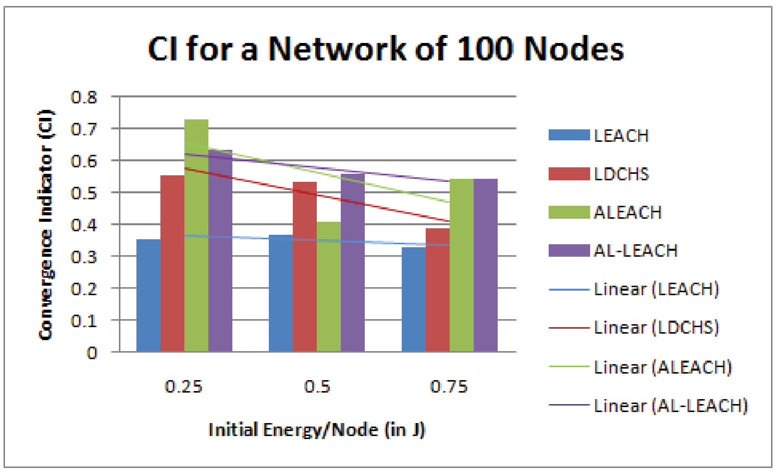


Figure 3.8: Convergence Indicator (CI) for a network of 100 nodes for the AL-LEACH protocol

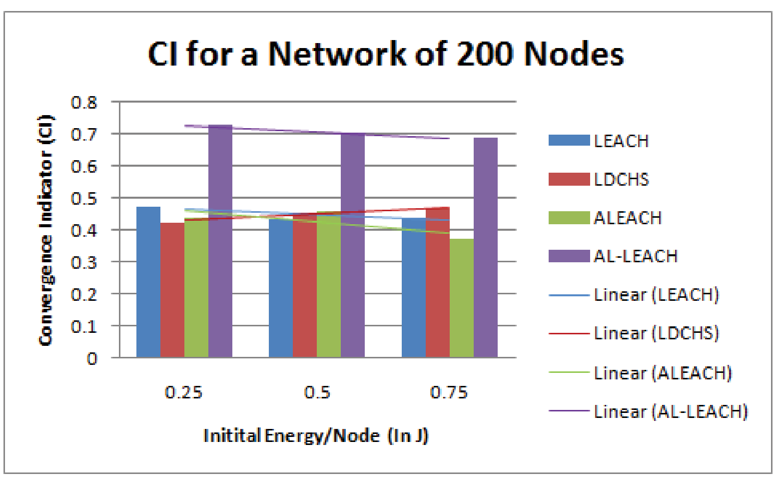


Figure 3.9: Convergence Indicator (CI) for a network of 200 nodes for the AL-LEACH protocol

Total Nodes	**Energy** (J/Node)	**Protocol**	**FND** (rounds)	**HNA** (rounds)	**LND** (rounds)	**CI**	**Packets Received by BS**
50	0.25	LEACH	434	604	858	1.494	1643
		LDCHS	434	619	828	1.1297	1617
		ALEACH	**453**	**651**	844	0.975	1707
		AL-LEACH	434	621	**961**	**1.818**	**1865**
	0.5	LEACH	881	1252	1584	0.895	3373
		LDCHS	862	1208	1609	**1.159**	3253
		ALEACH	**939**	**1264**	1614	1.077	3359
		AL-LEACH	881	1251	**1641**	1.054	**3538**
	0.75	LEACH	1321	1848	2258	0.778	4878
		LDCHS	1306	1826	2247	0.810	4878
		ALEACH	**1436**	1890	2402	**1.128**	4986
		AL-LEACH	1321	**1889**	**2483**	1.046	**5092**
	0.25	LEACH	397	580	645	0.355	2931
		LDCHS	394	589	697	0.554	2950
		ALEACH	**419**	585	706	**0.729**	2998
		AL-LEACH	397	**596**	**722**	0.633	**3259**
		LEACH	744	1187	1351	0.370	5806

Table 3.3: (Continued) Performance metrics for the AL-LEACH protocol

Total Nodes	**Energy** (J/Node)	**Protocol**	**FND** (rounds)	**HNA** (rounds)	**LND** (rounds)	**CI**	**Packets Received by BS**
100	0.5	LDCHS	782	1168	1375	0.536	5879
		ALEACH	**849**	**1190**	1330	0.411	5908
		AL-LEACH	744	1181	**1425**	**0.558**	**6136**
	0.75	LEACH	1114	1760	1972	0.328	8749
		LDCHS	1145	1758	1997	0.390	8789
		ALEACH	**1297**	**1772**	2031	**0.545**	8884
		AL-LEACH	1114	1767	**2123**	**0.545**	**9291**
200	0.25	LEACH	399	591	682	0.474	5989
		LDCHS	**409**	**592**	670	0.426	5948
		ALEACH	374	589	684	0.442	5924
		AL-LEACH	399	587	**724**	**0.729**	**6399**
	0.5	LEACH	**799**	1171	1332	0.433	11963
		LDCHS	773	1173	1355	0.455	11901
		ALEACH	778	1167	1346	0.460	11866
		AL-LEACH	**799**	**1177**	**1444**	**0.706**	**13001**
	0.75	LEACH	**1215**	1754	1990	0.438	17757
		LDCHS	1212	1754	2008	0.469	17883

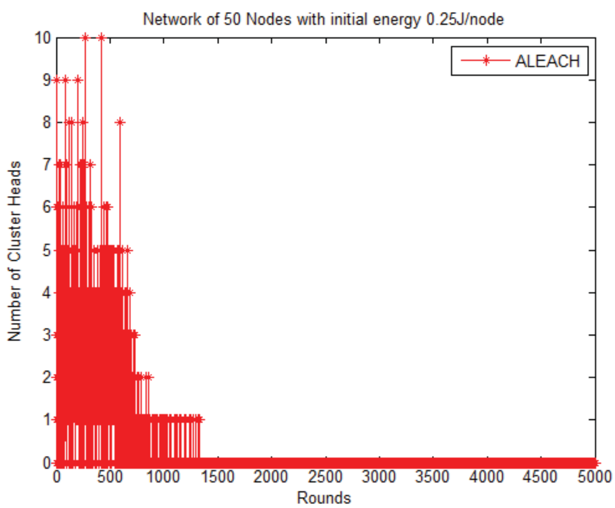
Table 3.3: (Continued) Performance metrics for the AL-LEACH protocol

Total Nodes	**Energy** (J/Node)	**Protocol**	**FND** (rounds)	**HNA** (rounds)	**LND** (rounds)	**CI**	**Packets Received by BS**
		ALEACH	1124	**1767**	2009	0.376	17667
		AL-LEACH	**1215**	1766	**2145**	**0.688**	**19117**

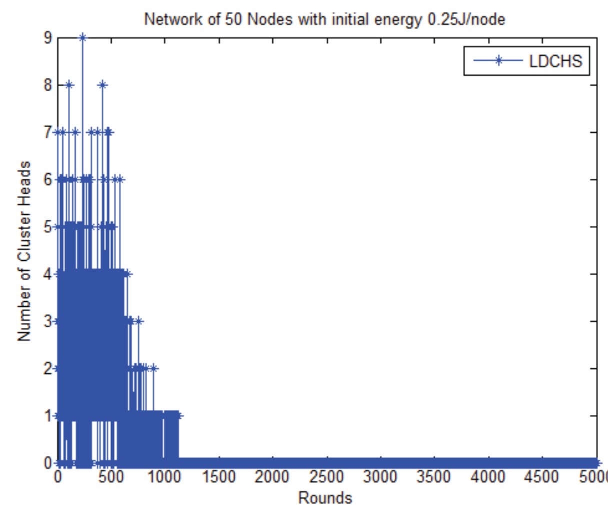
Table 3.3: Performance metrics for the AL-LEACH protocol

3.3 S-LEACH: A Sequential selection approach to elect cluster heads for LEACH protocol

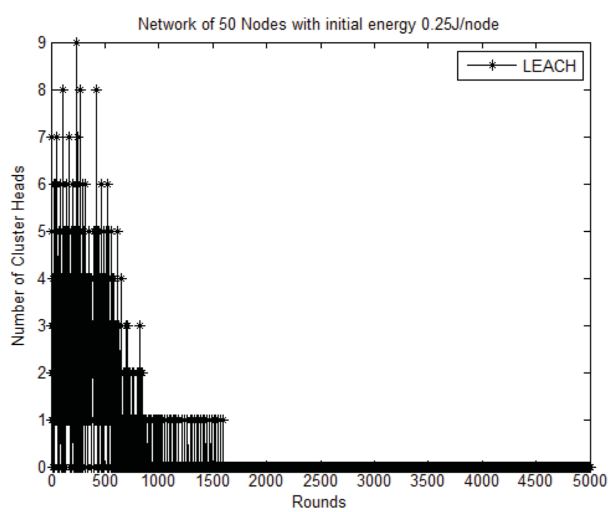
LEACH gives optimal performance when the number of cluster heads are 5% of the total nodes deployed in the network (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks"). However, LEACH and its descendants are unable to maintain the desired number of cluster heads during each round because of the stochastic nature of these algorithms (see Figures 3.10a-3.10c). In this section, a decentralized clustering scheme based on sequential selection (S-LEACH) is proposed to maintain the desired number of cluster heads during each round until the death of the first node. Also, upper bound on the number of CHs during each round of this protocol is given by the desired percentage of CH. LEACH assumes that each node is aware about its node id (see page 26) and the proposed approach takes the benefit of this assumption. During the cluster head election phase, a node elects itself as a CH, if it's node identifier (id) is within the set of node identifiers that should be a cluster head during a particular round; otherwise it works as a member node (non-CH node) for the current round. For example, if total nodes are 100 and the desired percentage of cluster heads is set to 5% of the total nodes, then first five nodes are elected as CHs during first round, nodes with the ids 6 to 10 would be elected as the cluster heads during second round; and so on.



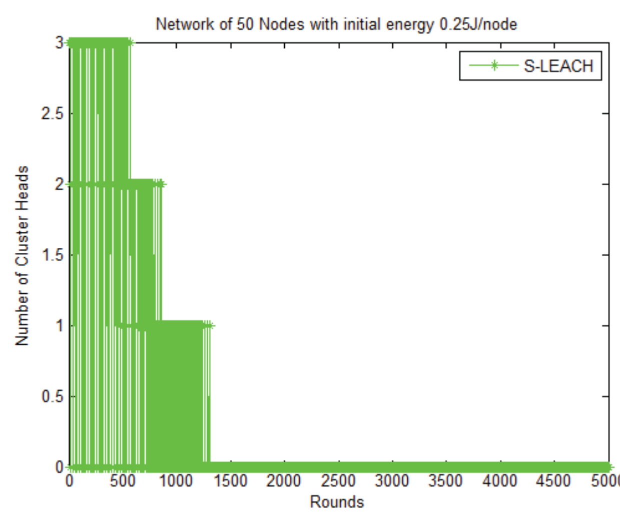
(a) Cluster Heads for ALEACH protocol



(b) Cluster Heads for LDCHS protocol



(c) Cluster Heads for LEACH protocol



(d) Cluster Heads for SLEACH protocol

Figure 3.10: Variation in number of CHs for a network of 50 nodes with initial energy 0.25J/Node

This process continues until all nodes become cluster heads i.e. $\frac{1}{p}$ rounds. When all the nodes become cluster heads, the process repeats with nodes with ids 1 to 5 as the CHs. This process ensures that each node becomes a cluster head exactly once during $\frac{1}{p}$ rounds, where p is the desired percentage of cluster heads. The proposed approach also ensures that a desired percentage of cluster heads should be maintained until the death of first node. Once nodes are aware that they are elected as CHs during a particular round, they inform their status to the non-CH nodes within the network. Non-CH node associates with the one of the CHs for which minimum communication energy is required; and sends a join message to the selected CH. After receiving join messages from the non-CH nodes, CHs prepare TDMA schedule and inform to the member nodes of their own cluster. Steady state phase is same as the LEACH protocol.

Simulation parameters are same as the AL-LEACH protocol (Table 3.2) and performance metrics are same as mentioned in the section 3.2.2.3. The death of the nodes is measured using FND, HNA and LND. Here, LND refers to the time when 90% of the total nodes die (Qiu et al.). The results are shown in Table 3.4. S-LEACH attains the highest value of FND, HNA and LND for 0%, 44.44% and 100% times respectively. Comparison of the CI values is shown in the Figures 3.11-3.13 for 50, 100 and 200 nodes respectively. It can be concluded from the figures that the proposed approach is preferred one compared to the prevalent ones. The trend line in the figures shows that CI value for S-LEACH protocol either increases or remains same with the increase in the initial energy of the nodes. The trend line also shows that CI value decreases with an increase in the node density with the given initial energy. S-LEACH receives 66.67% times highest and 33.33% times second highest number of packets compared to prevalent ones.

Total Nodes	**Energy** (J/Node)	**Protocol**	**FND** (rounds)	**HNA** (rounds)	**LND** (rounds)	**CI**	**Packets Received by BS**
		LEACH	434	604	858	**1.494**	1643

Table 3.4: (Continued) Performance metrics for the S-LEACH protocol

Total Nodes	**Energy** (J/Node)	**Protocol**	**FND** (rounds)	**HNA** (rounds)	**LND** (rounds)	**CI**	**Packets Received by BS**
50	0.25	LDCHS	434	619	828	1.1297	1617
		ALEACH	**453**	651	844	0.975	1707
		S-LEACH	423	**694**	**863**	0.62	**1742**
	0.5	LEACH	881	1252	1584	0.895	3373
		LDCHS	862	1208	1609	**1.159**	3253
		ALEACH	**939**	1264	1614	1.077	3359
		S-LEACH	845	**1388**	**1802**	0.76	**3490**
	0.75	LEACH	1321	1848	2258	0.778	4878
		LDCHS	1306	1826	2247	0.810	4878
		ALEACH	**1436**	1890	2402	**1.128**	4986
		S-LEACH	1267	**2085**	**2723**	0.78	**5236**
100	0.25	LEACH	397	580	645	0.355	2931
		LDCHS	394	**589**	697	0.554	2950
		ALEACH	**419**	585	706	**0.729**	2998
		S-LEACH	273	569	**720**	0.51	**3041**
	0.5	LEACH	744	1187	1351	0.370	5806
		LDCHS	782	1168	1375	0.536	5879

Table 3.4: (Continued) Performance metrics for the S-LEACH protocol

Total Nodes	**Energy** (J/Node)	**Protocol**	**FND** (rounds)	**HNA** (rounds)	**LND** (rounds)	**CI**	**Packets Received by BS**
		ALEACH	**849**	**1190**	1330	0.411	5908
		S-LEACH	546	967	**1434**	**1.11**	**5958**
	0.75	LEACH	1114	1760	1972	0.328	8749
		LDCHS	1145	1758	1997	0.390	8789
		ALEACH	**1297**	**1772**	2031	**0.545**	**8884**
		S-LEACH	821	1704	**2166**	0.52	8818
200	0.25	LEACH	399	591	682	**0.474**	5989
		LDCHS	**409**	**592**	670	0.426	5948
		ALEACH	374	589	684	0.442	5924
		S-LEACH	181	591	**768**	0.43	**6002**
	0.5	LEACH	**799**	1171	1332	0.433	**11963**
		LDCHS	773	1173	1355	0.455	11901
		ALEACH	778	1167	1346	**0.46**	11866
		S-LEACH	381	**1182**	**1532**	0.44	11954
	0.75	LEACH	**1215**	1754	1990	0.438	17757
		LDCHS	1212	1754	2008	**0.469**	**17883**
		ALEACH	1124	**1767**	2009	0.376	17667

Table 3.4: (Continued) Performance metrics for the S-LEACH protocol

Total Nodes	Energy (J/Node)	Protocol	FND (rounds)	HNA (rounds)	LND (rounds)	CI	Packets Received by BS
		S-LEACH	561	1765	**2284**	0.43	17881

Table 3.4: Performance metrics for the S-LEACH protocol

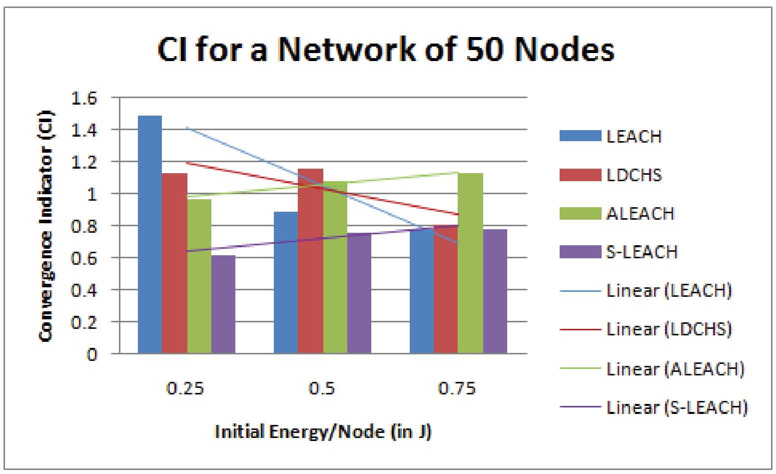


Figure 3.11: Convergence Indicator (CI) for a network of 50 nodes for the S-LEACH protocol

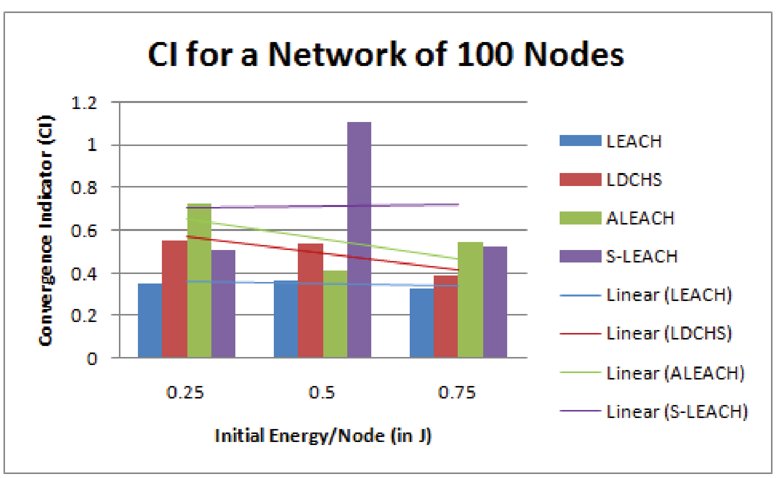


Figure 3.12: Convergence Indicator (CI) for a network of 100 nodes for the S-LEACH protocol

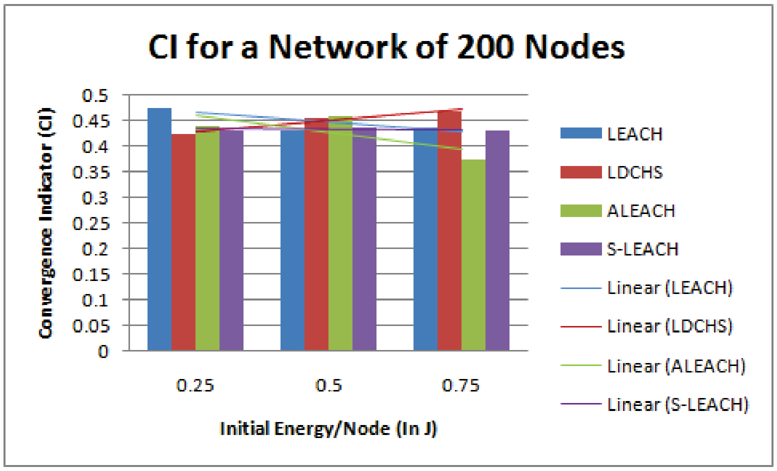


Figure 3.13: Convergence Indicator (CI) for a network of 200 nodes for the S-LEACH protocol

3.4 CVLEACH: Coverage based energy efficient LEACH algorithm

LEACH uses a stochastic approach to elect cluster heads, and thus it is possible that during a particular round, more than one cluster heads may sit nearby. This makes non-uniform distribution of cluster heads, where the LEACH protocol assumes uniform distribution of cluster heads (Kim and Youn). Hence, more number of nodes are required to transmit directly to the BS. This results in more network energy expense per round as shown below:

The energy consumption of a node to communicate with cluster head and the BS is E_{CH} and E_{BS} respectively, where $E_{CH} <<< E_{BS}$. Assume that there can be C nodes, which can be elected as cluster heads during each round. Also, each node can be elected as the cluster head only once in $\frac{1}{p}$ rounds, where p is desired percentage of cluster heads. For the LEACH algorithm, energy consumption per round E_{round} is given by Equation 3.4, where M and N refer to the total member nodes during the round and total alive nodes during the round respectively.

$$E_{round} = M * E_{CH} + (N - M) * E_{BS} \tag{3.4}$$

It is possible that more than one node, which are near to each other, may elect themselves as CHs using the stochastic approach. In this case, the total number of nodes covered by the cluster heads is reduced. Hence, from Equation 3.4, E_{round} increases. The Coverage LEACH (CVLEACH) algorithm is proposed that minimizes overlapping of the area covered by the cluster heads.

From Equation 3.4, it can be seen that as more number of member nodes are covered with the desired number of cluster heads, C, the overall energy consumption during a round decreases. This can be achieved by creating non-overlapping cluster regions using over hearing property of sensor nodes as they communicate using broadcast communication.

CVLEACH is the coverage based LEACH algorithm, that increases the number of member nodes of a cluster by creating non-overlapping clusters. CVLEACH also works in round, which is fixed amount of time during which the selected node can act as cluster head and serves to other nodes in the cluster. Like LEACH, at the beginning of each round, each node selects a random number between 0 and 1 and calculates the threshold value $T(n)$, given by Equation 2.1. If the selected random number is less than the threshold value $T(n)$, the node elects itself as a cluster head. However, the node announces itself as cluster head for the current round, if it has not received a cluster head announcement from the neighboring nodes. Also, if the node receives cluster head advertisement from other cluster heads before it announces itself as a CH, the node withdraws itself as a cluster head during that round and decides to join as a member. A node will join to one of the clusters, from which it has received cluster head announcement. A node will send join message to one of the clusters for which minimum energy is required for communication with the cluster head. This algorithm also ensures that a node can become a cluster head only once in $\frac{1}{p}$ rounds.

CVLEACH divides rounds into Cluster Setup Phase and Steady State Phase. Cluster setup phase is used to elect cluster heads and its algorithm is shown in Algorithm 3.1. Steady state phase is used by member nodes to send data to their cluster heads and its algorithm is shown in Algorithm 3.2.

3.4.1 Simulation Parameters and Results Discussion

The performance of CVLEACH is investigated against ALEACH and LEACH algorithm using the Castalia simulator (Boulis, “Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User’s manual”). Castalia uses the

Algorithm 3.1 Cluster Setup Phase of the proposed CVLEACH protocol

Require: $Total\_Round\_Time > 0$ and $Round\_Duration > 0$ and $Total\_Round\_Time \geq Round\_Duration$ and $N > 0$ and $0 \leq P < 1$

```
for all i ∈ N do
    ClusterHeadInLastRound = false
end for
rounds = ⌈(SimulationTime/RoundTime)⌉
for r = 0 to rounds − 1 do
    CHAdvReceived = false
    for all i ∈ N do
        if ClusterHeadInLastRound or CHAdvReceived then
            T(i) = 0
            Wait_For_TDMA_Schedule(t)
            if CHAdvReceived then
                Send_Join_Request(i)
            end if
        else
            if T(i) > random(0, 1) then
                ClusterHeadInLastRound = true
                Do_Cluster_Head_Announcement(i)
                Wait_For_Join_Request(t)
                for all j ∈ Members do
                    Send_TDMA_Schedule(j)
                end for
            else
                if CHAdvReceived then
                    Send_Join_Request(i)
                end if
                Wait_For_TDMA_Schedule(t)
            end if
        end if
        CallAlgorithm3.2(i)
    end for
    if (round + 1) = ⌈N/(P ∗ 100)⌉ then
        ClusterHeadInLastRound = false
    end if
end for
```

Algorithm 3.2 Steady State Phase of the proposed CVLEACH protocol

```
Require: i
if t < RoundTime then
    if i ∈ CH then
        for all j ∈ Members(i) do
            Collect_Data_From_Member_Nodes(j)
        end for
        Send_Aggregate_Data_To_Sink_By_CH(i)
    else
        if t < Scheduled_Start_Time or t > Scheduled_End_Time then
            Sleep_Node(i)
        else
            Send_Data_To_CH_By_Member(i)
        end if
    end if
end if
```

realistic radio energy model (see page 29). Simulation parameters are shown in the Table 3.5.

The network lifetime is measured using First Node Dies (FND), Half of the Nodes Alive (HNA) and the Last Node Dies (LND). Here, LND refers to the time when the last node of the network dies (Zheng and Jamalipour). The minimum and maximum percentage of improvement in FND, HNA and LND is shown in the Figures 3.14-3.16 respectively. It can be concluded from these figures that CVLEACH improves network lifetime compared to LEACH and ALEACH protocols. The maximum percentage of improvement in FND, HNA and LND are 0.38%, 15.96% and 16.87% respectively. The average energy reduction per node is shown in the Figure 3.17. An average energy reduction per node is improved between −0.59% to 6.76% for varying node density. The percentage of improvement in average node lifetime is shown in the Figure 3.18. An average node lifetime is improved between 3.35% to 11.41% for varying node density.

3.5 WALEACH: Weight based Advanced LEACH protocol

ALEACH (Ali, Dey, and Biswas) improves LEACH (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks") protocol by improving threshold equation $T(n)$, given by Equation 2.5. In

Parameter Name	**Value**
Node Deployment Area	100m X 100m
Number of Nodes	1) 100 2) 200 3) 300 4) 400 5) 500
Initial Energy/Node	1) 10 Joules 2) 18720 Joules
Simulation Time	1500 seconds
Transceiver	CC2420
Tx Power	0dBm
Baseline Node Power	6mW
Packet Size	30 Bytes
percentage of CH	5% [1]
Algorithms	1) ALEACH [2] 2) CVLEACH 3) LEACH [1]
Sink Node Id	Node 0
Sink Location	1) Center of the deployment area 2) At location (0,0)
Node Deployment	1) [1..$totalNodes - 1$]->uniform [3] 2) [1..$totalNodes - 1$]->10x10 [3,4] 3) [1..$totalNodes - 1$] ->randomized_10x10 [3,5]
Simulation Runs	Repeated 10 times for each configuration and mean value is recorded for the parameter of interest

[1] (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks")
[2] (Ali, Dey, and Biswas)
[3] (Boulis, "Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User's manual")
[4] This deployment pattern is shown as *Grid* in plotted results.
[5] This deployment pattern is shown as *RGrid* in plotted results.

Table 3.5: Parameters used for the simulation of the CVLEACH protocol

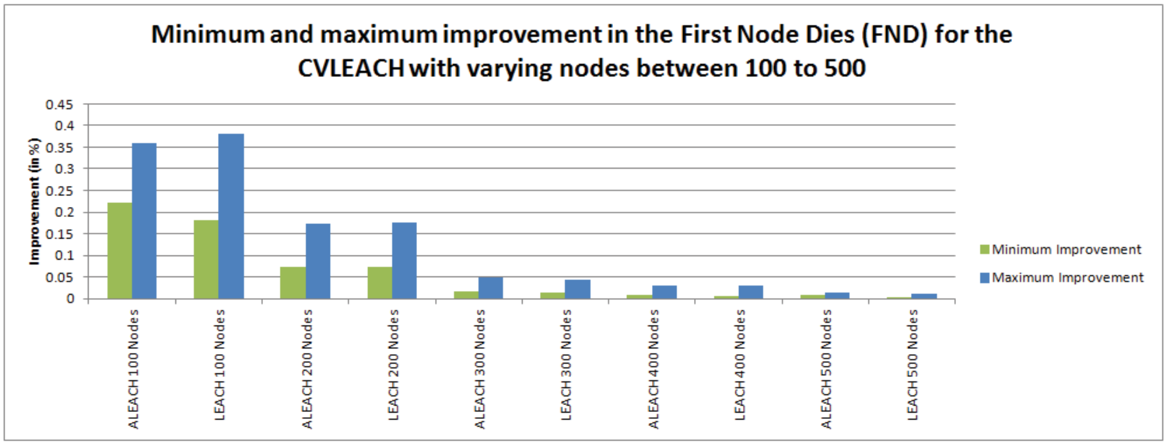


Figure 3.14: Minimum and maximum percentage of improvement in the First Node Dies (FND) for the CVLEACH protocol

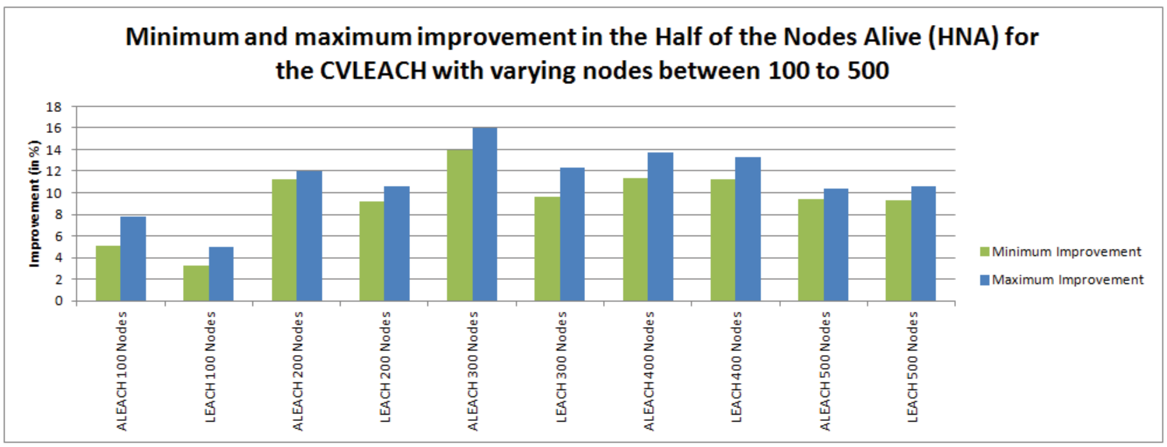


Figure 3.15: Minimum and maximum percentage of improvement in the Half of the Node Alive (HNA) for the CVLEACH protocol

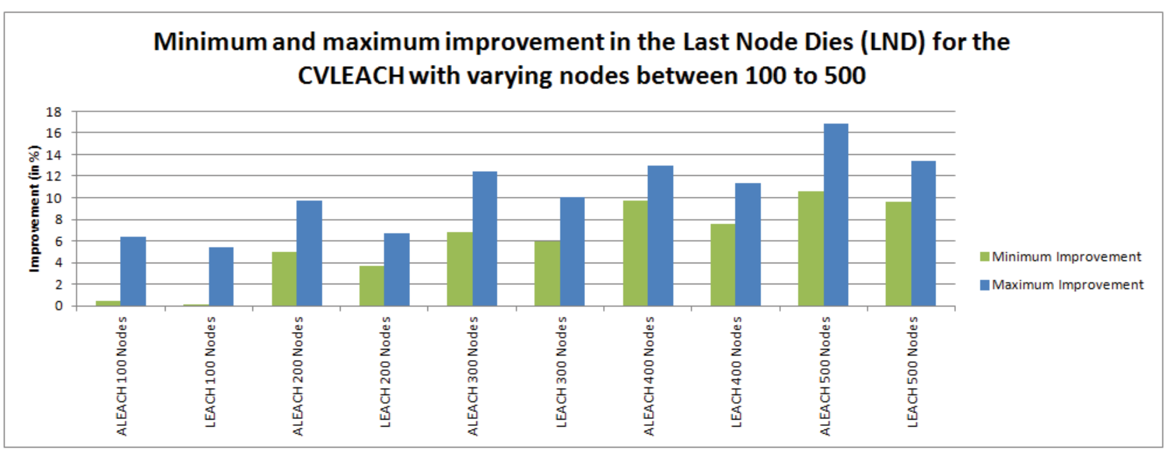


Figure 3.16: Minimum and maximum percentage of improvement in the Last Node Dies (LND) for the CVLEACH protocol

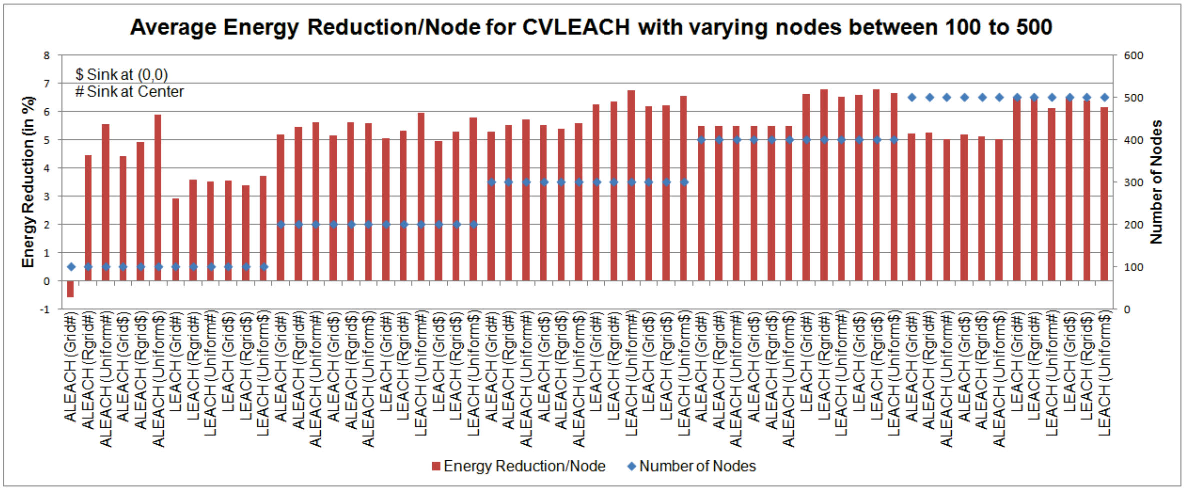


Figure 3.17: Average energy reduction per node for the CVLEACH protocol

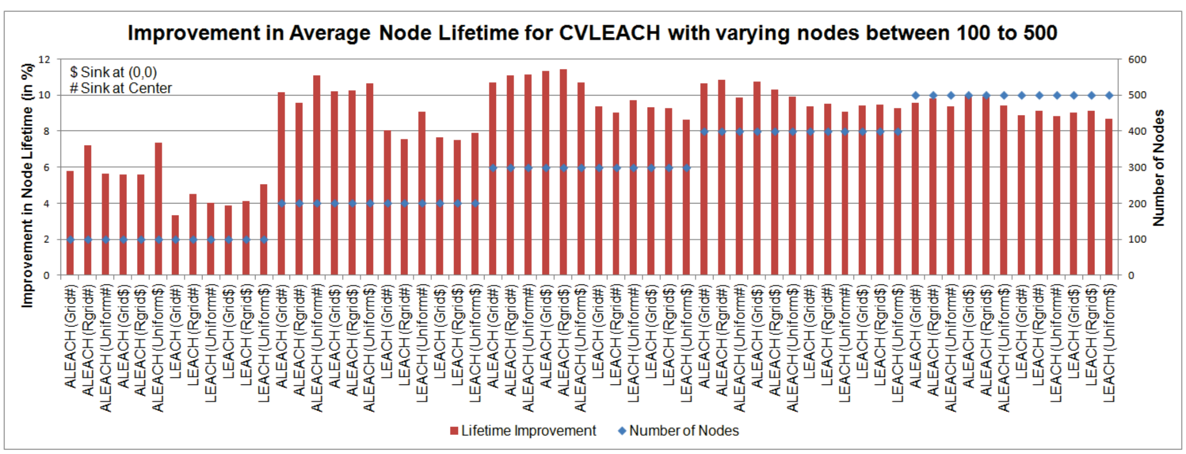


Figure 3.18: Average improvement in the node lifetime for the CVLEACH protocol

this section, an improved ALEACH protocol is proposed by assigning weights to the cluster head election parameters chosen by ALEACH protocol, as given by Equation 3.5, where G_p and CS_p are the general probability and current state probability which is given by Equation 3.6 and 3.7 respectively.

$$T(n) = G_p + CS_p \tag{3.5}$$

$$G_p = \frac{N - (w * k)}{N} * \frac{k}{N - k * (\text{r mod } \frac{N}{k})} \tag{3.6}$$

$$CS_p = \frac{w * k}{N} * \frac{E_{current}}{E_{max}} \tag{3.7}$$

In Equations 3.6 and 3.7, w is the weight factor for the CH election parameters chosen by ALEACH algorithm.

In (Ying-ying, Ji-ji, Cheng-lei, et al. Li-fang and Lim), the authors have proposed weight based cluster head election scheme by considering different parameters that affects the network lifetime. Also, weight value of different parameters, are to be determined by the system property and protocol requirements (Ying-ying, Ji-ji, Cheng-lei, et al. Li-fang and Lim). The value of w is determined empirically for the proposed scheme as 3.81.

The performance of the WALEACH is investigated against LEACH and ALEACH algorithms using Castalia simulator (Boulis, "Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User's manual"). A network of size 500m x 500m is created with randomly distributed 100 sensor nodes. Each node has CC2420 as the transceiver. Simulation parameters are shown in the Table 3.6.

The network lifetime is measured using FND, HNA and LND parameters, where LND refers to the time when Last Node Dies. To measure these parameters, 6 Joules of initial energy was given to each node. The results of FND, HNA and LND parameters is shown in the Table 3.7. The average lifetime of the node is also shown in the Table 3.7. The proposed approach improves the average lifetime of the nodes by 3.17% compared to the LEACH protocol and 2.19% compared to ALEACH protocol. To measure average energy consumption per node, the experiment is repeated by giving 18720 Joules of initial energy to each node. The proposed approach improves the average energy reduction per node by 0.33% compared to the LEACH algorithm

Parameter Name	**Value**
Node Deployment Area	500m X 500m
Number of Nodes	100
Initial Energy/Node	1) 6 Joules 2) 18720 Joules
Simulation Time	1000 seconds
Transceiver	CC2420
Tx Power	0dBm
Baseline Node Power	6mW
Packet Size	30 Bytes
percentage of CH	5% [1]
Algorithms	1) ALEACH [2] 2) LEACH [1]
Sink Node Id	Node 0
Sink Location	Center of the deployment area
Node Deployment	$[1..totalNodes - 1]$->uniform [3]
Weight factor (w)	3.81

[1] (Heinzelman, Chandrakasan, and Balakrishnan, “Energy-efficient communication protocol for wireless microsensor networks”)
[2] (Ali, Dey, and Biswas)
[3] (Boulis, “Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User’s manual”)

Table 3.6: Parameters used for the simulation of the WALEACH protocol

Algorithm	FND[1,2]	HNA[1,2]	LND[1,2]	Average Node Lifetime[1,2]	Average Consumed Energy/Node [3]
ALEACH	88.248	**89.076**	103.677	91.763	66.451
LEACH	88.243	88.855	103.710	90.891	66.579
WALEACH	**88.268**	88.999	**116.169**	**93.776**	**66.361**

[1] in Seconds
[2] with initial energy 6 Joules/Node
[3] with initial energy 18720 Joules/Node

Table 3.7: Performance metrics for the WALEACH protocol

and 0.13% compared to the ALEACH protocol.

The performance of the proposed approach, WALEACH, is also verified by other researchers in (Rahul and Richa) using the first order radio energy model (see page 28).

3.6 WCVALEACH: Weight and Coverage based energy efficient Advanced LEACH protocol

In this section, a hybrid approach is proposed using approaches discussed in the section 3.4 and 3.5 to see its effect on the network longevity. In this hybrid scheme, a node selects a random number between 0 and 1 and elects itself as a CH, if the generated random number is less than the threshold value given by Equation 3.5. This process is applicable to the set of nodes, if these nodes had not received any CH announcements from its neighboring node. This ensures non-overlapping cluster regions and selects the best node as a CH according to weigh factors assigned to the nodes. Simulation parameters are same as used for WALEACH (Table 3.6).

Simulations are carried out using Castalia that uses realistic radio energy model. The network lifetime is measured using FND, HNA and LND parameters, where LND refers to the time when Last Node Dies. To measure this performance metric, 6 Joules of initial energy was given to each node. The results of FND, HNA and LND parameters is shown in the Table 3.8. The average lifetime of the node is also shown in the Table 3.8. The proposed approach improves the average lifetime of the nodes by

Algorithm	FND[1,2]	HNA[1,2]	LND[1,2]	Average Node Lifetime[1,2]	Average Consumed Energy/Node [3]
ALEACH	88.248	89.076	103.677	91.763	66.451
LEACH	88.243	88.855	103.710	90.891	66.579
WALEACH	88.268	88.999	116.169	93.776	66.361
WCVALEACH	**88.273**	**90.509**	**127.242**	**95.542**	**66.243**

[1] in Seconds
[2] with initial energy 6 Joules/Node
[3] with initial energy 18720 Joules/Node

Table 3.8: Performance metrics for the WCVALEACH protocol

5.12% compared to the LEACH protocol, 4.12% compared to ALEACH protocol and 1.88% compared to WALEACH protocol. To measure average energy consumption per node, the experiment is repeated by giving 18720 Joules of initial energy to each node. The proposed approach improves the average energy reduction per node by 0.51% compared to the LEACH algorithm, 0.31% compared to the ALEACH protocol and 0.18% compared to the WALEACH protocol.

3.7 Summary

LEACH is one of the prominent cluster head election protocols. It inspires researchers to design new routing protocols using hierarchical clustering scheme as it provides energy efficiency through load balancing and reducing long distance communication. In this chapter, improvement areas for LEACH and few of its decedents are discussed. Also, solutions are proposed for the identified improvement areas and validated using extensive simulations. Two different types of energy models are also discussed as energy model affects the network lifetime. In the next chapter, cluster head election technique for energy and delay constraint applications of WSN will be discussed.

Chapter 4

Cluster Head Election for Energy and Delay Constraint Applications of Wireless Sensor Network

Designing of multi-hop Wireless Sensor Network (WSN) depends upon requirements of the underlying sensing application. The main objective of WSNs is to monitor the physical phenomenon of interest in a given Region of Interest using sensors and provide collected data to sink. WSN is made of a large number of energy, communication and computational constraint nodes, to overcome the energy constrain replacing or recharging the batteries of the WSN nodes is an impossible task, once they are deployed in hostile environments. Therefore, to keep the network alive as long as possible, communication between the WSN nodes must be done with load balancing. Time critical applications like forest fire detection, battle field monitoring demands reception of data by the sink with the bounded delay to avoid disasters. Hence, there is a need to design a protocol which enhances the network lifetime and provides the information to sink with a bounded delay. The chapter will address this problem and solution. In the chapter, a routing algorithm is proposed by introducing Energy Delay Index for Trade-off (*EDIT*) to optimize both objectives – energy and delay. *EDIT* is used to select Cluster Heads (CHs) and "next hop" by considering energy and/or delay requirements of a given application. The proposed approach is derived using two different aspects of distances between a node and the sink named Euclidean distance and Hop-count, and further proven using realistic parameters of radio to get data closest to the test bed implementation. The results aspires to give sufficient insights to others before doing test bed implementation.

4.1 Introduction

Recent development in sensor technology and wireless communication makes the sensor nodes inexpensive. Researchers across the globe are giving attention to these very attractive cost-effective applications like environmental monitoring, battle field monitoring, structural monitoring to name a few. A WSN network is made of a large number of sensor nodes, which are densely deployed in an area required to be monitored called Region of Interest (ROI). Sensor nodes collect data and forward it to sink or Base Station (BS) directly, or through multi-hop communication. But these sensor nodes have limited amount of memory, processing capacity, communication range, and above all limited amount of energy (power) because sensor nodes are battery powered. It is difficult to replace or recharge batteries of the sensor nodes when they operate in hostile environments. Hence, energy saving is an important issue for a WSN. Many techniques for energy savings are developed, which includes sleep scheduling, MAC protocols, routing protocols, data aggregation, topological control, etc. (Li, Bandai, and Watanabe)

This chapter focuses on the cluster formation process by considering energy-delay trade-off. Cluster formation is a part of hierarchical routing protocols. These protocols are energy efficient and provides scalability (Al-Karaki and Kamal). A survey on various routing techniques and protocols can be found in (Al-Karaki and Kamal Akyildiz et al. Akkaya and Younis). Each cluster consists of member nodes and a cluster head (CH). CH is responsible for collecting and aggregating data from the member nodes and sending it to other CH or BS.

A survey on different attributes of clustering of WSN is given in (Abbasi and Younis). As mentioned previously, energy is the most scarce resource of WSN. Hence, the objective of the CH election is to provide energy efficiency to enhance the lifetime of the WSN. Data aggregation is one of the ways which can provide energy efficiency (Li, Bandai, and Watanabe). Routing between the clusters can be direct or multi-hop. Direct transmission is very easy to use, and therefore, this technique is widely used in many applications (Shahraki, Rafsanjani, and Saeid). Efficiency of direct transmission will be reduced, if the geographical zone is bigger than the certain threshold (Chiang, Huang, and Chang Shahraki, Rafsanjani, and Saeid). Hence, to enhance the lifetime of the scalable network, it is required to use multi-hop communication for intra-cluster routing as well as inter-cluster routing. There are some applications of WSN like forest fire detection for which information must be received by the BS within the bounded delay to avoid disaster. For such delay constraint applications, it is difficult to enhance the lifetime of a WSN (Ammari Manjeshwar and Agrawal, "TEEN: ARouting Protocol for Enhanced Efficiency in Wireless Sensor Networks." "APTEEN: A Hybrid Protocol for Efficient Routing and Comprehensive Information Retrieval in Wireless Sensor Networks."). Direct transmission provides minimal delay, but increases energy consumption of WSN nodes. On the other hand, multi-hop communication is energy efficient as nodes have to transmit over a shorter distance; and energy consumption is directly proportional to the distance (Ammari Younis, Youssef, and Arisha), but it increases the delay. Also, one should select direct transmission or multi-hop transmission between CH and member nodes, and between CH and other CHs or BS to balance between the energy consumption of a node and delay encountered by the data. If a multi-hop communication is used, then the selection of the "next hop" is also a challenging issue. If the same node is selected as a "next hop", then it runs out of energy within a short period. Hence, there is a need to design a CH election process which takes care of the trade-off between energy and delay by selecting direct transmission or multi-hop transmission for intra-cluster and inter-cluster communication. If multi-hop transmission is used, then selection of "next hop" to balance between the energy and delay is also a challenging task.

4.1.1 Major contributions

Following is the summary of contributions:

- A Cluster Head Election approach *EDIT* is proposed to optimize two conflicting objectives named "Energy" and "Delay".

- A trade-off between Energy and Delay is found by considering two different types of distances between CH and its member nodes: i) Euclidean distance and ii) Hop-count.

- It is shown that how the selection of "next hop" in multi-hop communication affects the Energy and/or Delay requirements of the underlying application.
- It is also shown that how controlling parameters of *EDIT* affect on Energy and Delay.
- The proposed approach is proven by extensive simulations using realistic radio parameters to get simulation results closest to the test bed.

4.2 Related Work

In (Bandai and Watanabe), authors have analyzed trade-off between delay and energy for data aggregation. They have shown that WSN suffers with energy consumption with non-aggregation methods and WSN suffers with delay when the full aggregation method is used. In (Zhang et al.), a lower bound of energy-delay trade-off and energy efficiency was proposed by the authors using a realistic unreliable link model in AWGN, Rayleigh fast fading and Rayleigh block fading channels. In (Akkaya, Younis, and Youssef), the authors have proposed a packet scheduling mechanism at each node and it is based on Weighted Fair Queuing to get bounded delay for constrained traffic with maximal possible energy saving with data aggregation. In (Durresi, Paruchuri, and Barolli), the authors have proposed Delay-Energy Aware routing Protocol (DEAP) for heterogeneous sensor and actor networks. Energy saving is achieved by using the resources of actor nodes whenever possible. It not only uses adaptive energy management scheme to control wakeup cycle of the sensor nodes based on the delay experienced by the packets, but also uses geographical information for load balancing to achieve energy conservation.

In (Pothuri, Sarangan, and Thomas), the authors have used topological control techniques to find energy efficient paths for delay constrained applications. In (Moscibroda, Von Rickenbach, and Wattenhofer), the authors have analyzed energy delay trade-off during the deployment of the sensor network. They have proposed a formal model that can be used to compare performance of the different protocols and algorithms. In (Cohen and Kapchits), the authors have divide energy efficient routing into two sub problems: i) How to construct efficient routing trees? and ii) How to assign wakeup frequency assignment with multiple routing trees? The authors have provided a solution to the first problem by optimal algorithm and they have proven second problem as NP-hard and provide a polynomial time approximation algorithm. In (Ammari), the authors have proposed data forwarding protocols for Trade-off Energy with Delay (TED) by slicing communication range of sensors into concentric circles. In (Bai et al.), the authors have proposed Delay-bounded Energy constrained Adaptive Routing (DEAR) problem by considering adaptive multi-path routing, energy and delay constrained jointly. In (Shahraki, Rafsanjani, and Saeid), the authors have proposed energy delay trade-off for intra-cluster routing in WSN.

In this chapter, Energy Delay Index for Trade-off (*EDIT*) for WSN is proposed by considering two different types of distances: i) Euclidean Distance and ii) Hop-count. This chapter is the first attempt to find the energy delay trade-off using two different kinds of distances for delay constrained applications. The proposed protocol along with the results are presented and discussed in the following sections.

4.3 Cluster Head election with Energy Delay Trade-off

The proposed algorithm works in rounds and each of these rounds are divided into two phases: i) Cluster Setup Phase and ii) Steady State Phase. A neighbor discovery phase executed once before the commencement of the first round and it is explained below.

4.3.1 Neighbor discovery phase

The algorithm begins with neighbor discovery phase, which is initiated by the sink by sending a *Hello* packet. A *Hello* packet consists of Sender Id, Hop-count and Euclidean distance to reach the sink and the location of the sender. Hop-count and Euclidean distance both are used to measure distance from the sink. Receiving nodes of a *Hello* packet, add the sender as its neighbor and record information like Sender Id, Hop-count and location, and then send *Hello Reply* to the sender. Each receiving node also forwards the *Hello* packet by setting its id as Sender Id, location parameter, and both distances, Hop-count and Euclidean distance, to reach the sink.

Whenever any node is having its energy less than the threshold (depending on the application), it will broadcast itself as a dead node by sending *Dead* message. The receiving nodes update their neighbor table on reception of *Dead* messages. Neighbor discovery phase should be done only once at the time of network deployment.

4.3.2 Cluster Setup Phase

$$\text{WaitTime}_{Energy} = \frac{1}{\text{Remaining Energy}} \tag{4.1}$$

At the end of Neighbor discovery phase, each node waits for WaitTime_{Energy}, before it broadcasts its energy level. A node compares its energy level with the energy level of the nodes from which it has received *Energy Messages*. If a node has less energy, then the node will cancel its timer and decides to be a cluster member.

The probable cluster heads are the set of nodes, which have sent *Energy Messages* and after that, either they do not receive any *Energy Messages* or their energy is higher than the energy received in *Energy Messages*. It may possible that more than one node may have the same energy level and they are in communication range of each other. To break a tie in such cases, Energy Delay Index for Trade-off (*EDIT*) is used. *EDIT* is calculated from Equation 4.2 only for the probable cluster heads. Values of α and β lie in the range of [0,1] and $\alpha + \beta \neq 0$ in Equation 4.2.

$$EDIT = \left(\frac{\text{TotalNeighbors}}{\text{TotalNodes}}\right)^{\alpha} + \left(\frac{1}{\text{Avg\_Dist\_from\_Sink}}\right)^{\beta} \tag{4.2}$$

Each probable cluster head will wait for $\frac{1}{EDIT}$ time before doing announcement that it is a final cluster head. All probable cluster heads, which receives *Final Cluster Head* announcement becomes the member nodes for the current round provided that a *Final Cluster Head* announcement is yet to be done by them. These member nodes cancel their *EDIT* timers and go to *sleep* state until the commencement of Steady State Phase. It helps to save energy of nodes. This double filtering scheme ensures that the node with the highest energy among the neighboring nodes will be elected as cluster head. It also ensures that these highest energy nodes must also have more number of neighboring nodes (good amount of aggregation helps to save energy) and minimal distance from the sink (helps to reduce communication delay) for a given value of α and β. After CH announcements, non-CH nodes will select one of the CHs as their Cluster Head. Selection of CH is based on minimum communication energy expenditure between non-CH node and selected CH node. After selection of CH node, non-CH nodes will send *Cluster Join* message, including their current energy level. Each final CH node prepares TDMA schedule for its own member nodes from which it has received *Cluster Join* messages. It also selects one of the member nodes as a gateway node, if two CH nodes are not in a communication range of each other. Selection of a gateway node depends on the energy/delay requirements of the underlying application. If network longevity is a prime concern for underlying application, then the highest energy member node will be selected as a gateway node, and if the delay is a prime concern for a given application, then a node having minimum distance from the sink would be selected as a gateway node. A TDMA schedule itself carries information regarding the active time period for the identified gateway node. This piggybacking scheme helps to save energy of a CHs by reducing the number of bits required to be communicated. This scheme also helps to save energy of gateway nodes as the duration to activate gateway nodes is informed by CHs in advance. Steady State Phase begins after TDMA schedule is informed to all the nodes.

4.3.3 Steady State Phase

All nodes remain in the *sleep* state except CHs nodes. Data transmission from non-CH nodes to CH node is done as per TDMA schedule announced by the CH. This scheme avoids collision of the data messages, and each member node remains in *transmit* state for a short duration. This helps to save energy of member nodes.

4.4 Simulation Parameters and Result Discussion

4.4.1 Simulator and Parameters used for experiments

EDIT protocol is tested using Castalia Simulator (Boulis, “Castalia: revealing pitfalls in designing distributed algorithms in WSN” “Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User’s manual”). Energy-Delay Trade-off is analyzed by considering two different types of distances of neighboring nodes from the sink: i) Euclidean distance ii) Hop-count. WSN nodes were uniformly deployed in the area of 250mx250m with varying node density between 50 to 250. Each simulation was carried out for 1500 seconds and repeated five times. The results were plotted by taking the mean value of the parameter of interest. Simulation parameters are shown in Table 4.1.

Parameter Name	**Value**
Node Deployment Area	250m X 250m
Number of Nodes	1) 50 2) 100 3) 150 4) 200 5) 250
Initial Energy/Node (in Joules)	1) 10 2) 18720
Simulation Time	1500 seconds
Transceiver	CC2420
Maximum Transmission Power	0 dBm
Baseline Node Power	6mW
Packet Size	30 Bytes
Sink Node Id	Node 0
Simulation Runs	Repeated 5 times for each configuration and mean value is recorded for the parameter of interest

Table 4.1: Parameters used for the simulation of the EDIT protocol

4.4.2 Result Discussion

End to end latency is shown in Figure 4.1. Figures are kept side by side to compare latency values recorded with Euclidean distance and Hop-count for a given node density. Each node was given the initial energy of 18720 Joules which is equivalent to AA batteries (Boulis, "Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User's manual"). It can be easily seen from the Figure 4.1 that end to end delay felt by the packets are small when Euclidean distance is used in Equation 4.2 compared to Hop-count. An average energy consumption per node is also measured for the same simulation set up and it is shown in Figure 4.2.

Energy consumption per node is more when Euclidean distance is used in Equation 4.2 compared to Hop-count.

Simulations are repeated by giving 10 Joules of initial energy to each node. Results for end to end delay is shown in Figure 4.3. This result also confirms the result that obtained with 18720 Joules of the initial energy.

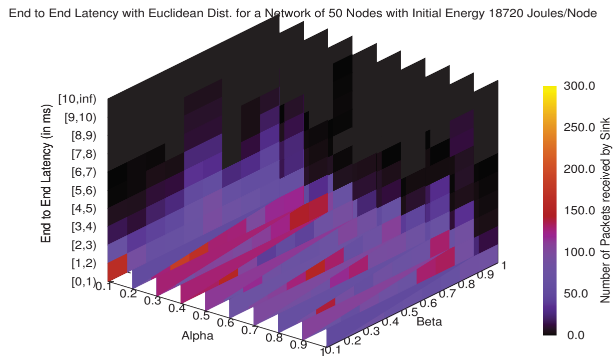
Network lifetime is measured in terms of First Node Dies (FND), Half of the Nodes Alive (HNA) and Last Node Dies (LND) and it is shown in Figures 4.4-4.6 respectively. Number of rounds after which first node dies, 50% of the nodes alive and the last node dies is more when Hop-count is used as a distance in Equation 4.2 compared to Euclidean distance.

Nodes have to transmit for a longer distance when Euclidean distance is used in *EDIT* protocol. Since, there would be a less number of forwarders encountered by the packet to reach to the sink. Hence, smaller delay felt by the packets. As mentioned earlier that energy expenditure of a node is directly proportionate to the distance. Hence, there would be huge energy expenditure when Euclidean distance is used in the *EDIT* protocol. The same reason is also applicable to Hop-count for getting higher delay and lower energy consumption.

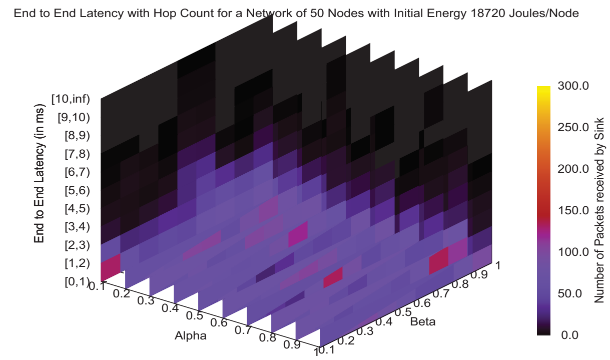
4.4.3 Effect of α and β

α and β are controlling parameters of *EDIT* protocol, and it is application dependent. α is used to control the importance of energy conservation and β is used to control the importance of end to end latency. To see the effect of α and β on *EDIT* protocol, values of α and β are set to 1 and 0 respectively, and end to end delay and energy consumption values are measured. The experiment is repeated by setting values of α and β to 0 and 1 respectively.

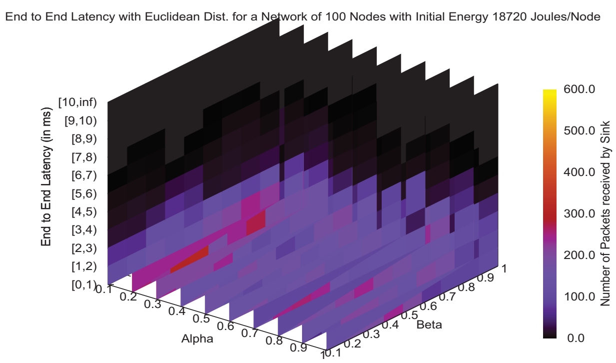
When $\alpha = 0$ and $\beta = 1$, variation in the values of *EDIT* in Equation 4.2 is due to β. Hence, it indicates that end to end delay is more important for a given application. On the other hand, when $\alpha = 1$ and $\beta = 0$, variation in the values of *EDIT* in Equation 4.2 is due to α, which indicates that energy conservation is more important for the underlying application compared to end-to-end delay. The same is proven with the simulation and it is shown in Figure 4.7.



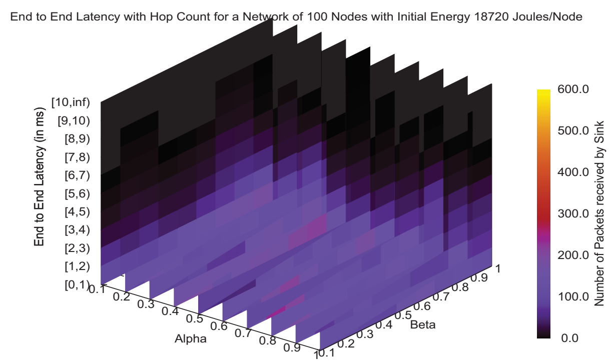
(a) Delay for 50 Nodes with Euclidean Distance



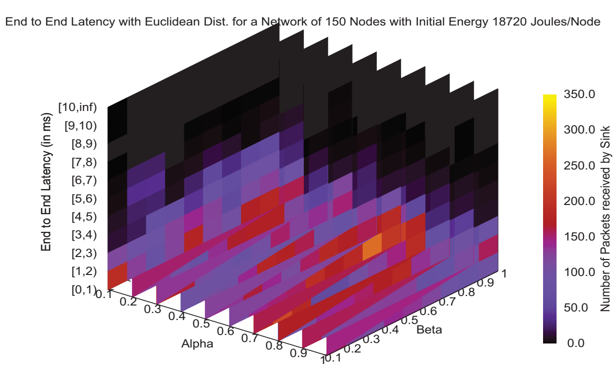
(b) Delay for 50 Nodes with Hop-count Distance



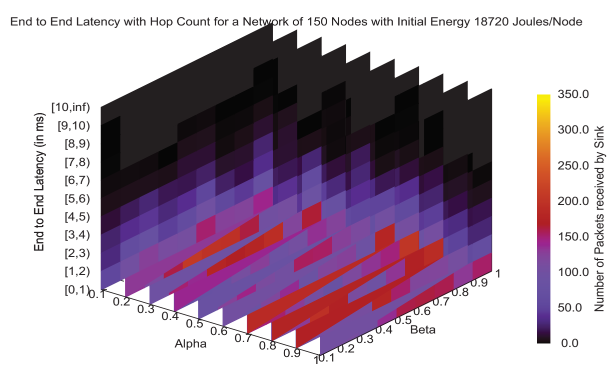
(c) Delay for 100 Nodes with Euclidean Distance



(d) Delay for 100 Nodes with Hop-count Distance

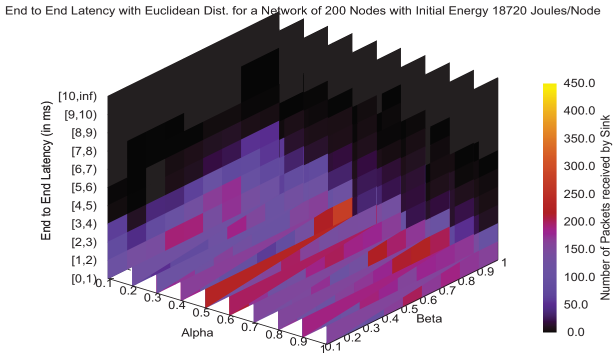


(e) Delay for 150 Nodes with Euclidean Distance

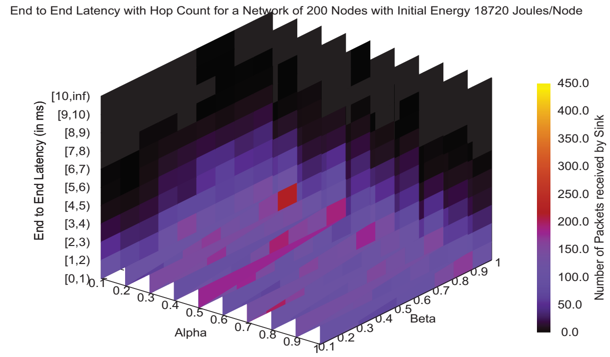


(f) Delay for 150 Nodes with Hop-count Distance

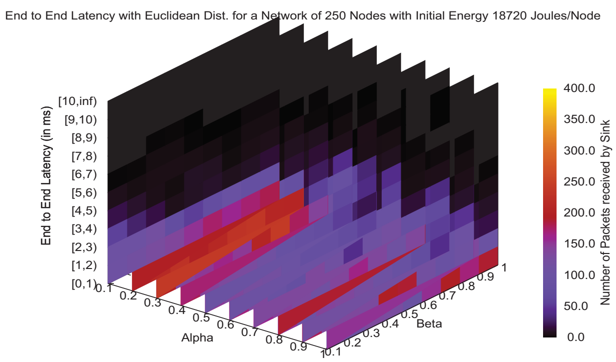
Figure 4.1: End to End delay for a network of varying node density between 50 to 250 nodes and each node was given initial energy of 18720 Joules.



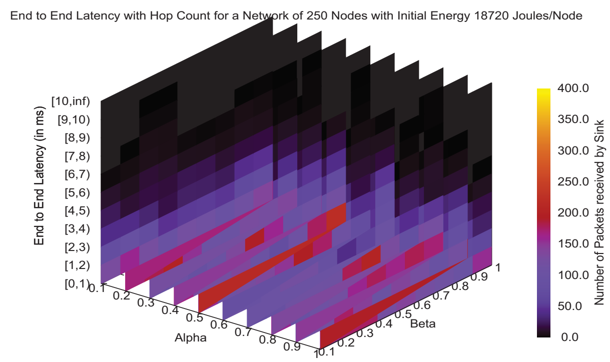
(g) Delay for 200 Nodes with Euclidean Distance



(h) Delay for 200 Nodes with Hop-count Distance

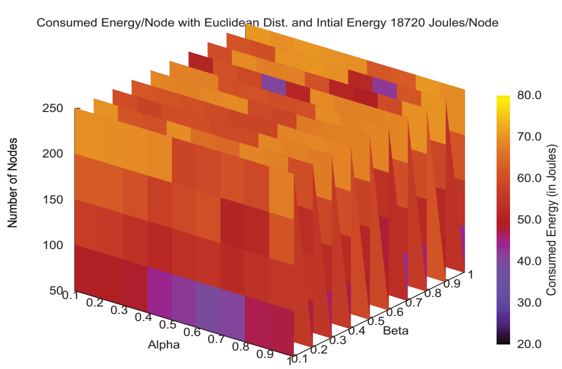


(i) Delay for 250 Nodes with Euclidean Distance

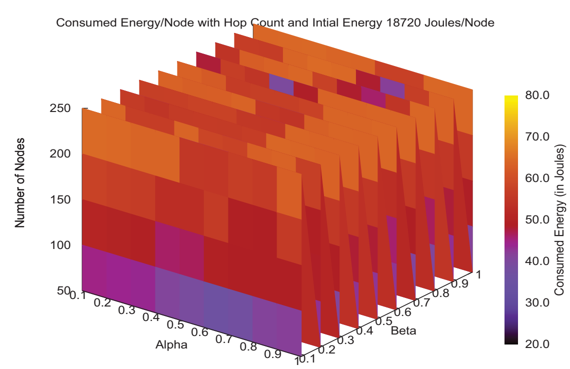


(j) Delay for 250 Nodes with Hop-count Distance

Figure 4.1: (Continued) End to End delay for a network of varying node density between 50 to 250 nodes and each node was given initial energy of 18720 Joules.

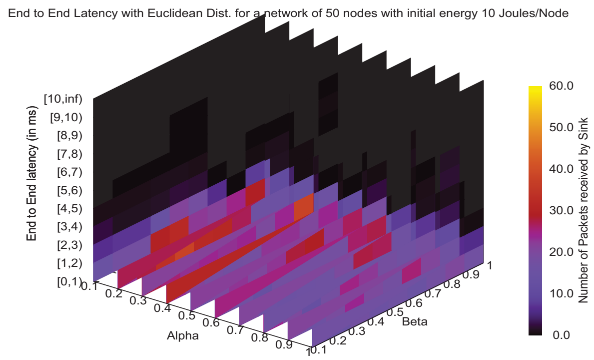


(a) Per Node Energy Consumption with Euclidean Distance

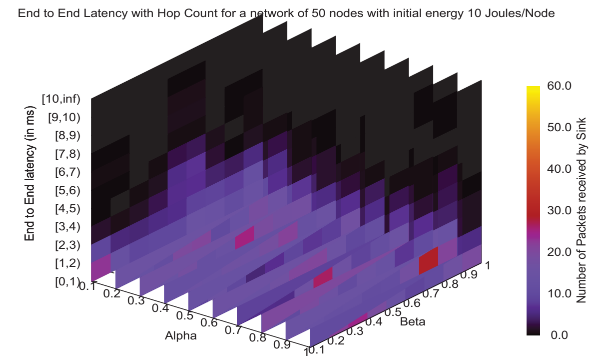


(b) Per Node Energy Consumption with Hop-count Distance

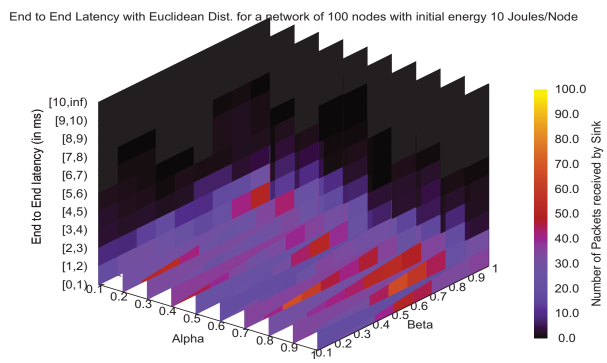
Figure 4.2: Per Node Energy Consumption for a network of varying node density between 50 to 250 nodes and each node was given initial energy of 18720 Joules.



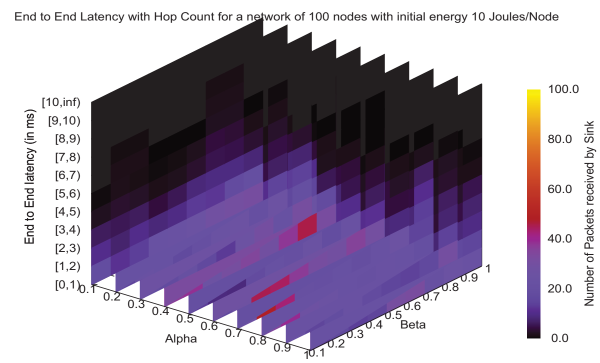
(a) Delay for 50 Nodes with Euclidean Distance



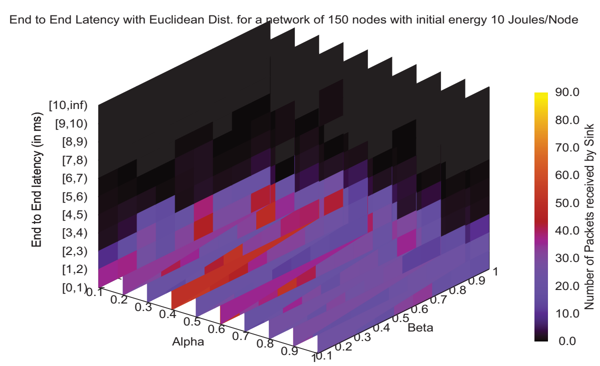
(b) Delay for 50 Nodes with Hop-count Distance



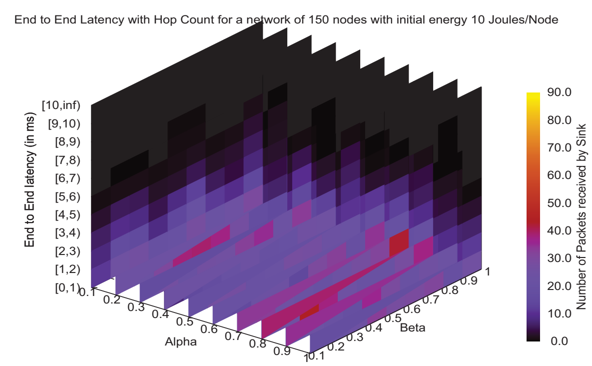
(c) Delay for 100 Nodes with Euclidean Distance



(d) Delay for 100 Nodes with Hop-count Distance

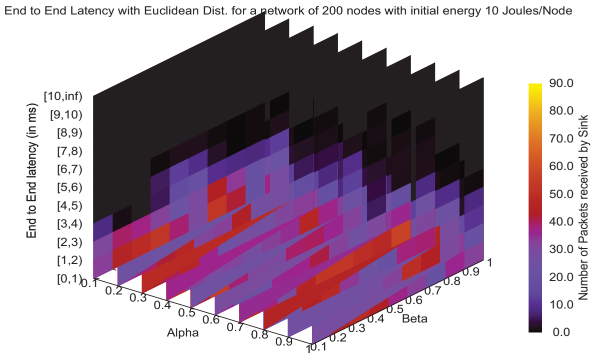


(e) Delay for 150 Nodes with Euclidean Distance

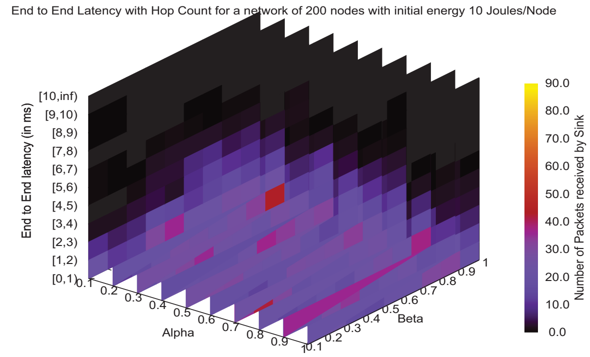


(f) Delay for 150 Nodes with Hop-count Distance

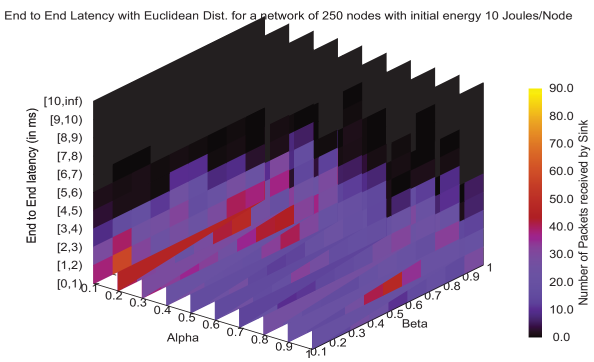
Figure 4.3: End to End delay for a network of varying node density between 50 to 250 nodes and each node was given initial energy of 10 Joules.



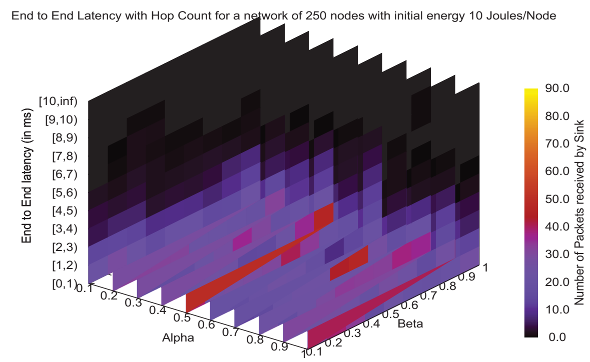
(g) Delay for 200 Nodes with Euclidean Distance



(h) Delay for 200 Nodes with Hop-count Distance

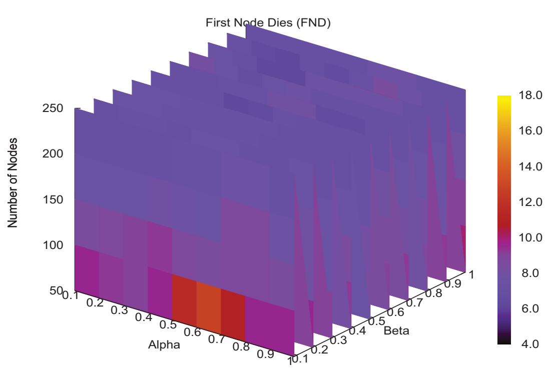


(i) Delay for 250 Nodes with Euclidean Distance

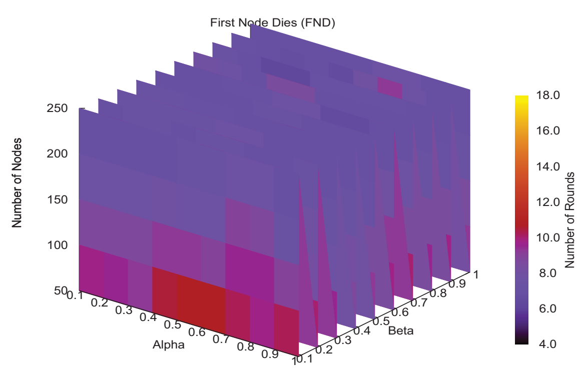


(j) Delay for 250 Nodes with Hop-count Distance

Figure 4.3: (Continued) End to End delay for a network of varying node density between 50 to 250 nodes and each node was given initial energy of 10 Joules.

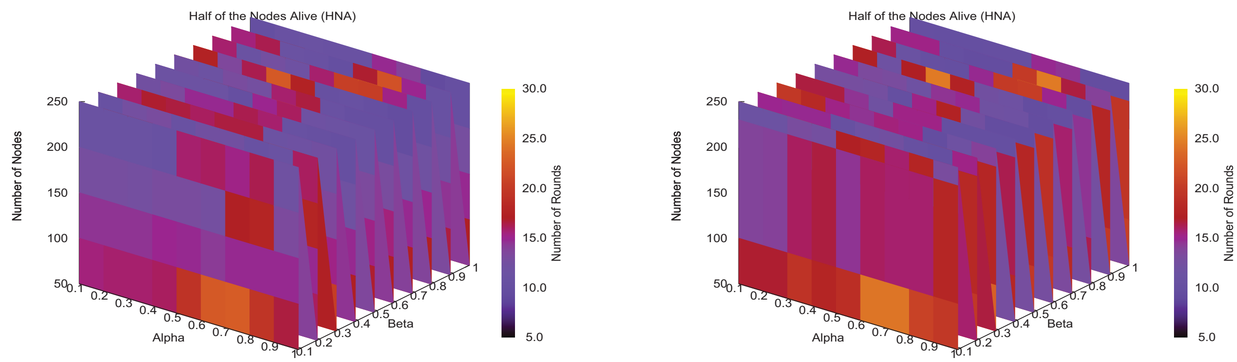


(a) First Node Dies (FND) with Euclidean Distance



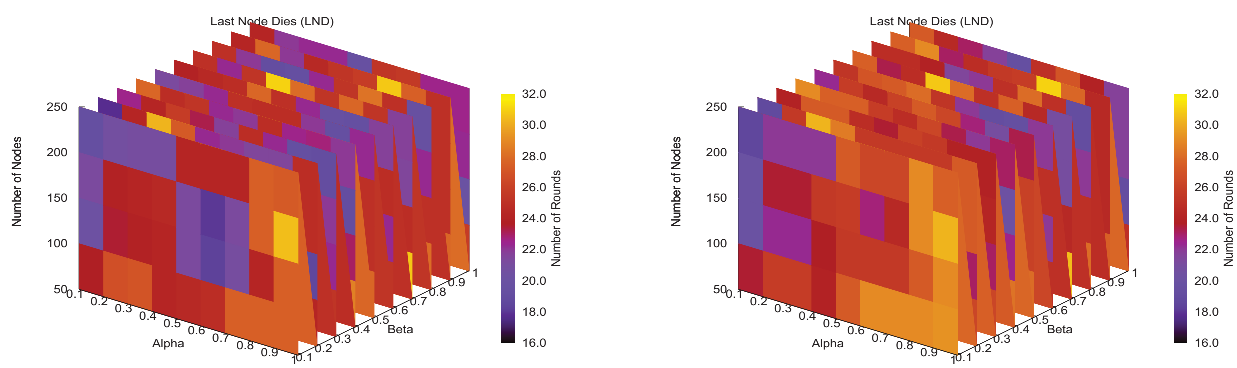
(b) First Node Dies (FND) with Hop-count Distance

Figure 4.4: First Node Dies (FND) for a network of varying node density between 50 to 250 nodes and each node was given initial energy of 10 Joules.



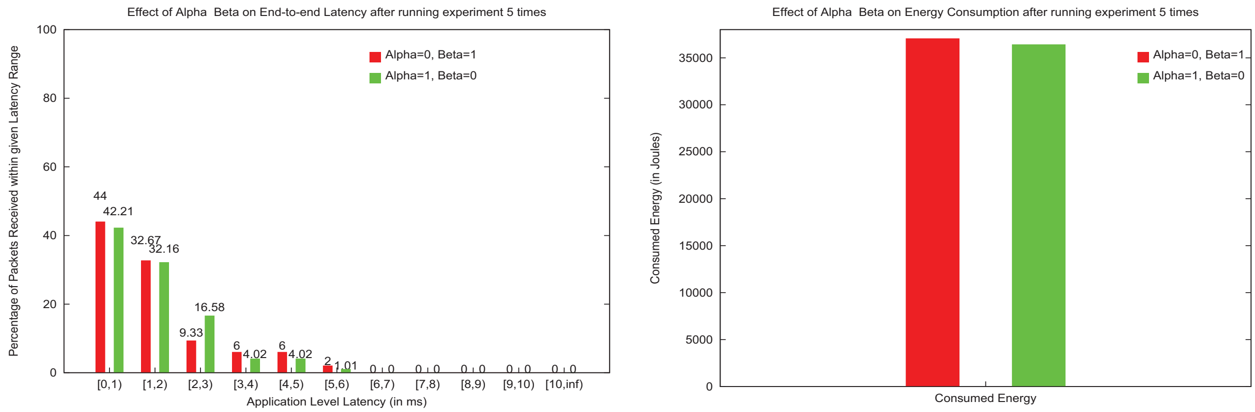
(a) Half of the Nodes Alive (HNA) with Euclidean Distance (b) Half of the Nodes Alive (HNA) with Hop-count Distance

Figure 4.5: Half of the Nodes Alive (HNA) for a network of varying node density between 50 to 250 nodes and each node was given initial energy of 10 Joules.



(a) Last Node Dies (LND) with Euclidean Distance (b) Last Node Dies (LND) with Hop-count Distance

Figure 4.6: Last Node Dies (LND) for a network of varying node density between 50 to 250 nodes and each node was given initial energy of 10 Joules.



(a) Effect of α and β on end to end delay (b) Effect of α and β on energy consumption

Figure 4.7: Effect of α and β on end to end delay and energy consumption

4.5 Summary

The protocol, *EDIT*, is proposed, examined and derived to analyze energy-delay trade-off by doing extensive simulations. The effect of two types of distances to be used to elect cluster heads using *EDIT* protocol is successfully demonstrated and their effect on delay and energy. In the course of research, the effect of controlling parameters for *EDIT* protocol were manifested. The simulation results presented will be useful to other researchers to analyze of two contradicting parameters, namely energy and delay before implementing it on a real test bed.

In the next chapter, a protocol for energy efficient routing is proposed through cross-layer optimization, wherein, Ant Colony Optimization (ACO) is used to elect the cluster heads. Later, an approach is proposed to minimize cluster formation overhead by relaxing maximum energy criteria to elect cluster heads. In addition to that, a scheme is proposed that enforces a node to become the cluster head, if it has not received any cluster head announcement within the specified duration.

Chapter 5

Cross-layer Design and Energy Threshold based improved Cluster Head election strategies for Wireless Sensor Networks

This chapter focuses on two important aspects: i) using Cross-layer Design (CLD) with ACO for CH election, and ii) relaxing maximum energy criteria for the CH election process. The use of cross-layer architecture with ACO for the CH election process is discussed in section 5.1 and relaxation in the maximum energy criteria for the CH election process is presented in section 5.2.

5.1 Bio-inspired based cluster head election using RSSI and LQI

Design and implementation of the energy efficient protocol stack for WSNs is a challenging task due to power and computational constraints. In this section, an ant based optimized energy-efficient cluster head election algorithm is proposed that uses Received Signal Strength Indicator (RSSI) and Link Quality Indicator (LQI). This algorithm is derived from T-ANT algorithm (Selvakennedy, Sinnappan, and Shang). This approach is based on cross-layer optimization technique as the radio layer provides useful information to network layer that helps in the CH election process.

5.1.1 Introduction to Swarm Intelligence

The emergent collective intelligence of groups of simple agents can be termed as Swarm Intelligence (SI) ("Swarm Intelligence"). Social insects' community can interact with each other in order to complete a specific task, where each individual has to perform a simple task. This collective behavior of social insects has inspired computer scientists to replicate them as they exhibit many attractive features, such as distributed system of interacting autonomous agents, performance optimization, robustness, self-organized control, decentralized cooperation, division of labor through distributed task allocation and reliability through redundancy. There are three basic controlling behaviors that govern movements of the agents within the swarm. It is shown in Table 5.1 which is taken from (Kadrovach and Lamont Reynolds Selvakennedy, Sinnappan, and Shang); two of them, separation and alignment, are implemented in the proposed protocol by extending T-ANT (Selvakennedy, Sinnappan, and Shang) algorithm.

Behavior	**Description**
Separation	Avoid collision with the nearby particles
Alignment	Attempt to match velocity with nearby particles
Cohesion	Attempt to stay with nearby particles

Table 5.1: Swarm Particle Behavior (Kadrovach and Lamont Reynolds Selvakennedy, Sinnappan, and Shang)

The proposed approach uses pheromone control to achieve an energy-efficient near uniform distribution of the CHs to reduce end-to-end delay experienced by packets and to improve the packet reception rate. Artificial ants based swarms are used to calculate pheromone. Also, multiple parameters are considered to calculate pheromone to prolong the network lifetime through the CH election process. Load balancing is achieved by rotating the role of the CH with every round, and hence, anti-pheromone is used to reduce the pheromone value of a node. T-ANT clustering algorithm is explained in the following section.

5.1.2 T-ANT Clustering Algorithm

T-ANT is an SI based clustering algorithm. It works in two phases: i) Cluster head election phase and ii) Steady state phase. The CH election phase uses swarm of ants to elect the cluster heads.

The sink releases a number of ants (control messages) during the node initialization phase and starts the Cluster Setup (CS) timer. The number of ants should be 10% of the total nodes (Ramos and Merelo). The sink randomly chooses one of its neighbors and forward ant to it. Time To Live (TTL) field is used to control traveling of ants. Nodes having ants check the TTL field before forwarding it to neighbors. If TTL is zero, then ant is retained by the node. The nodes possessing ants are elected as CHs, on the expiration of CS timer and send $CHADV$ message which contains the sender's ID, CH ID, distance to CH and CHAdvTTL field. The recipient nodes record all this information about the $CHADV$ message and broadcasts it, if CHAdvTTL in $CHADV$ is greater than zero.

A node joins one of the CHs, after expiration of its join-timer. A node, then computes its pheromone level based on its total hop distance (h) to CHs, the number of CHs (n) in its neighborhood, and its normalized residual energy. If the CH is in range, the message is transmitted directly; otherwise forwarded through its parent to the CH. When a CH receives $JOIN$ messages, it finds the member with the highest pheromone level to attract its ant for the next round (Selvakennedy, Sinnappan, and Shang). The pheromone expression is based on the forwarding probability formula used in the ant routing algorithm (Ohtaki et al.), but expanded as:

$$p = \frac{p + \Delta p}{1 + \Delta p}, \tag{5.1}$$

where Δp is given by

$$\Delta p = \frac{k}{{h_*}^2} X \frac{E_{resi}}{E_{max}} X \frac{\Sigma_{i=1}^{n} h_i}{n} \tag{5.2}$$

In Equation 5.2, h_* is the node's hop distance to the selected CH, E_{resi} is the residual energy, E_{max} is the reference maximum battery energy and k is the learning rate of the algorithm ($k = 0.1$). This expression ensures that Δp is higher when the node is only reachable by fewer CH nodes (smaller n), far from CHs (Σh), has higher residual energy (E_{resi}) or is nearer to its selected CH (h_*) (Selvakennedy, Sinnappan, and Shang).

Before the next CS timer expires, the ants wander to the nodes with the highest pheromone level among their neighbors, and these nodes will be the future CHs. An anti-pheromone is laid to achieve a rapid decay of the pheromone level before ant leaves the current node. The pheromone removal is computed with the anti-pheromone rate (β) (Selvakennedy, Sinnappan, and Shang).

5.1.3 The Modified T-ANT (MT-ANT) Clustering Algorithm

The Modified T-ANT (MT-ANT) clustering algorithm uses RSSI and LQI along with the parameters used by T-ANT, to calculate the pheromone level. The importance of RSSI and LQI values is discussed in section 5.1.3.1 and Modified T-ANT (MT-ANT) clustering algorithm is discussed in section 5.1.3.2.

5.1.3.1 Importance of RSSI and LQI

Link estimation is an important factor in protocol design. LQI (Link Quality Indicator) is a metric of the current quality of the received signal. LQI is best used as a relative measurement of the link quality (a low value indicates a better link than what a high value does), ("Calculation and usage of LQI and RSSI").

Received Signal Strength Indicator (RSSI) does not care about the "quality" or "correctness" of the signal, while LQI does not care about the actual signal strength. However, signal quality often is linked to signal strength. This is because a strong signal is likely to be less affected by noise and thus will be seen as "cleaner" or more "correct" by the receiver. There are four to five "extreme cases" that can be used to illustrate how RSSI and LQI work ("Calculation and usage of LQI and RSSI"):

- A weak signal in the presence of noise may give low RSSI and high LQI.
- A weak signal in "total" absence of noise may give low RSSI and low LQI.
- Strong noise (usually coming from an interferer) may give high RSSI and high LQI.
- A strong signal without much noise may give high RSSI and low LQI.

- A very strong signal that causes the receiver to saturate may give high RSSI and high LQI.

It is shown that RSSI is a promising indicator when its value is above the sensitivity threshold of $CC2420$ ($-87dBm$) (Srinivasa and Levis). Moreover, it is also shown that generally for RSSI values greater than $-87dBm$, PRR is at least 85% indicating a very good link (Srinivasa and Levis). LQI values are usually between 110 and 50 (Srinivasa and Levis).

5.1.3.2 The Modified T-ANT (MT-ANT) clustering algorithm

The Modified T-ANT (MT-ANT) is an extension of T-ANT clustering algorithm. MT-ANT works similar to T-ANT in all aspects except the method used to calculate the pheromone, which helps to elect CHs. The pheromone expression is based on Equation 5.1, where Δp is given by

$$\Delta p = \frac{k}{h_*^2} X \frac{E_{resi}}{E_{max}} X \frac{\Sigma_{i=1}^{n} h_i}{n} X (\frac{RSSI_{sth}}{RSSI_{rec}})^2 X (\frac{LQI_{min}}{LQI_{rec}})^2 \tag{5.3}$$

In Equation 5.3, $RSSI_{sth}$ represents the sensitivity threshold, $RSSI_{rec}$ represents the RSSI value of the $CHADV$ message of the CH, LQI_{min} is the minimum LQI value and LQI_{rec} is the LQI value of the received $CHADV$ message of the CH. This equation ensures the properties mentioned by Equation 5.2, however, it also ensures that higher value of RSSI and the lower value of LQI for $CHADV$ increases the pheromone level of a node to be elected as CH by attracting ants before next CS time expires.

The pheromone given by Equation 5.3 helps to achieve the separation behavior between ants. The area served by each ant represents the alignment behavior (Selvakennedy, Sinnappan, and Shang). It is reflected by the number of members in a cluster. The CH election fitness function S to capture the separation behavior is given by Equation 5.4 (Selvakennedy, Sinnappan, and Shang):

$$S = \Sigma_{i=1}^{n_c} \frac{n_i}{\Sigma_{j=1}^{n_i} h_{ij}} \tag{5.4}$$

where n_c is the number of CH nodes, n_i is the number of $CHADV$ seen by CH_i and h_{ij} is CH_i's hop distance to CH_j. The clustering fitness function A to represent the alignment behavior is given by Equation 5.5 (Selvakennedy, Sinnappan, and Shang):

$$A = \Sigma_{i=1}^{n_r} h_i \tag{5.5}$$

where n_r is the number of regular nodes and h_i is the node i's hop distance to its CH.

5.1.4 Results and Discussions

The performance of MT-ANT is investigated against T-ANT using Castalia simulator (Boulis, "Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User's manual"). For this simulation experiment, 100 sensor nodes are uniformly distributed in the area of 250m x 250m. CC2420 is used as a transceiver in each sensor node. Each node constantly draws $6mW$ and sensing device within the node draws $0.02mW$. The transceiver energy parameters are set as: $ETx = 0dBm$. The other parameters for radio are set as discussed in Section 3.1.2. The packet size is set to 30 bytes for both control and data messages, and sensor senses the value every two seconds. Each CH node retains its CH status for 20 seconds. The number of ants is fixed to 10 (i.e. 10% of the total nodes) and the anti-pheromone rate is 0.1. CHAdvTTL field is set to 3. $RSSI_{sth}$ and LQI_{min} is set to -87 dBm and 50 respectively.

With the above simulation parameters, following performance metrics are investigated:

- **Clustering fitness:** It represents the goodness of the cluster formation involving all regular nodes.

- **CH election fitness:** It represents the goodness of all the elected CH nodes.

- **Packet Reception Rate:** It represents the goodness of the link of the elected cluster.

- **Energy consumption:** It represents energy consumption of a node.

Simulation is carried out for 1500 seconds, in that first 60 seconds are used for discovering neighbor nodes by sending neighbor discovery packet.

Clustering fitness over time is shown in Figure 5.1. For MT-ANT, the initial value is high indicates that the alignment is not achieved yet because ants are ran-

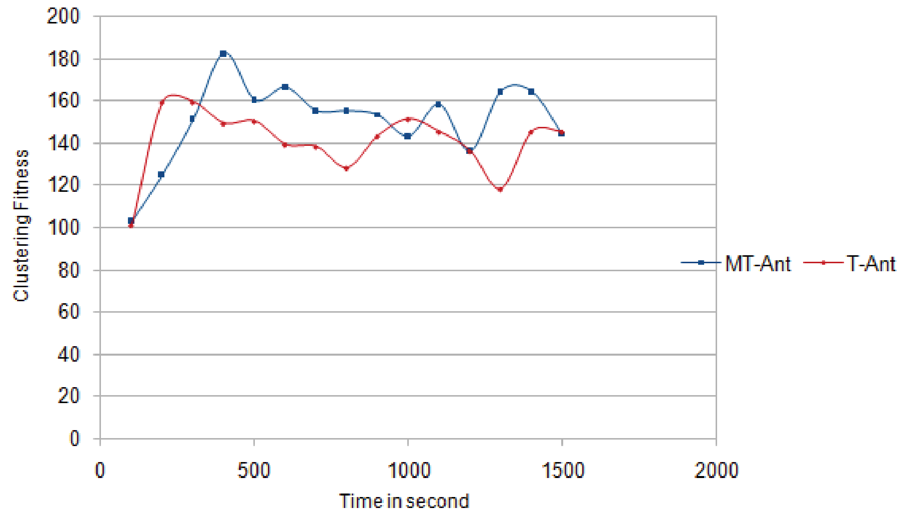


Figure 5.1: Clustering Fitness

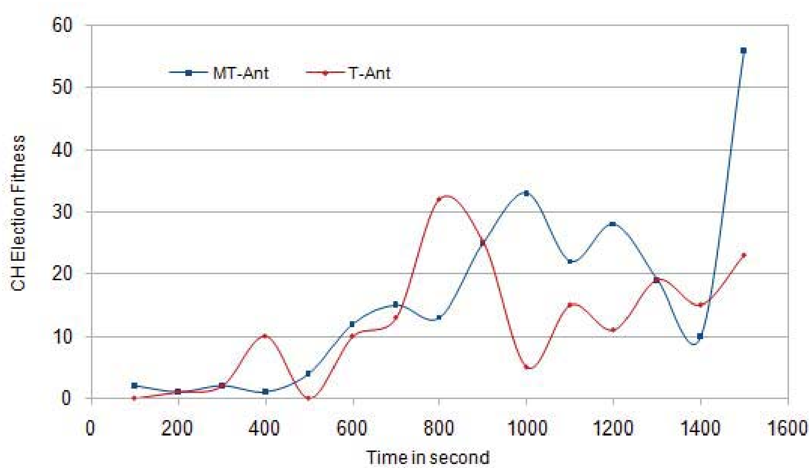


Figure 5.2: CH Election Fitness

domly released into the network. The alignment improves for both MT-ANT and T-ANT over as pheromone is laid and anti-pheromone takes effect. However, from the Figure 5.1, it can be seen that MT-ANT provides good clustering fitness compared to T-ANT.

CH Election fitness over time is shown in Figure 5.2 for MT-ANT and T-ANT. Initially, MT-ANT has lower fitness compared to T-ANT but as soon as alignment takes place MT-ANT gives good clustering fitness compared to T-ANT. The packet

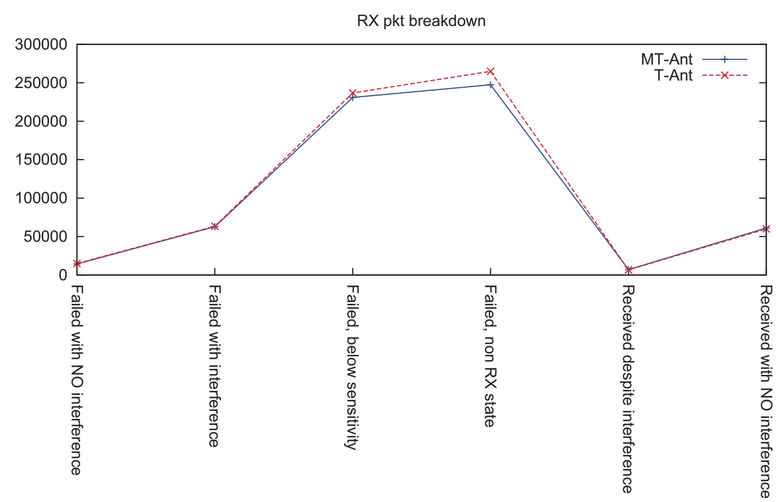


Figure 5.3: RX Packet Breakdown

reception rate of MT-ANT and T-ANT is shown in Figure 5.3. It can be seen from the Figure 5.3 that packet failure is reduced and reception rate is increased. During this experiment, packet failure rate is decreased by 0.60%. An average energy consumption per node is recorded as 43.567 Joules and 44.217 Joules for MT-ANT and T-ANT respectively, and it is shown in the Figure 5.4. The results show that average energy consumption per node is reduced by 1.49%. To verify the effect of alignment and separation behavior on MT-ANT and T-ANT protocols, the average energy consumption per node is measured at different time intervals as shown in the Table 5.2. To improve the accuracy of the forecast the improvement in the average energy reduction, the experiment is carried out for 2000 seconds and the parameter of interest is measured at the interval of 500 seconds. The forecast is carried for 10 periods, and it is shown in Figure 5.5. It can be seen from the figure that after 7000

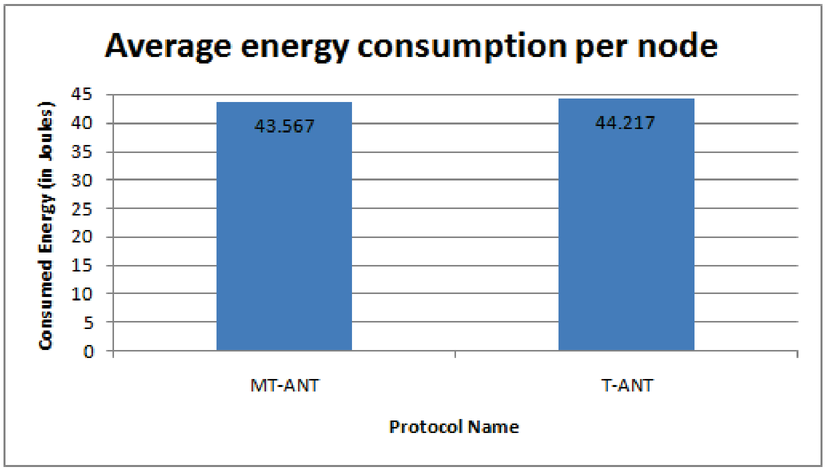


Figure 5.4: Average Energy Consumption per node (in Joules)

seconds the percentage of energy reduction is found between 19 to 20%. This value is closest to the actual implementation, as the value of R^2 is 0.955, which is close to 1. This shows that alignment and separation behavior improves over time for the MT-ANT protocol.

Time (in Seconds)	**Average energy consumption per node for MT-ANT**	**Average energy consumption per node for T-ANT**	**Energy reduction (in %)**
500	15.871	15.731	-0.882
1000	29.595	29.569	-0.088
1500	43.567	44.217	1.492
2000	57.533	59.714	3.791

Table 5.2: Average Energy Consumption/Node (in Joules) and percentage of Energy Reduction/Node at different time intervals

To verify the lifetime of a node for the MT-ANT and T-ANT clustering algorithms, each node was given 10 Joules of initial energy. Minimum, average and Maximum lifetime for both algorithms is shown in Figure 5.6. Maximum and minimum lifetime refers to the LND and FND respectively. FND and the average lifetime of MT-ANT is better than T-ANT, while the difference between two algorithms are negligible for the LND.

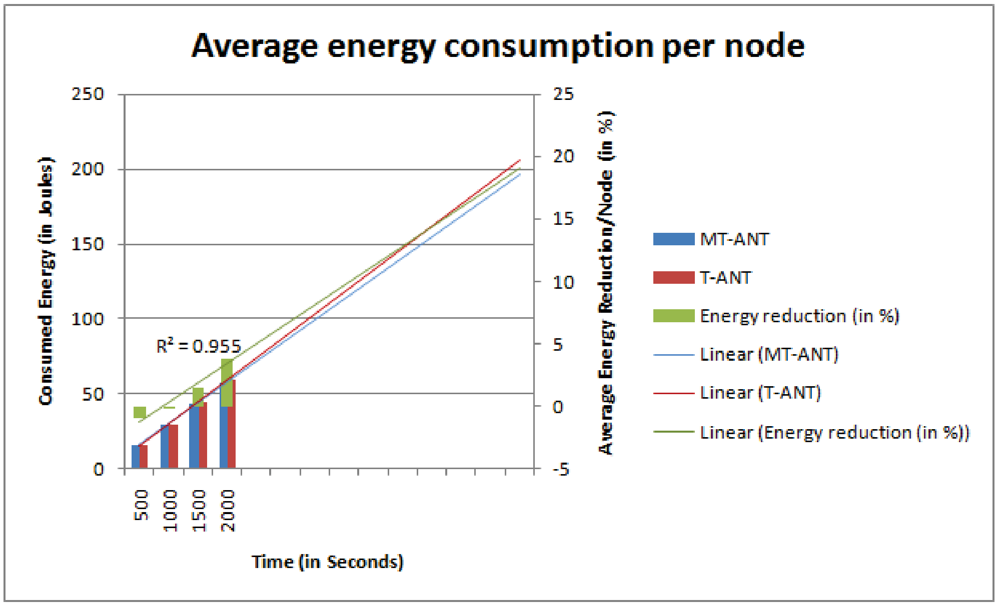


Figure 5.5: Average Energy Consumption/Node (in Joules) and percentage of energy reduction/node

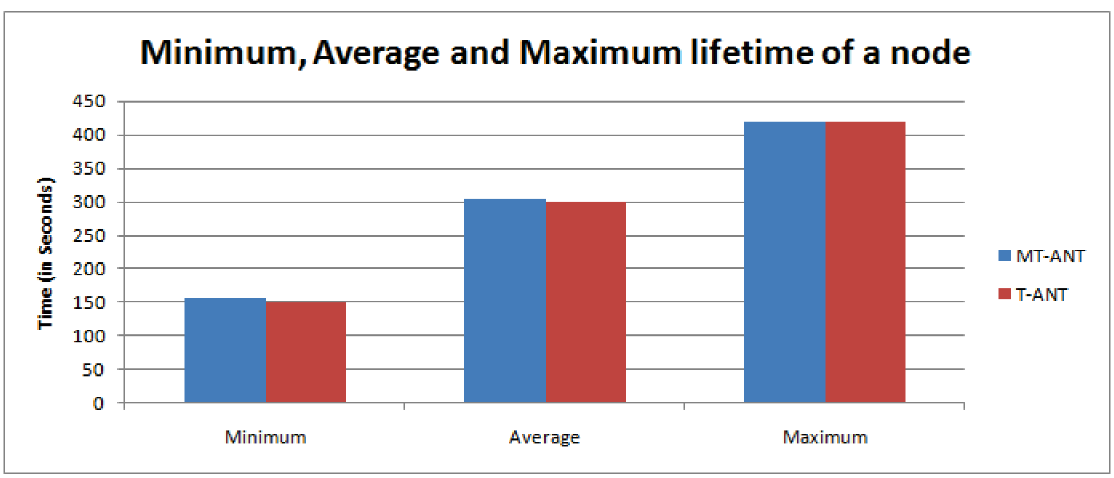


Figure 5.6: Minimum, Average and Maximum lifetime of node (initial energy was 10 Joules)

5.2 Energy threshold based dynamic clustering scheme for energy efficient routing in Wireless Sensor Network

For clustered based routing scheme, many parameters are considered by researchers to elect CH. One of them is the current energy of a node with respect to maximum energy within the network or current energy of a node with respect to the initial energy given to the nodes. Some clustering algorithms give predefined number of cluster heads and others calculate it during the run by considering only maximum energy level of a node within the cluster or across the network.

This chapter proposes a new algorithm by relaxing maximum energy criteria for the cluster head election process. It also introduces a *forced CH* scheme to ensure that the non-CH node must be a member of some cluster. This scheme is referred as the proposed approach. Extensive simulations are carried out to compare the proposed approach with ALEACH, CVLEACH, ECBRP, LDCHS, LEACH and ACA-LEACH, and final solution is compared using following performance metrics: i) Network lifetime ii) Stability period iii) Packet Reception Rate (PRR) iv) Speed of convergence v) Overhead for the Cluster Head election. In addition, the proposed approach has been tested by placing the sink node at best and worst position (in terms of the maximum distance of any node from the sink).

5.2.1 Problem Definition

Algorithms related to LEACH and its variations can be classified in two categories: i) centralized algorithms and ii) distributed algorithms. The centralized algorithm cannot provide scalability. Also, central node becomes a bottleneck. Distributed algorithms can be grouped into two categories as far as the CH election process is concerned. The use of the stochastic approach to elect CH i) without considering energy of a node and ii) with energy consideration of a node participating in the CH election process. In most algorithms, discussed in Chapter 2, it is shown that each node will be a CH for one round within $\frac{1}{p}$ rounds, where p is the desired percentage of CHs. Also, the value of p is known to the algorithm apriori. Few algorithms have considered other parameters like distance to BS, distance between CHs and others (Han et al. Heinzelman, Chandrakasan, and Balakrishnan, “An application-specific protocol architecture for wireless microsensor networks” Guifeng, Yong, and Xiaoling Behboudi and Abhari Kim and Youn Handy, Haase, and Timmermann Sehgal and Choudhary). Also, in ACO based approaches (Okdem and Karaboga Camilo et al. Thakkar and Kotecha, “Bio-inspired based optimized algorithm for Cluster Head election using RSSI and LQI” Selvakennedy, Sinnappan, and Shang Guifeng, Yong, and Xiaoling), the ratio of the current energy level of a node with respect to the maximum energy of a node across the network, within the neighboring region or the initial energy of a node is taken into consideration to elect CH or to choose the next hop.

A CH election algorithm for WSN should be distributed, energy efficient, faster and self-adaptive. The algorithm should also consider all the nodes in the CH election process, those are having an energy, lesser than the maximum energy within the neighboring node within the acceptable bounds. It should also ensure that each node should be a member of some cluster. The algorithm should also consider node density, node deployment pattern and position of a CH while electing a CH. Distributed algorithm overcomes the problems of centralized algorithm and provides scalability. Since, sensor nodes are battery powered, the algorithms designed for WSN must be energy efficient. These algorithms should be as simple as possible with low computational overhead as nodes have limited processing capacity. The proposed algorithm should also maintain Packet Reception Rate (PRR) at least as good as existing algorithms.

5.2.2 The energy threshold based approach for cluster head election in Wireless Sensor Network

Like LEACH, the proposed approach also works in rounds. Each round is divided into Cluster Setup Phase and Steady State Phase. CHs are elected during Cluster Setup Phase, which is followed by Steady State Phase. After receiving *Cluster Head announcement* messages from CHs during Cluster Setup Phase, each node selects maximum energy node as its CH from a set of nodes from which it has received CH announcements. A node sends a *Cluster Join* message to the selected CH. After receiving *Cluster Join* messages from the nodes, each CH prepares a TDMA schedule and inform to members. During Steady State Phase, a node remains in a sleep state until its turn comes as per schedule provided by its CH. After receiving the data, CHs aggregate data received from their members and send to the BS directly, if BS in communication range of CH or through multi-hop communication. The proposed approach has modified Cluster Setup Phase by introducing local energy threshold (ET) value and *forced CH* scheme. The algorithm is explained in the following subsection.

5.2.2.1 Cluster Setup Phase

In most of the cluster based algorithm, it is shown that node with maximum remaining energy should be elected as the cluster head. However, message complexity to find maximum energy node in a distributed environment is proportional to the number of alive nodes. Hence, message complexity increases with the increase in node density. Also, the protocols, discussed in the Chapter 2, have also assumed that CHs are uniformly distributed. However, due to the stochastic nature of the algorithms, it is difficult to ensure that each node can work as either CH or a member node. Also, if the node is not a member of any cluster, then it has to communicate directly with BS. This results in long distance communication and thus higher energy depletion. To overcome these problems, rather than selecting a node with maximum energy, energy restriction is relaxed by threshold Th(n), where Th(n) is given by Equation 5.6.

$$\mathrm{Th(n)} = \mathrm{percentage\_of\_CH} * \frac{\sqrt{\mathrm{Area(Node\_Deployment)}}}{\mathrm{totalNodes}} \tag{5.6}$$

where the percentage_of_CH depends on the application. Since, the proposed approach is compared with LEACH and others, the value of the percentage_of_CH is set to 5% as in LEACH. It is assumed that each node is capable of storing maximum energy announcement that it has received during the last round. If the ratio of energy level of any node and energy level that the node has received during the last round is greater than (1 + Th(n)), then that node withdraws its participation to become a CH for the current round and decides to become a member node. This filters the nodes with more energy than the threshold Th(n). Also, if the ratio of energy level of any node and energy that node has received in the current round is less than Th(n), then that node withdraws its participation to become a CH for the current round, and decides to become a member node. For example, if the ratio of energy levels of

Algorithm 5.1 Cluster Setup Phase for the energy threshold based proposed approach

Require: Total_Round_Time > 0 AND Round_Duration > 0 AND Total_Round_Time ≥ Round_Duration AND N > 0 AND 0 < percentageofCH< 1 AND $t_1 >> t_2 >> t_3$ AND 0 < maxSleep < 1

Wait_Time = maxSleep $* \frac{random(\text{totalNodes})}{\text{totalNodes}}$
for all nodes i ∈ N **do**
    isCHAdvReceived = isCH = isMember = false
end for
for all nodes i∈N **do**
    if $\frac{\text{NodeEnergy}}{\text{maxAdvEnergy}} \leq (1 + \text{Th}(n))$ OR round = 1 **then**
        Activate(CH_Announcement_Timer(Wait_Time))
        Activate(Forced_CH_Timer(maxSleep))
        if isTriggered(CH_Announcement_Timer) **then**
            if isCHAdvReceived AND $\frac{\text{NodeEnergy}}{\text{maxAdvEnergy}} \leq (1 + \text{Th}(n))$ **then**
                Deactivate(CH_Announcement_Timer)
                Deactivate(Forced_CH_Timer)
                Activate(Join_Timer(t_2+random_wait))
            else
                Send(CH_Adevertisement)
                isCH = true
                Activate(TDMA_Schedule_Timer(t_1+random_wait)
                if isTriggered(TDMA_Schedule_Timer) **then**
                    for j ∈ Members **do**
                        Send(TDMA_Schedule(j))
                    end for
                end if
            end if
        else if isTriggered(Forced_CH_Timer) AND isCH = false AND isMember = false **then**
            Activate(CH_Announcement_Timer(t_3+random_wait))
        end if
    else
        Activate(Join_Timer(t_2+random_wait))
        if isCHAdvReceived AND isTriggered(Join_Timer) **then**
            Send_Join_Request(i)
            Wait_For_TDMA_Schedule(random_wait)

```
            if isScheduleReceived then
                isMember = True
                Activate(TurnTimer(ScheduledTime - CurrentTime))
            else
                Activate(TurnTimer(random_wait))
            end if
            Go to Sleep State
        end if
    end if
    Call Algorithm 5.2(i)
end for
```

Algorithm 5.2 Steady-State Phase for the energy threshold based proposed approach

Require: i ∈ Nodes

```
if t<RoundTime then
    if i∈CH then
        for all j∈Members(i) do
            Collect_Data_From_Member_Nodes(j)
        end for
        Send_Aggregate_Data_To_sink_By_CH(i)
    else
        if  isTriggered(TurnTimer) AND isScheduleReceived  then
            Send_Data_To_CH_By_Member(i)
        else
            Send_Data_To_sink_By_Node(i)
        end if
        Go to Sleep State
    end if
else
    Call Algorithm 5.1(i)
end if
```

any two nodes i and j is $\frac{E_j}{E_i} < (1 + \mathrm{Th(n)})$ with $E_i < E_j$ and node j receives energy announcement from node i, then node j withdraws its participation to become a CH for the current round and becomes a member node as $E_i \approx E_j$. This double filtering approach reduces the number of messages transmitted for cluster head announcements by the nodes participated in the CH election process. It has two benefits: i) It saves energy of the nodes by reducing transmission of the CH announcements and ii) It reduces the probability of collision between CH announcement messages.

Cluster Setup Phase for the proposed approach is shown in Algorithm 5.1 and described as follows: At the beginning of each round, each node assumes a random integer number between 0 and totalNodes. Each node also calculates waitTime to make CH announcement and energy announcement for the current round, where waitTime is given by the Equation 5.7

$$\mathrm{waitTime} = \mathrm{maxSleep}\ * \frac{\mathrm{random(totalNodes)}}{\mathrm{totalNodes}} \tag{5.7}$$

where maxSleep is the maximum amount of time before which a node must decide to be a CH or a member of the current round; random(totalNodes) is a function that selects any random integer number between [0, totalNodes) and totalNodes denotes the number of nodes in a network. maxSleep is a tuning parameter which is application dependent. The value of maxSleep is always between 0 and 1.

Cluster Head announcement along with current energy level is done by nodes after waitTime, given by the Equation 5.7. It helps to save energy of the node. If any node receives CH announcement before waitTime and its energy level is less than (1 + Th(n)), then the node decides to be a member node for the current round. Each and every node, which are eligible to become CH for the current round also sets a timer known as *forcedCH* with a wait time parameter is maxSleep. After expiration of *forcedCH* timer, a node checks that whether it has received any announcement from the neighboring nodes or not. If a node has not received any announcement, then it declares itself as a CH for the current round after the expiration of *forcedCH* timer.

This approach ensures that each and every node must be covered by at least one of the cluster heads. It helps to conserve energy, as member nodes are required to remain in an active state (transmit or receive) for a short duration and in a sleep state for a longer duration. After getting cluster head announcements, each and every member node waits for a random amount of time and sends a *Cluster Join* message to the one of the cluster heads. The selection of the cluster head is based on the energy level. A member node always selects the highest energy cluster head from which it has received CH announcements. After receiving the *Cluster Join* messages, Cluster Head prepares TDMA schedule and sends to the member nodes.

5.2.2.2 Steady State Phase

During Steady State Phase, member nodes send data to their cluster heads as per TDMA schedule. After sending data to CH nodes, member nodes go to sleep state to save energy. Member nodes remain in transmitting state only for the duration provided by their cluster head. Apart from this scheduled time, the member node remains in the sleep state in Steady State Phase. It helps to conserve energy of a node. Steady State Phase is shown in Algorithm 5.2.

5.2.3 Experiments and Results

In this section, the performance of the proposed approach is evaluated by comparing it with six different clustering algorithms, including LEACH (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks"), which is the widely accepted and used as a reference algorithm for the cluster formation in WSN.

5.2.3.1 Simulator and Parameters used for the experiments

Castalia (Boulis, "Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User's manual") simulator is used to compare the proposed approach with other six algorithms. Energy consumption of a sensor node depends upon the amount of time a node remains in transmit, receive and sleep state (Thakkar and Pradhan Instruments Boulis, "Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User's manual"). As shown in (Stetsko, Stehlik, and Matyas), energy consumption of a node given by Castalia simulator is closest to real measurement.

Parameter Name	Value
Node Deployment Area	100m X 100m
Number of Nodes	1) 100 2) 200 3) 300 4) 400 5) 500
Initial Energy/Node	1) 10 Joules 2) 18720 Joules
Simulation Time	1500 seconds
Transceiver	CC2420
Tx Power	0dBm
Baseline Node Power	6mW
Packet Size	30 Bytes
percentage of CH	5% [1]
Algorithms	1) ALEACH [2] 2) Proposed Approach 3) CVLEACH [3] 4) ECBRP [4] 5) LDCHS [5] 6) LEACH [1] 7) ACA-LEACH [6]

[1] (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks")
[2] (Ali, Dey, and Biswas)
[3] (Thakkar and Kotecha, "CVLEACH: Coverage based energy efficient LEACH Algorithm")
[4] (Han et al.)
[5] (Handy, Haase, and Timmermann)
[6] (Guifeng, Yong, and Xiaoling)

Table 5.3: Parameters used for the simulation of the proposed approach

Parameter Name	Value
Sink Node Id	Node 0
Sink Location	1) Center of the deployment area 2) At location (0,0)
Node Deployment	1) [1..$totalNodes - 1$]->uniform [7] 2) [1..$totalNodes - 1$]->10x10 [8,7] 3) [1..$totalNodes - 1$] ->randomized_10x10 [9,7]
Simulation Runs	Repeated 10 times for each configuration and mean value is recorded for the parameter of interest

[7] (Boulis, "Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User's manual")
[8] This deployment pattern is shown as *Grid* in plotted results.
[9] This deployment pattern is shown as *RGrid* in plotted results.

Table 5.3: (Continued) Parameters used for the simulation of the proposed approach

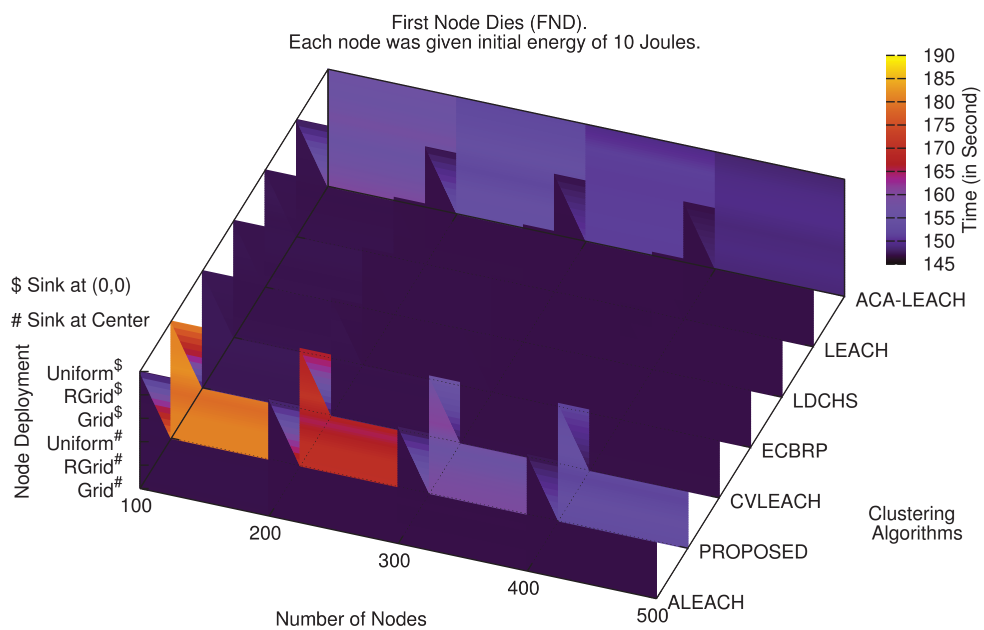


Figure 5.7: First Node Dies (FND) for varying node density between 100 to 500 nodes with initial energy 10 Joules/Node

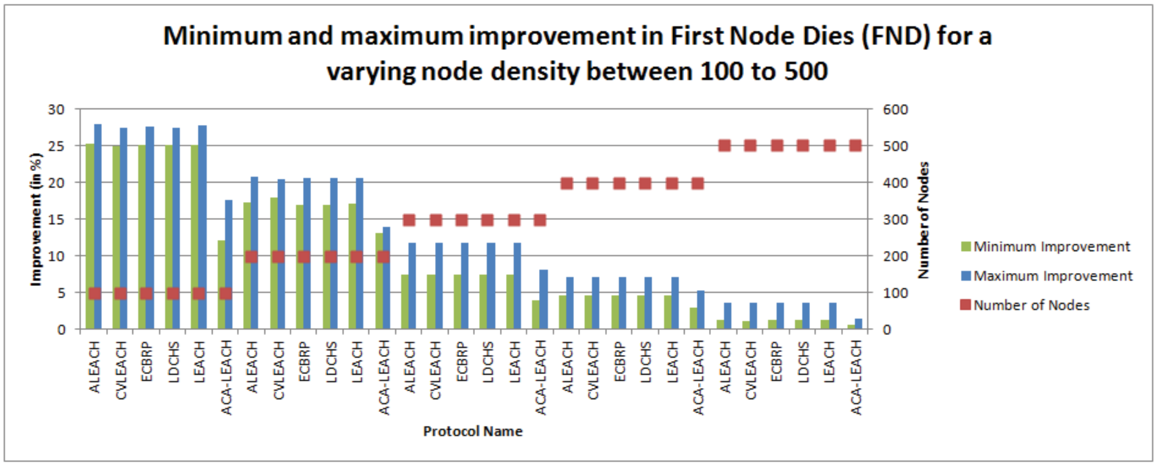


Figure 5.8: Minimum and Maximum percentage of improvement in First Node Dies (FND) for varying node density between 100 to 500 nodes with initial energy 10 Joules/Node

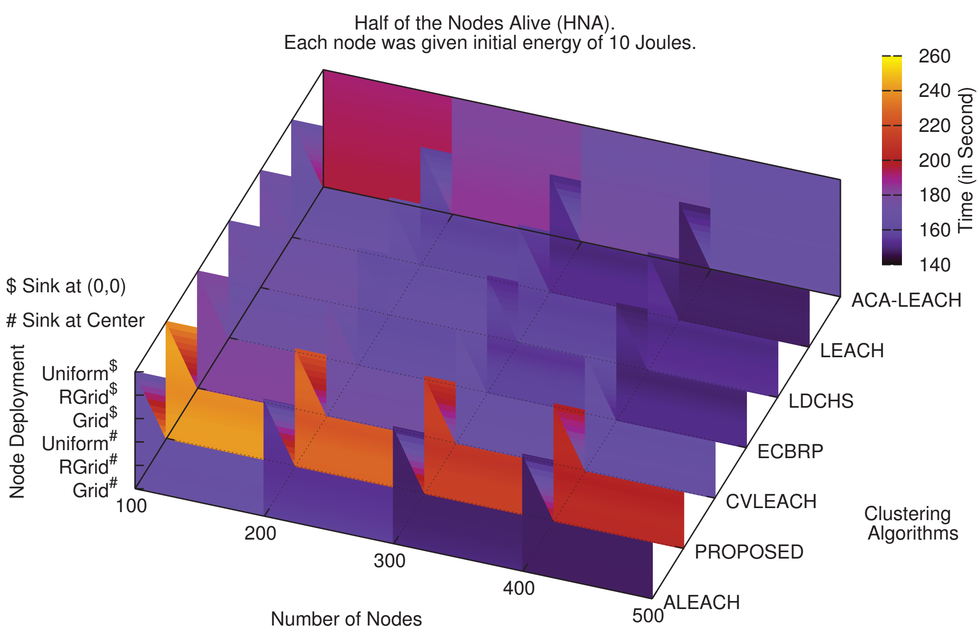


Figure 5.9: Half of the Nodes Alive (HNA) for varying node density between 100 to 500 nodes with initial energy 10 Joules/Node

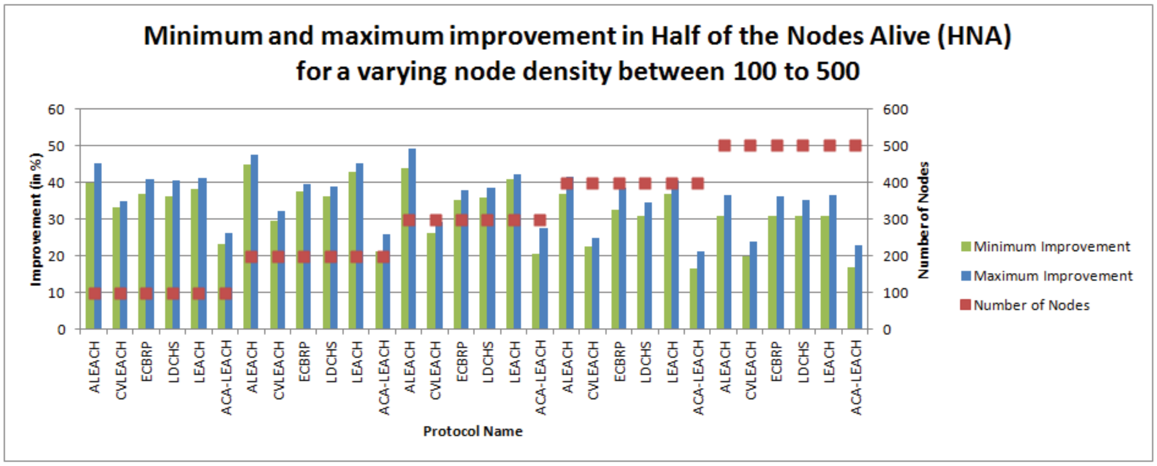


Figure 5.10: Minimum and Maximum percentage of improvement in Half of the Nodes Alive (HNA) for varying node density between 100 to 500 Nodes with initial energy 10 Joules/Node

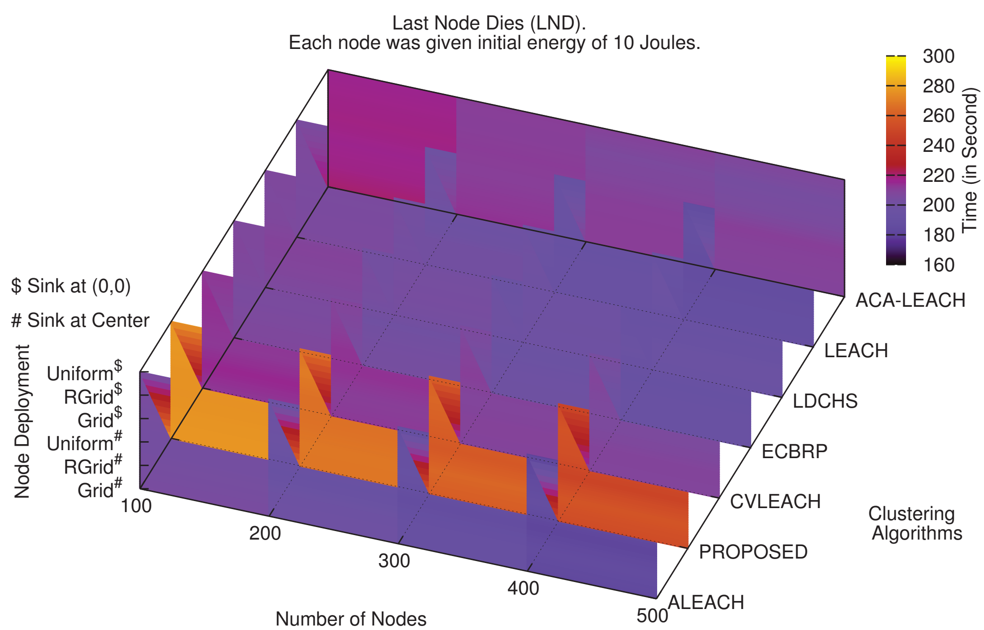


Figure 5.11: Last Node Dies (LND) for varying node density between 100 to 500 nodes with initial energy 10 Joules/Node

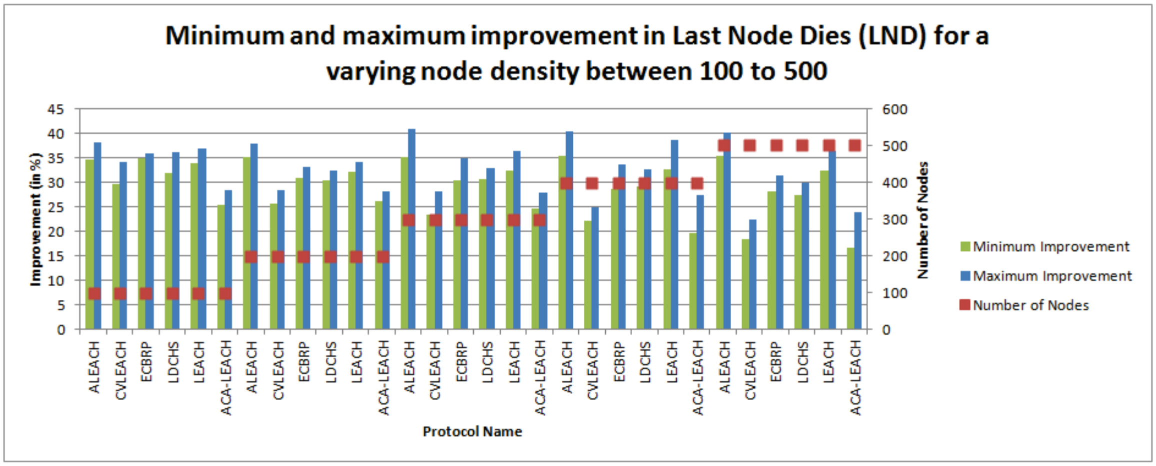


Figure 5.12: Minimum and Maximum percentage of improvement in Last Node Dies (LND) for varying node density between 100 to 500 Nodes with initial energy 10 Joules/Node

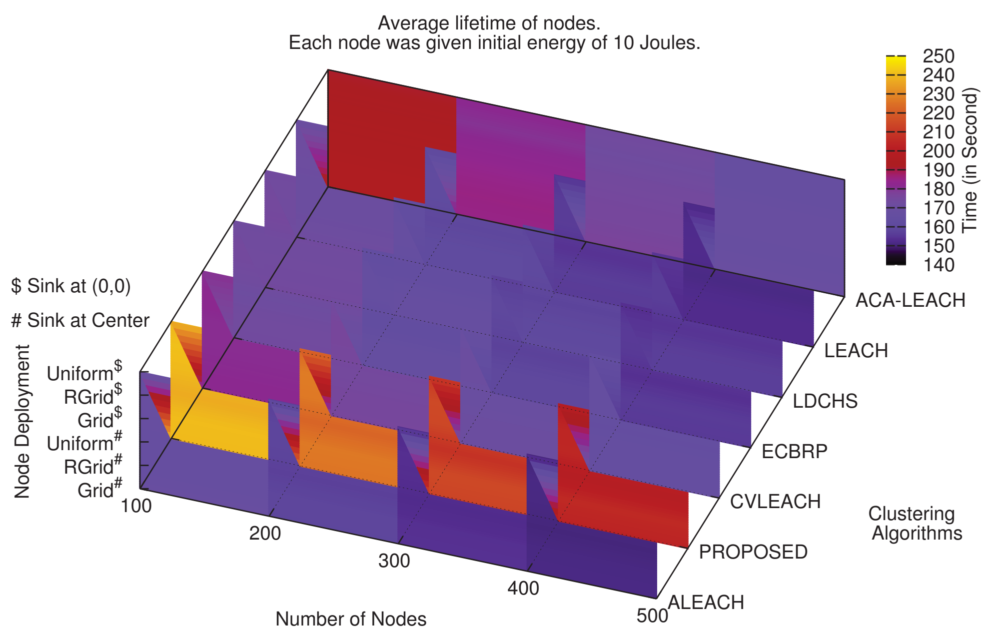


Figure 5.13: Average lifetime of a node for varying node density between 100 to 500 nodes with initial energy 10 Joules/Node

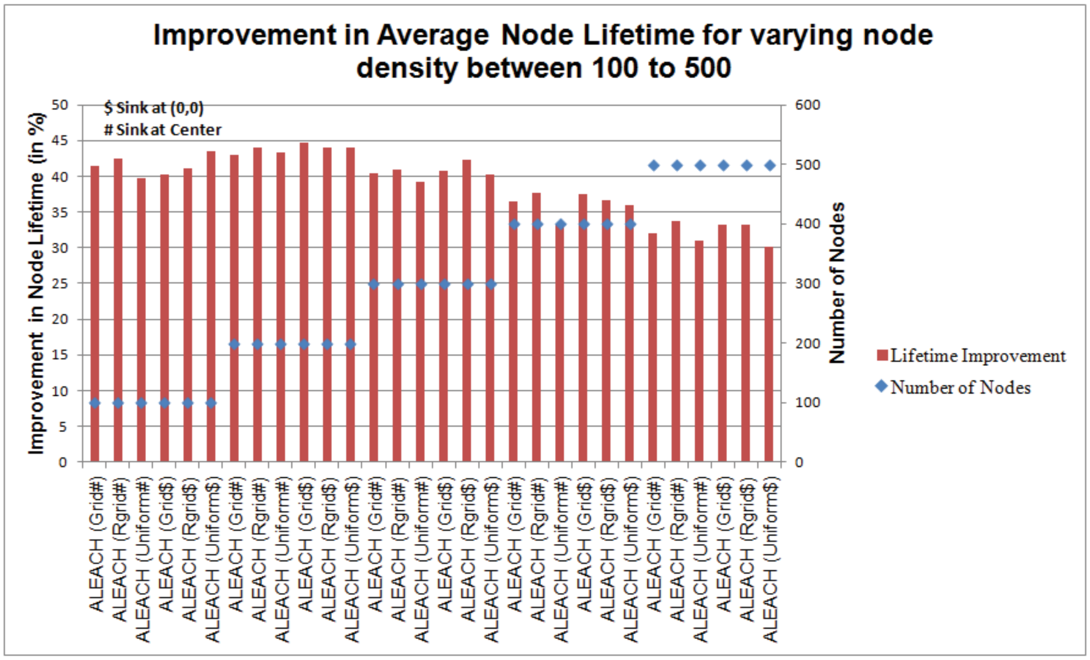


Figure 5.14: Improvement in the Average lifetime of a node compared to ALEACH for varying node density between 100 to 500 nodes with initial energy 10 Joules/Node

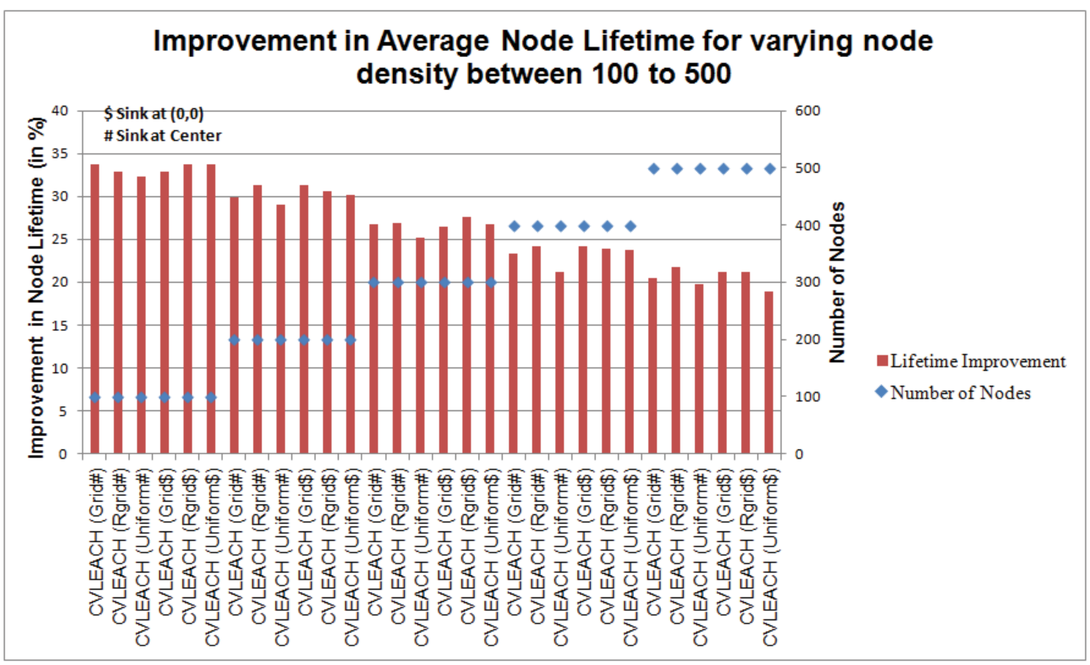


Figure 5.15: Improvement in the Average lifetime of a node compared to CVLEACH for varying node density between 100 to 500 nodes with initial energy 10 Joules/Node

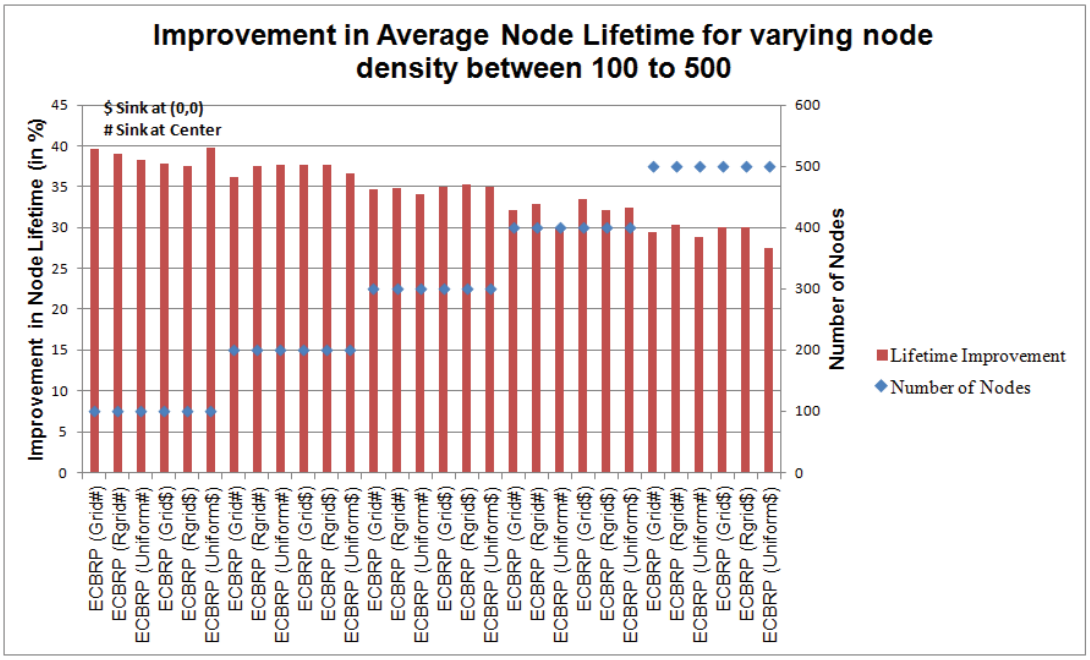


Figure 5.16: Improvement in the Average lifetime of a node compared to ECBRP for varying node density between 100 to 500 nodes with initial energy 10 Joules/Node

5.2.3.2 Simulation Strategy

This chapter focuses on three major points while comparing the proposed approach with other state-of-the-art clustering algorithms: i) Simplicity and speed of the algorithm to elect cluster heads ii) Improvement in the network lifetime of a WSN measured by the First Node Dies (FND), Half of the Nodes Alive (HNA) and Last Node Dies (LND) (Zheng and Jamalipour Tan and Körpeolu Demers et al. Yang, Wu, and Chen Khulbe, Srivastava, and Jain) and energy reduction per node and iii) Packet Reception Rate (PRR), which is a measure of the number of packets received successfully (Zuniga and Krishnamachari).

5.2.3.2.1 Simplicity and Speed of the proposed algorithm

Some standard measure is needed to compare the simplicity and speed of the algorithm between ALEACH, the proposed approach, CVLEACH, ECBRP, LDCHS, LEACH and ACA-LEACH, as all these algorithms use different approach to elect cluster heads. Message complexity and time complexity is used as a standard measure to check the speed and simplicity of the algorithm. A node can be elected as CH or a member node within maxSleep time, because the CH announcement by any node can

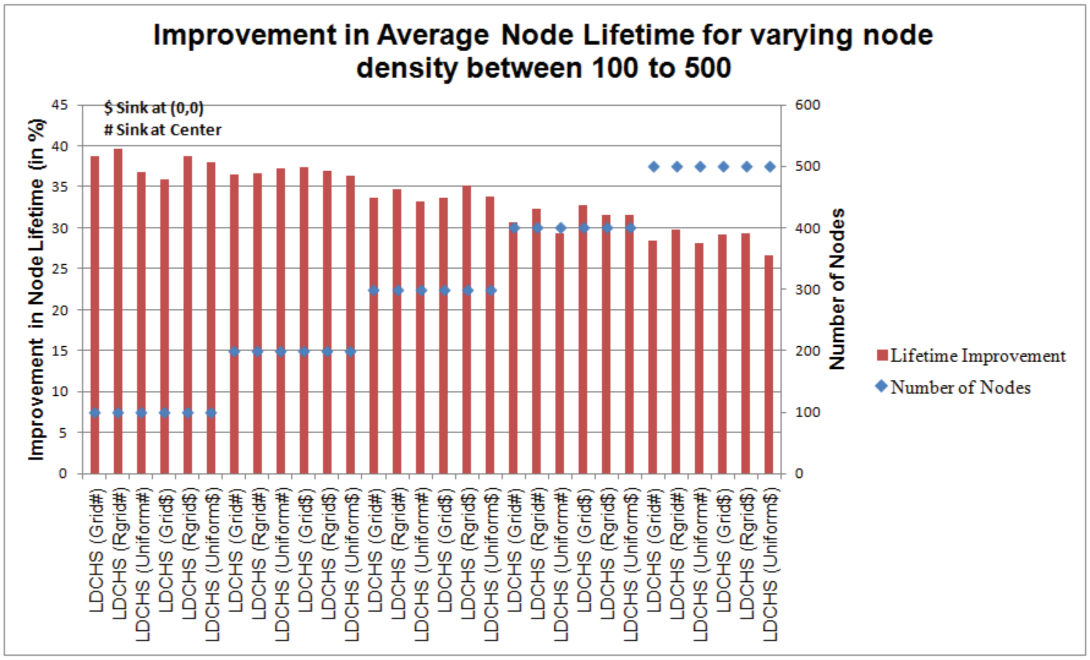


Figure 5.17: Improvement in the Average lifetime of a node compared to LDCHS for varying node density between 100 to 500 nodes with initial energy 10 Joules/Node

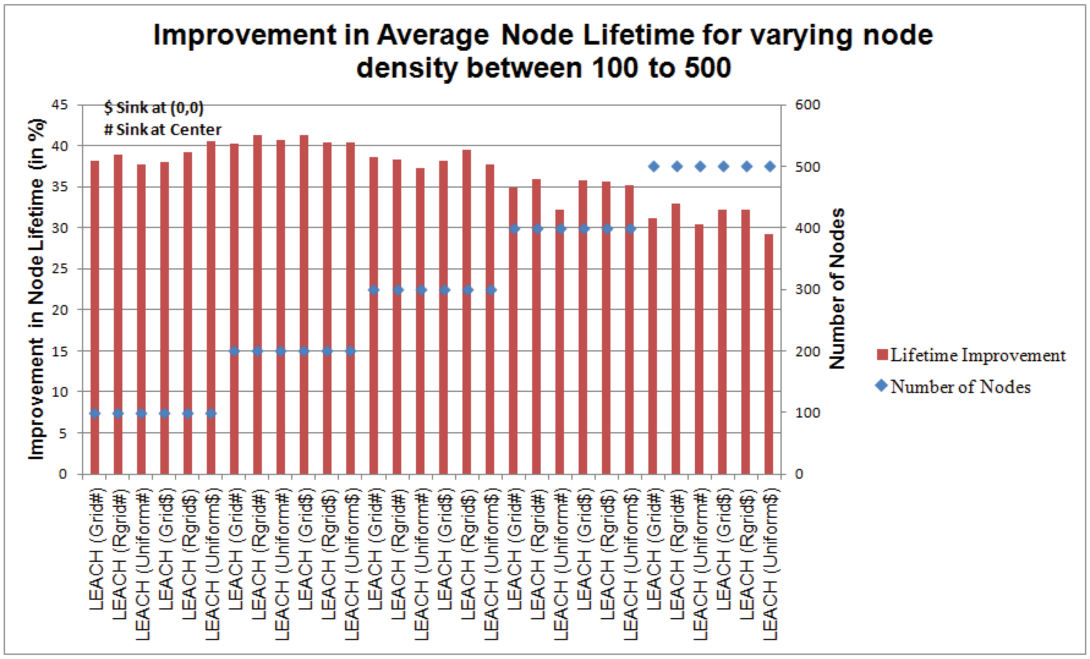


Figure 5.18: Improvement in the Average lifetime of a node compared to LEACH for varying node density between 100 to 500 nodes with initial energy 10 Joules/Node

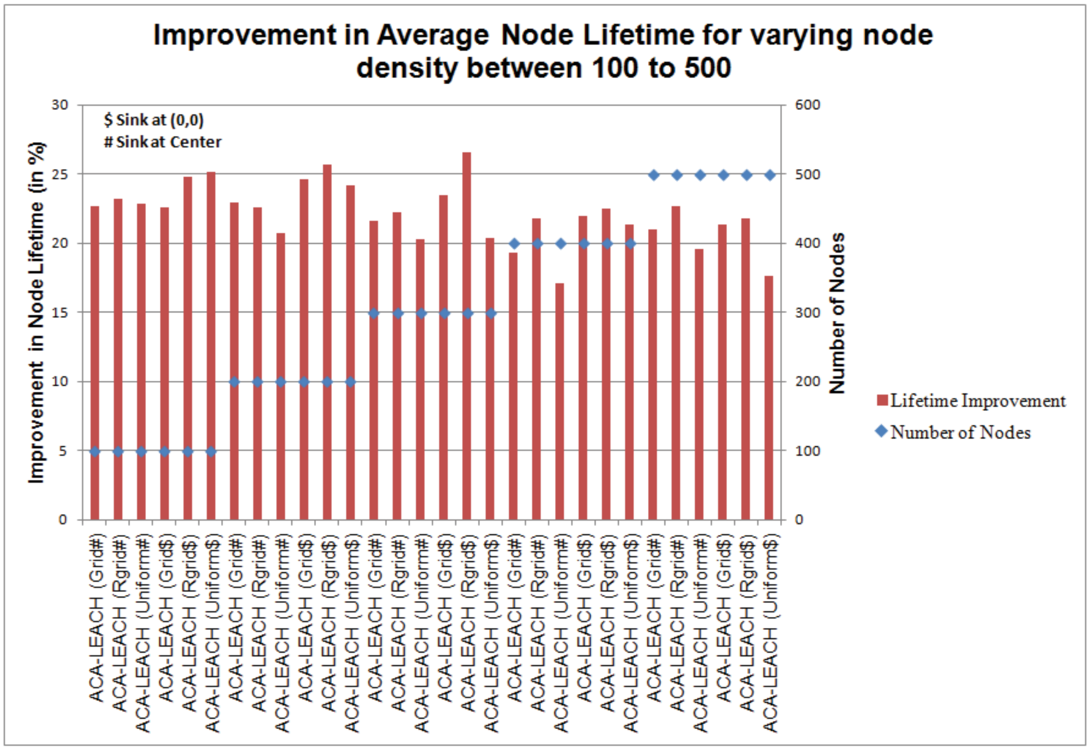


Figure 5.19: Improvement in the Average lifetime of a node compared to ACA-LEACH for varying node density between 100 to 500 nodes with initial energy 10 Joules/Node

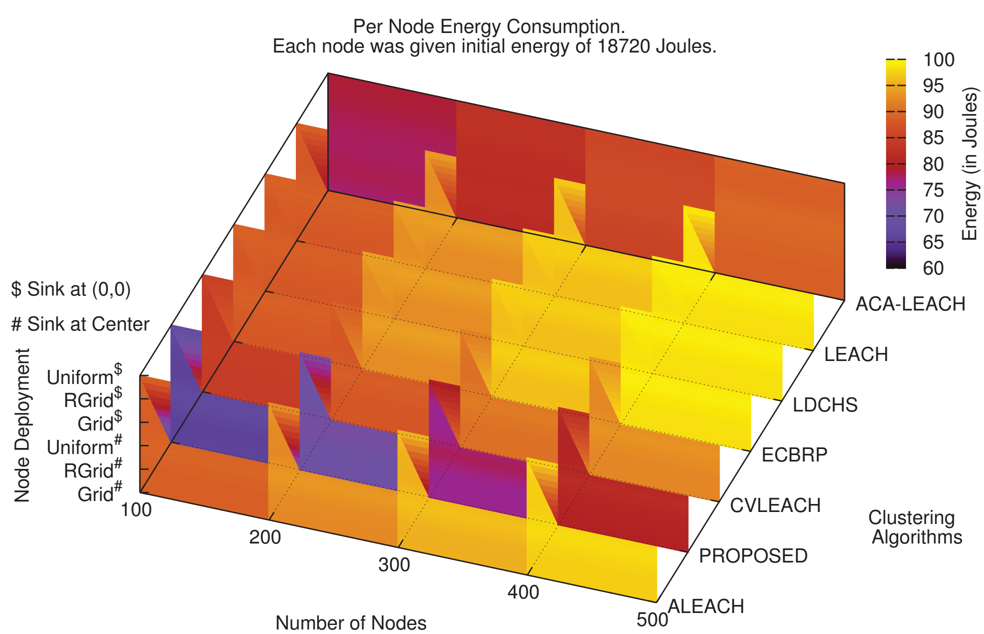


Figure 5.20: Average energy consumption of a node for varying node density between 100 to 500 nodes with initial energy 18720 Joules/Node

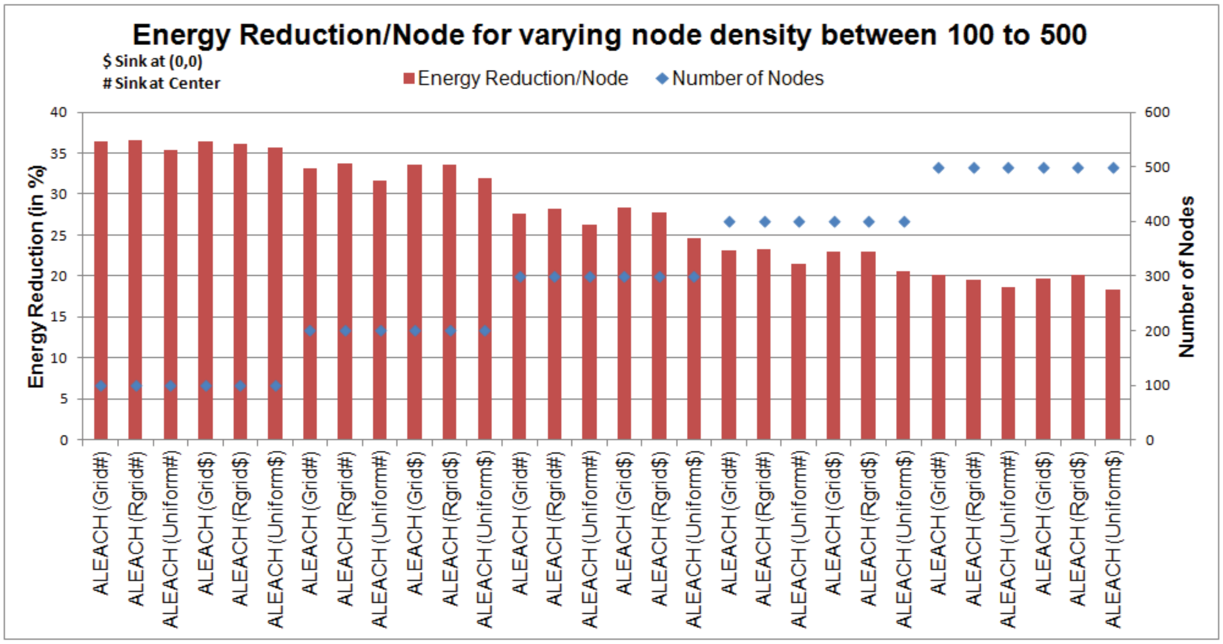


Figure 5.21: Percentage of Energy Reduction/Node compared to ALEACH for varying node density between 100 to 500 nodes with initial energy 18720 Joules/Node

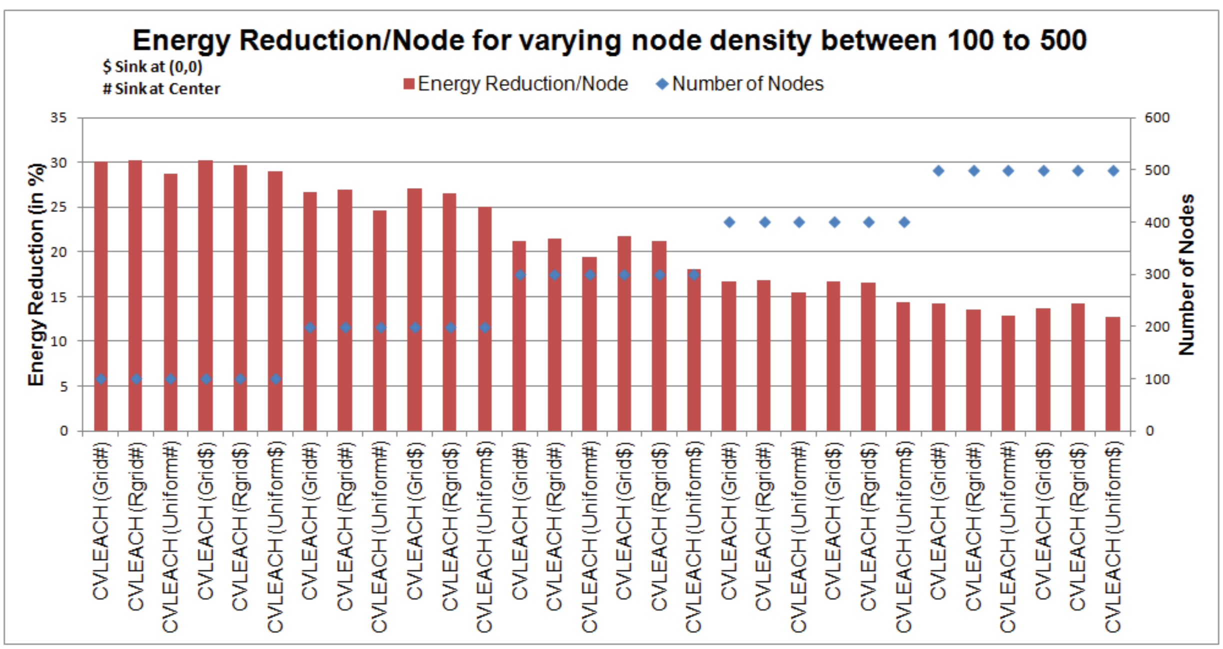


Figure 5.22: Percentage of Energy Reduction/Node compared to CVLEACH for varying node density between 100 to 500 nodes with initial energy 18720 Joules/Node

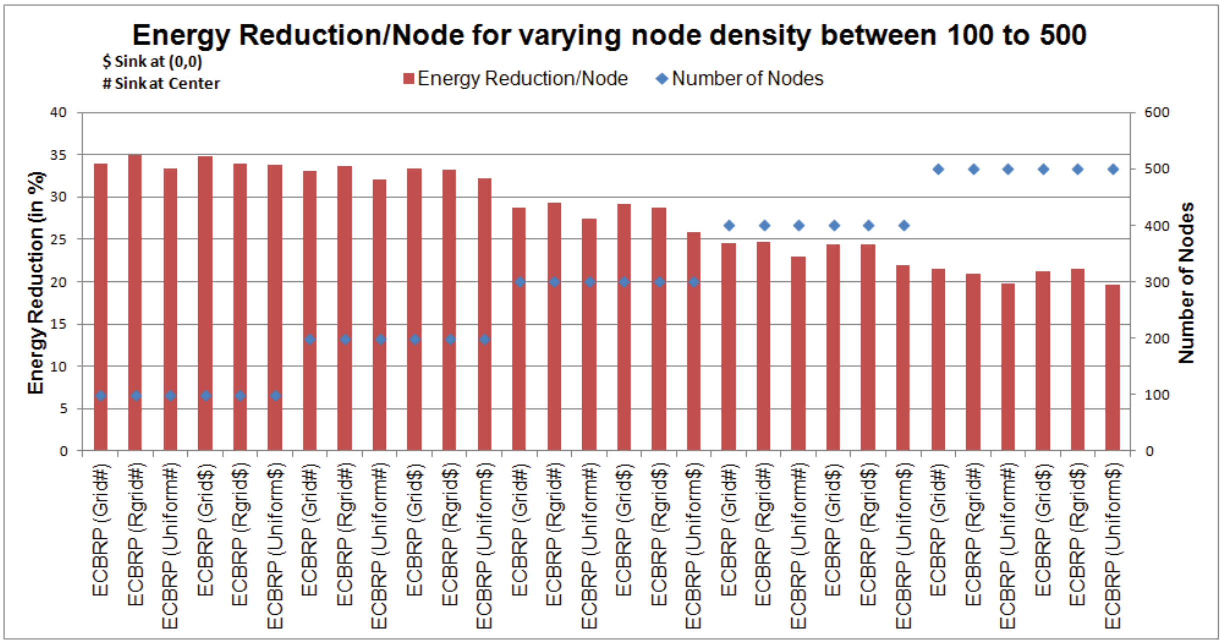


Figure 5.23: Percentage of Energy Reduction/Node compared to ECBRP for varying node density between 100 to 500 nodes with initial energy 18720 Joules/Node

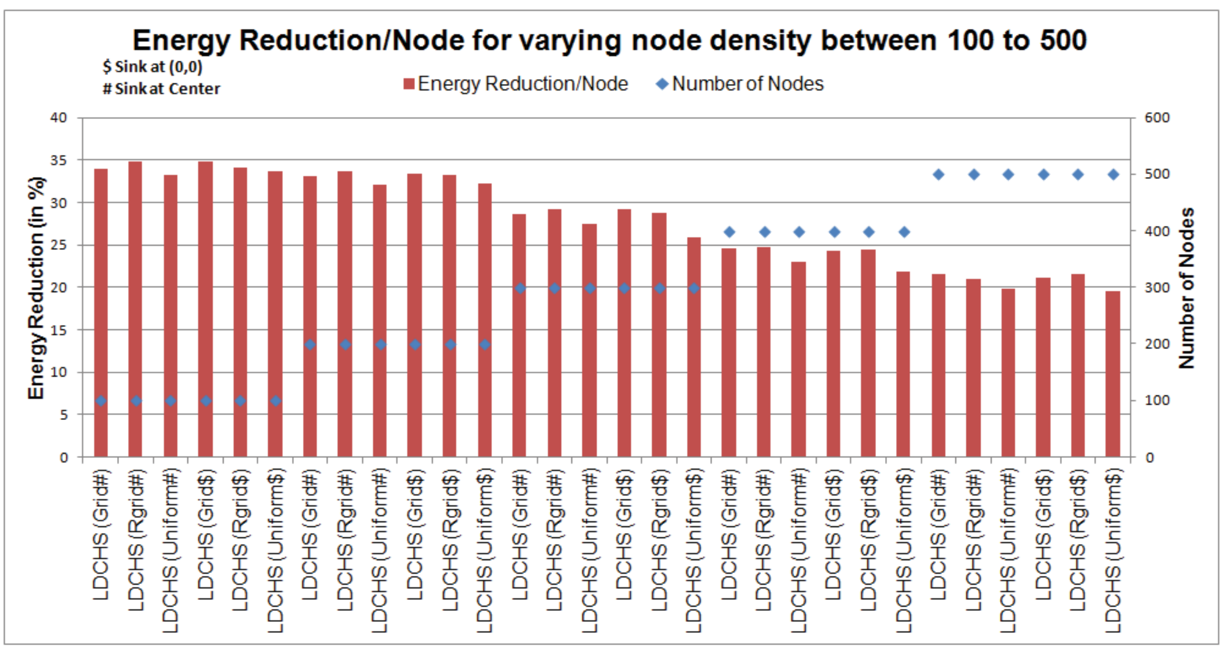


Figure 5.24: Percentage of Energy Reduction/Node compared to LDCHS for varying node density between 100 to 500 nodes with initial energy 18720 Joules/Node

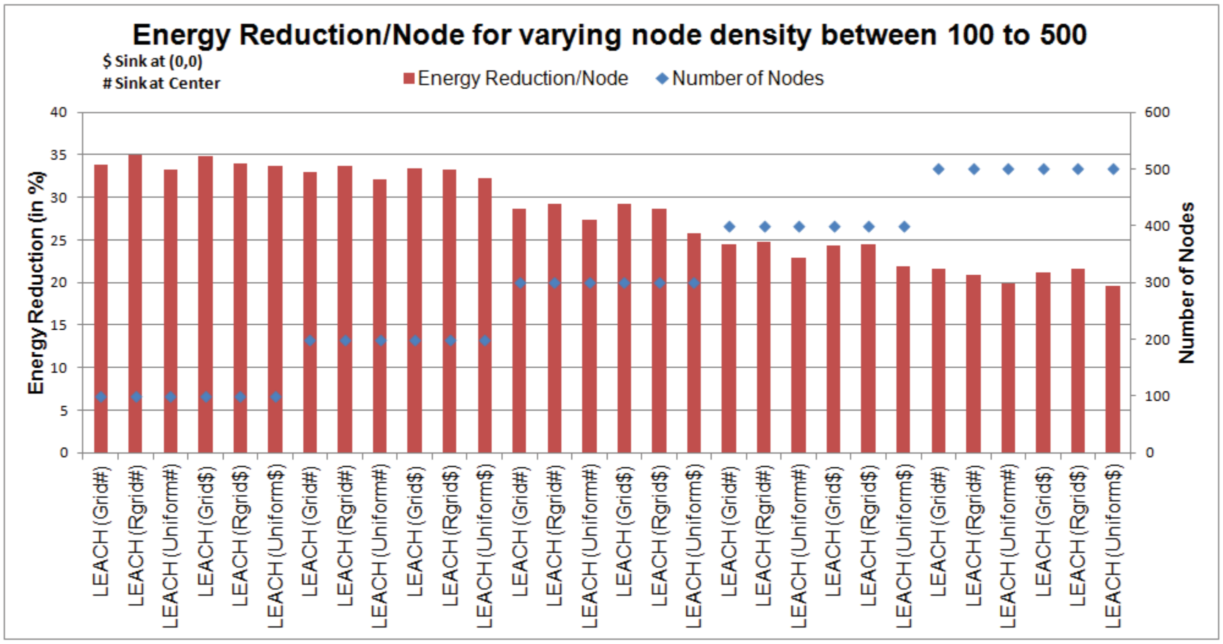


Figure 5.25: Percentage of Energy Reduction/Node compared to LEACH for varying node density between 100 to 500 nodes with initial energy 18720 Joules/Node

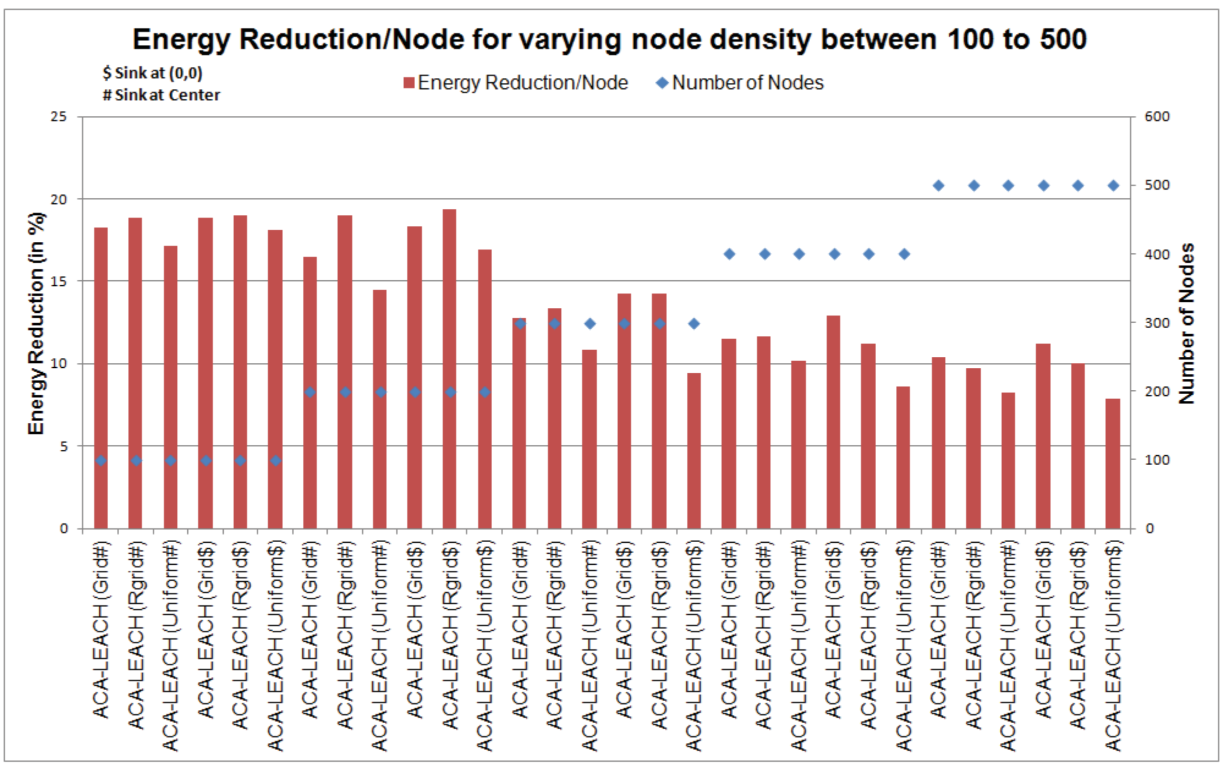


Figure 5.26: Percentage of Energy Reduction/Node compared to ACA-LEACH for varying node density between 100 to 500 nodes with initial energy 18720 Joules/Node

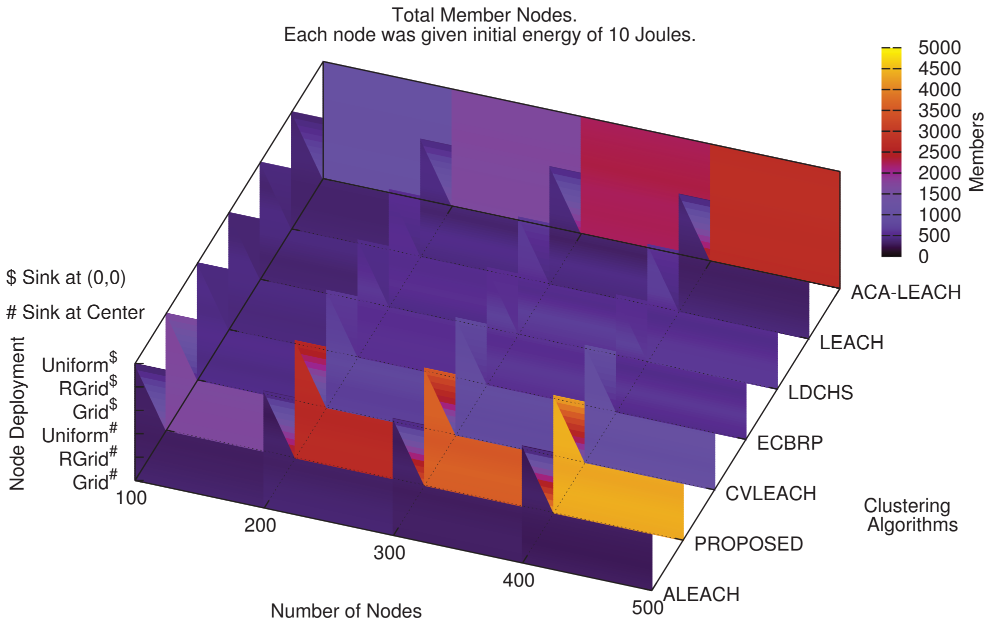


Figure 5.27: Total Member Nodes for varying node density between 100 to 500 nodes with initial energy 10 Joules/Node

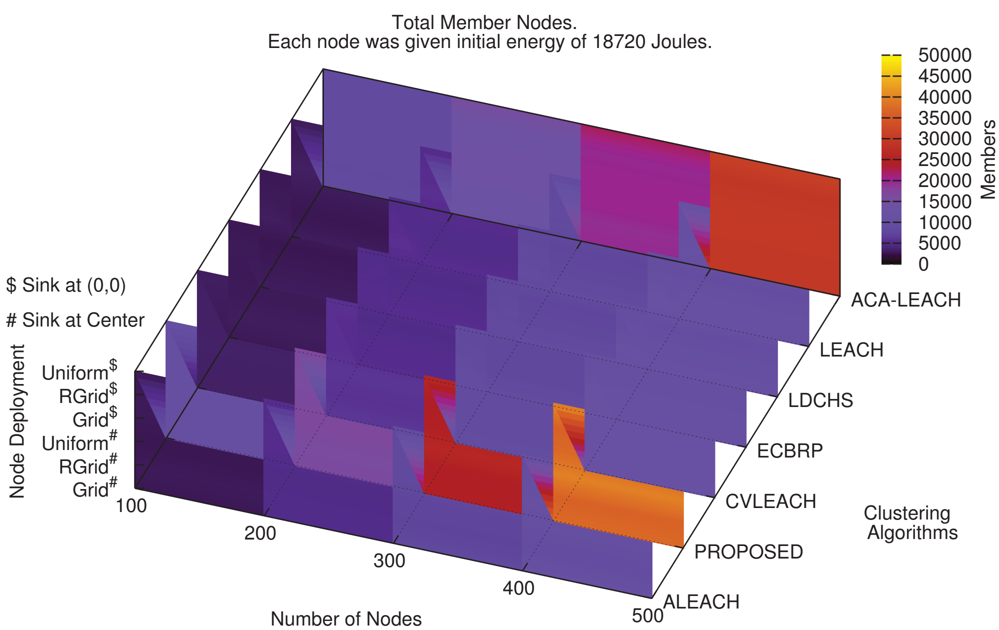


Figure 5.28: Total Member Nodes for varying node density between 100 to 500 nodes with initial energy 18720 Joules/Node

be done within waitTime interval which is given by Equation 5.7. Hence, the time complexity of the proposed algorithm is $O(1)$ as maxSleep is a constant and does not depend on node density. In the proposed approach, to elect the cluster head from a group of n neighboring nodes only one message is required and the number of clusters can be created dynamically depends on the current scenario. At any point of time, if there are m clusters of n nodes where $m*n$ makes total alive nodes N in the network, then tight lower bound on message complexity can be given by $\theta(m)$ and tight upper bound on message complexity can be given by $\theta(m*n)$.

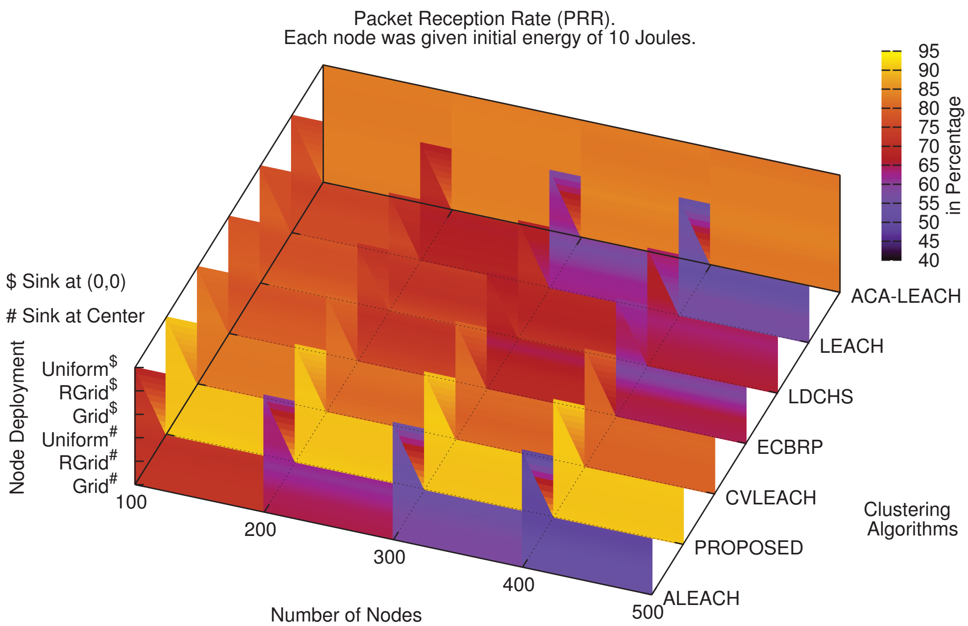


Figure 5.29: Packet Reception Rate (PRR) in percentage for varying node density between 100 to 500 Nodes with initial energy 10 Joules/Node

5.2.3.2.2 Network Lifetime

Network lifetime is measured in the form of First Node Dies (FND), Half of the Nodes Alive (HNA) and Last Node Dies (LND) (Zheng and Jamalipour Tan and Körpeolu Demers et al. Yang, Wu, and Chen Khulbe, Srivastava, and Jain). FND is also referred as a stability period (Smaragdakis, Matta, and Bestavros). The proposed approach selects a node as a cluster head, which has shortest wait time in its vicinity and also the ratio of its energy and the maximum energy that it has received is less than $(1 + Th(n))$ or a node has not received any CH announcement

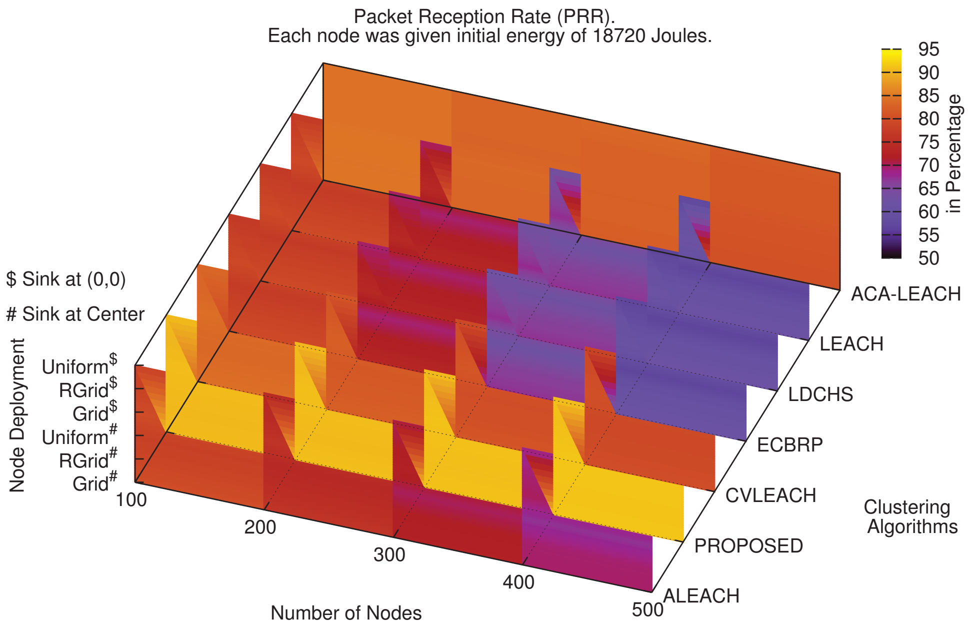


Figure 5.30: Packet Reception Rate (PRR) in percentage for varying node density between 100 to 500 Nodes with initial energy 18720 Joules/Node

before the expiration of its *forcedCH* timer. The proposed approach also creates non-overlapping clusters to cover more member nodes. Hence, more number of nodes are activated for a short duration and remain in the sleep state for a long duration to save their energy. This helps to increase the lifetime of the network.

ALEACH, the proposed approach, CVLEACH, ECBRP, LDCHS, LEACH and ACA-LEACH algorithms are simulated by varying node density between 100 to 500 nodes with initial energy 10 Joules/Node in the simulation area of 100m x 100m with three different node deployment criteria as mentioned in Table 5.3 and two different positions of the sink. Each simulation was run for 1500 seconds. Since all seven algorithms used for comparison are stochastic in nature, the results of two successive runs usually do not match. Hence, 10 independent runs are taken (with different seeds of the random number generator) for each algorithm and different node deployment and node density. The results have been stated in terms of the mean values over 10 runs for each case to calculate time duration after which First Node Dies (FND), time duration after which Half of the Nodes Alive (HNA) and time duration after which Last Node Dies (LND). Simulation results for FND, HNA and LND is shown in Figures 5.7,5.9, and 5.11 respectively. The minimum and maximum percentage of improvement in FND, HNA and LND is shown in Figures 5.8 ,5.10 and 5.12 respectively. It is concluded from the Figures 5.8,5.10 and 5.12, that improvement in FND, HNA and LND is between 0.63% and 27.87%, between 16.5% to 49.19% and between 16.62% and 40.9% respectively for varying node density between 100 to 500 nodes compared to ALEACH, CVLEACH, ECBRP, LDCHS, LEACH and ACA-LEACH protocols. An average lifetime of a node is also measured and is shown in Figure 5.13. The percentage of improvement in the average node lifetime due to the proposed approach with respect to prevalent ones are shown in the Figure 5.14-5.19. It can be concluded that the proposed approach improves average node lifetime between 17.12% to 44.68% for varying node density between 100 to 500 nodes compared to ALEACH, CVLEACH, ECBRP, LDCHS, LEACH and ACA-LEACH. An initial energy of 18720 Joules (18720 Joules is equivalent to two AA size batteries ("Energy for AA batteries")) is given to each node and repeated simulations to find the average energy consumption per node. The results for the same is shown in Figure 5.20. As shown in Figures 5.21-5.26, the proposed approach reduces average energy consumption per node between 18.30% and 36.63% compared to Advanced LEACH Routing Protocol for Wireless Microsensor Networks (ALEACH), 12.67% and 30.26% compared to Coverage based energy efficient LEACH algorithm (CVLEACH), 19.58% and 34.93% compared to An Enhanced Cluster Based Routing Algorithm for Wireless Sensor (ECBRP), 19.60% and 34.87% compared to Low energy adaptive clustering hierarchy with deterministic cluster-head selection (LDCHS), 19.60% and 34.93% compared to Low Energy Adaptive Clustering Hierarchy (LEACH) and 7.85% and 19.37% compared to An Ant Colony Clustering Routing Algorithm for Wireless Sensor Networks (ACA-LEACH) algorithms. The major factor that gives the improvement in FND, HNA, LND, network lifetime and energy conservation is large number of member nodes covered by the CHs as shown in Figures 5.27 and 5.28 for the network with initial energy of 10 Joules/Node and 18720 Joules/Node respectively.

5.2.3.2.3 Packet Reception Rate

Packet Reception Rate (PRR) is another important parameter because maximum information must be received by the sink node. If the algorithm is energy efficient, but could not provide enough information to the sink, it is of no use. %PRR with a different configuration with initial energy 10 Joules/Node and 18720 Joules/Node (18720 Joules is equivalent to two AA size batteries ("Energy for AA batteries")) is shown in Figure 5.29 and 5.30 respectively. As can be seen from the results that %PRR of the proposed approach is more than 91% where others can have between 58% to 90.532%. Hence, the proposed approach is able to provide more accurate information to the sink compared to other algorithms used for comparison. It can be seen that there is a noticeable decrease in %PRR for ALEACH, CVLEACH, ECBRP, LDCHS and ALEACH algorithms as node density increases, while minor variations are observed for ACA-LEACH.

5.3 Summary

Optimal cluster formation according to different parameters like node density, current energy level, the position of the sink and other sensor nodes is proven to be NP-hard (de Oliveira Matos et al.). It is difficult to design and analyze a routing algorithm which gives the best route for a given criteria in polynomial time. The MT-ANT algorithm presented in this chapter uses cross-layer architecture along with ACO to improve CH election scheme in WSN using RSSI and LQI values. The CC2420 radio measures RSSI and LQI values with no additional overhead. The MT-ANT is the extension of T-ANT clustering algorithm. It is distributed, energy efficient and increases PRR. Simulation results show that it outperforms to T-ANT.

Later, a new cluster head election scheme is proposed based on the energy threshold value and *forced CH* scheme. The proposed approach gives better solution when compared with other prevalent ones like ALEACH, CVLEACH, ECBRP, LDCHS, LEACH and ACA-LEACH. The presented algorithm is distributed, provides scalability and sustain with varying conditions of a WSN as far as speed, simplicity, network lifetime and PRR is concerned. The proposed approach improves average node lifetime between 17.12% to 44.68% for varying node density between 100 to 500 nodes compared to ALEACH, CVLEACH, ECBRP, LDCHS, LEACH and ACA-LEACH.

The next chapter discusses the Concentric Circle approach for the cluster head election in Wireless Sensor Networks. The effect of standard deviation in the number of cluster heads on the network lifetime is also manifested in the next chapter.

Chapter 6

Concentric Circle Approach for Cluster Head Election in Wireless Sensor Networks

Network longevity for WSNs is achieved through cluster based routing scheme as it reduces the effective communication distance by routing packets through elected CHs and minimizing number of messages exchanged between nodes. Also, load balancing is achieved by rotating role of CHs. However, the approaches discussed in the Chapter 2 are stochastic in nature. Hence, the size of the clusters are different because of number of CHs varies during each round. Also, from the results presented in the Chapter 3, it can be concluded that most of the algorithms are unable to maintain the desired number of CHs per round except S-LEACH (Thakkar and Kotecha, “S-LEACH: A Sequential selection approach to elect cluster heads for LEACH protocol”). However, the S-LEACH suffers by the selfishness of member nodes as they select the nearest node as CH from the set of CHs to save their own energy. Hence, there is a need to maintain the desired number of cluster heads to achieve uniform load distribution between cluster heads along with the near uniform size of the clusters. Also, the algorithms presented in the Chapter 2 do not consider node density while electing a cluster head. In addition to that LEACH (Heinzelman, Chandrakasan, and Balakrishnan, “Energy-efficient communication protocol for wireless microsensor networks”) and the protocols designed by extending LEACH, ensures that each node must be a cluster head for exactly once in every $\frac{1}{p}$ rounds and it remains constant even though the number of alive nodes reduces over a period of time. In this chapter, a concentric circle approach is proposed, to elect the cluster heads for the clustered routing algorithm, that helps to prolong the network lifetime. The proposed approach dynamically selects radius of concentric circles. Also, node density is considered while computing radius of the concentric circle. In addition, the length of the movement of concentric circles is controlled by the maximum distance between alive node and the sink. During a particular round, a set of nodes that falls in the region between two concentric circles are the probable candidates to become cluster heads.

6.1 Concentric Circle approach for cluster head election

6.1.1 The formation of Concentric Circle

To form concentric circles, one needs to identify the center and radius of the circles. In the proposed approach, BS or sink will work as a center of concentric circles and radius is calculated based on the node density, given by Equation 6.1. This equation ensures that as node density increases, radius difference between two concentric circles decreases. This can be easily seen from the Equation 6.1. If the node deployment area is kept constant and increases total nodes, then node density increases; and effective radius for concentric circles decreases. If the node deployment area is decreased for a given number of nodes, then also node density increases; and effective radius decreases.

$$Radius = \sqrt{\frac{Area(Node\_Deployment)}{totalNodes}} \tag{6.1}$$

To create concentric circles during the first round, the outer circle is created with a radius $Radius_{outer}$ which is greater or equal to the network diameter, i.e. the maximum distance between the sink and any point in the node deployment area, and it is evenly divisible by Radius, given by Equation 6.1; and inner circle has the radius $Radius_{inner}$ as given by Equation 6.2.

$$Radius_{inner} = Radius_{outer} - Radius \tag{6.2}$$

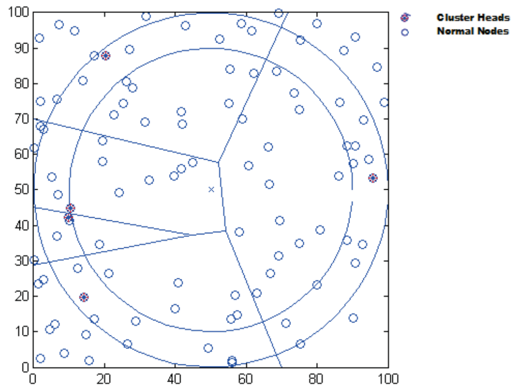
In the next subsequent rounds, $Radius_{outer}$ takes the value of $Radius_{inner}$ and after that $Radius_{inner}$ is reinitialized with the new value as per the Equation 6.2 i.e. with every round, both circle moves towards the sink as shown in Figures 6.1a- 6.1f. This process continues until $Radius_{outer}$ attains the value of $Radius$ (Equation 6.1). The entire process of movement of concentric circles towards the sink from the farthest alive node is repeated when either entire region containing alive nodes is covered by concentric circles or all alive nodes become cluster head exactly once. When region scan is completed by concentric circles, radius of the outer circle is set in such a way that it covers the farthest alive node from the sink. $Radius_{inner}$ always gets a value obtained by Equation 6.2. The formation of concentric circles and cluster regions during rounds 3, 4 and 5 are shown in Figures 6.1a- 6.1f.

6.1.2 Number of Cluster Heads during a round

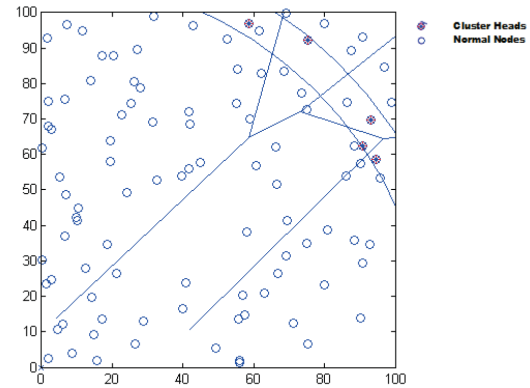
In this chapter, the proposed approach is compared with LEACH, LDCHS and ALEACH protocols, and thus expected number of Cluster Heads for the proposed approach is set to 5% of the total nodes as it gives optimal performance to the LEACH protocol (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks"). Also, to compare the proposed approach with E-LEACH, percentage of CH is set to $\frac{K_{opt}}{n}$ given by Equation 2.25. However, for the proposed approach, maximum number of cluster heads during each round is the minimum of two values: i) number of nodes in a probable set of cluster heads during a round and ii) expected number of cluster heads during each round.

6.1.3 Energy Consideration of a Node

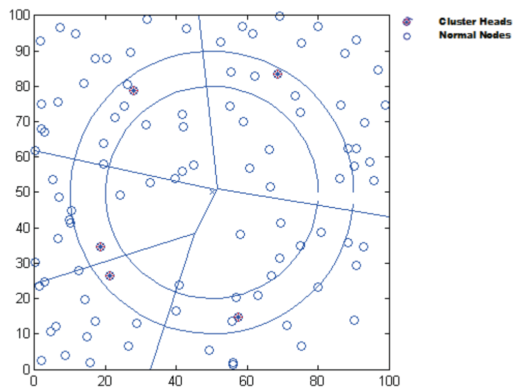
During a particular round, if all nodes within the region between two concentric circles are eligible to be a cluster head; the node with maximum energy is elected as a cluster head. Each eligible node, which is able to be cluster head during a particular round, waits for $WaitTime_i$ before making a cluster head announcement; where $WaitTime_i$ is given by Equation 6.3. This process continues until the desired number of cluster heads are elected or all nodes within a region between Concentric Circles become cluster heads. If more than one node has the same amount of energy, then the node with highest (or lowest) node id is elected as a cluster head. This is possible during



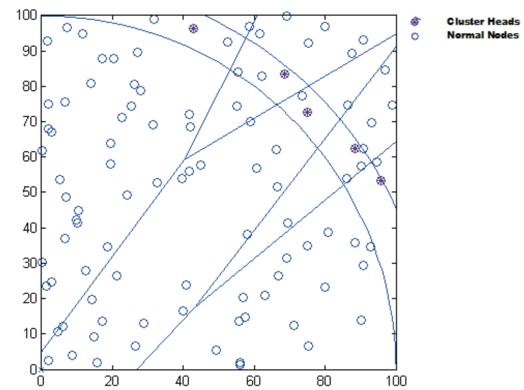
(a) Concentric Circles during round 3 sink at center



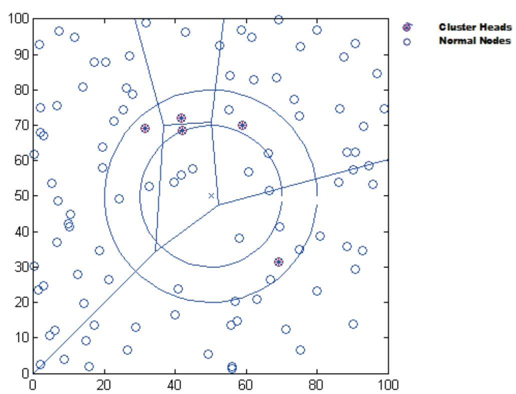
(b) Concentric Circles during round 3 sink at corner



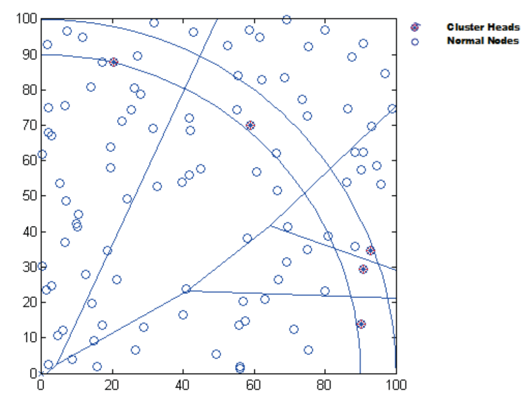
(c) Concentric Circles during round 4 sink at center



(d) Concentric Circles during round 4 sink at corner



(e) Concentric Circles during round 5 sink at center



(f) Concentric Circles during round 5 sink at corner

Figure 6.1: Formation of concentric circle and clusters for a network of 100 nodes uniformly distributed in an area of 100m x 100m. Sink is positioned at center and corner of the node deployment area. p is set to 5% in Equation 2.1

the early rounds of operations when all nodes are having the same amount of initial energy.

$$WaitTime_i = \frac{1}{Remaining\ Energy\ of\ Node_i};\ \text{if } Node_i \text{ is eligible to be a CH during round } r \tag{6.3}$$

6.2 Simulation Results and Analysis

6.2.1 Simulation Description

6.2.1.1 System Model

System model for the proposed approach is same as discussed on page 26. In addition to that, it is assumed that BS is available either at the center of the node deployment area or at corner, i.e. location (0,0).

6.2.1.2 Energy Model

The first order radio energy model is used for the simulation (see page 28).

6.2.1.3 Simulation Environment

Simulation is carried out in MATLAB. The code for the LEACH protocol is obtained from csr.bu.edu (Smaragdakis, Matta, and Bestavros). A total 108 simulation runs were executed, including 6 protocols (LEACH, LDCHS, ALEACH, e-LEACH, CC with p=5%, CC with p=$\frac{K_{opt}}{n}$), two different sink positions, three different initial energy levels and three different node densities. This helps in verifying the robustness of the proposed approach. Simulation parameters are shown in Table 6.1.

6.2.1.4 Performance Parameters

To compare concentric circle based approach with the prevalent ones, the following performance parameters are used.

- ***Network Lifetime:*** Network Lifetime is measured in terms of First Node Dies (FND), Half of the Nodes Alive (HNA) and Last Node Dies (LND), where LND refers to the time when 90% of the nodes die. It is treated as network failure (Qiu et al.).

- ***Number of Cluster Heads:*** LEACH gives optimal performance when num-

Parameter Name	**Value**
Node Deployment Area	100m X 100m
Number of Nodes (Excluding BS)	1) 50 2) 100 3) 200
Position of BS	1) (50,50) 2) (0,0)
Initial Energy/Node (in Joules)	1) 0.25 2) 0.5 3) 0.75
Simulation Stopping Criteria	maximum of 5000 rounds and death of 90% nodes
Transmitter Electronics ($E_{Tx-elec}$) Receiver Electronics ($E_{Rx-elec}$) ($E_{Tx-elec} = E_{Rx-elec} = E_{elec}$)	50 nJ/bit
Energy for Data Aggregation (EDA)	5 nJ/bit/message
Free Space (ϵ_{fs})	10 pJ/bit/m^2
Multi-path Fading (ϵ_{mp})	0.0013 pJ/bit/m^4
Packet Size	4000 bits
Percentage of Cluster Heads (for LEACH, LDCHS and ALEACH)	5% [1]
Percentage of Cluster Heads (for E-LEACH)	$\frac{K_{opt}}{n}$ (Equation 2.25)
Proposed Approach Compared with	1) LEACH [1] 2) LDCHS [2] 3) ALEACH [3] 4) e-LEACH [4]

[1] (Heinzelman, Chandrakasan, and Balakrishnan, “Energy-efficient communication protocol for wireless microsensor networks”)
[2] (Handy, Haase, and Timmermann)
[3] (Ali, Dey, and Biswas)
[4] (Randriatsiferana et al.)

Table 6.1: Parameters used for the simulation of the Concentric Circle approach

ber of cluster heads are 5% of the total nodes during each round. If more number of cluster heads are available during a round, then less data are available for aggregation; and if the less number of cluster heads is available during a round, then either it burdens the cluster heads or nodes are required to make long distance transmission. Both of these make higher energy drains to the cluster heads and member nodes. Hence, to achieve balanced energy consumption during each round, a good clustered routing algorithm should keep the stable expected number of cluster heads per round (Wang, Yang, and Sun).

- ***Energy:*** Minimizing average energy consumption per round helps to avoid premature death of nodes that helps to improve network longevity.

6.2.2 Network Lifetime

The network lifetime is measured using FND, HNA and LND. The maximum and minimum percentage of improvement in network lifetime for varying node density, initial energy and sink positions is shown in Table 6.2 The reason for getting improved network lifetime compared to LEACH, LDCHS, ALEACH and E-LEACH is the proposed Concentric Circle approach maintains the desired number of cluster heads during each round and the difference of relative distances of cluster heads with respect to sink is minimum. The percentage of improvement in FND, HNA and LND for varying node density, initial energy and sink position is shown in Figures 6.2-6.4. It can be observed from the figures that FND becomes poor with increased node density. However, the proposed approach outperforms for HNA and LND. It can also concluded that the proposed approach is sensitive to the sink position.

6.2.3 Number of Cluster Heads

The standard deviation in the number of cluster heads affects the average energy consumption per round and thus the network lifetime. The standard deviations in the number of CHs is shown in Figures 6.5-6.7. It can be concluded from the figures that the number of cluster heads are highly affected by node density. The variation in the number of cluster heads can be observed between 100% to 180% with an increase in node density. However, a negligible effect can be seen in standard deviation with the increase in the initial energy.

Total Nodes	**Sink Position**	**Parameter used to measure network lifetime**	**Minimum Improvement (in percentage)**	**Maximum Improvement (in percentage)**
50	(50,50)	FND	-55.80	51.61
		HNA	92.07	113.91
		LND	59.39	94.42
	(0,0)	FND	-56.88	27.44
		HNA	21.63	104.99
		LND	41.74	99.72
100	(50,50)	FND	-68.99	40.75
		HNA	126.79	155.97
		LND	160.06	184.66
	(0,0)	FND	-73.70	-15.01
		HNA	16.04	62.32
		LND	28.24	77.70
200	(50,50)	FND	-74.97	-15.12
		HNA	113.58	140.33
		LND	147.51	165.65
	(0,0)	FND	-76.81	-33.61
		HNA	12.52	91.75
		LND	74.62	122.11

Table 6.2: Maximum and minimum percentage of improvement in the network lifetime for varying node density, initial energy and sink positions

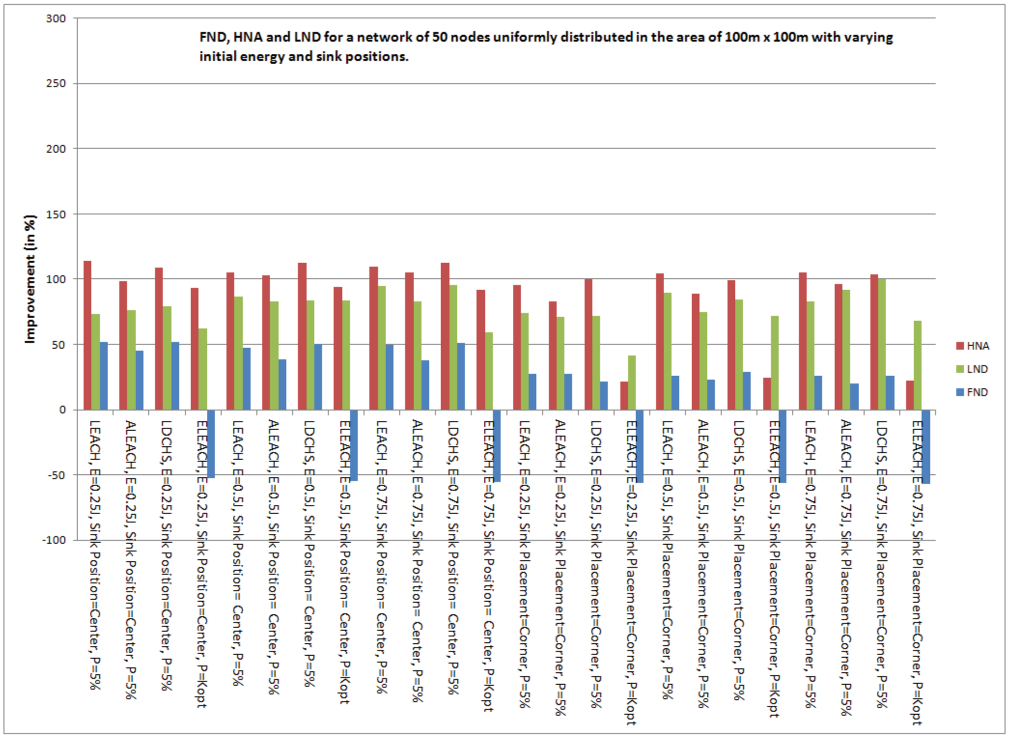


Figure 6.2: Percentage of improvement in FND, HNA and LND for a network of 50 nodes

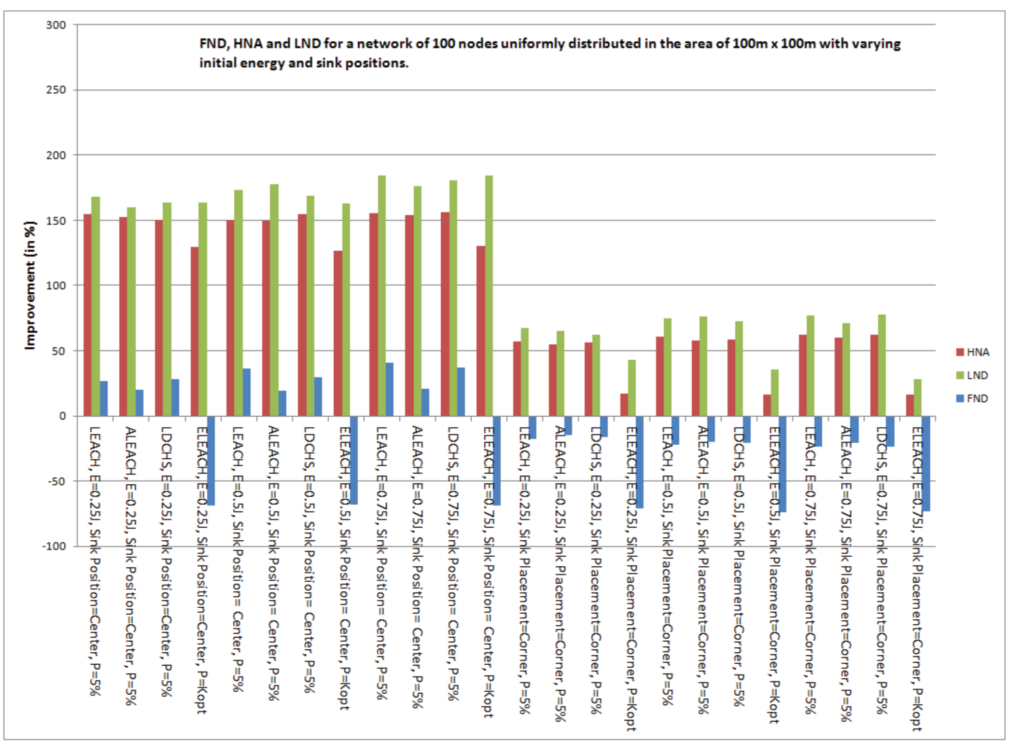


Figure 6.3: Percentage of improvement in FND, HNA and LND for a network of 100 nodes

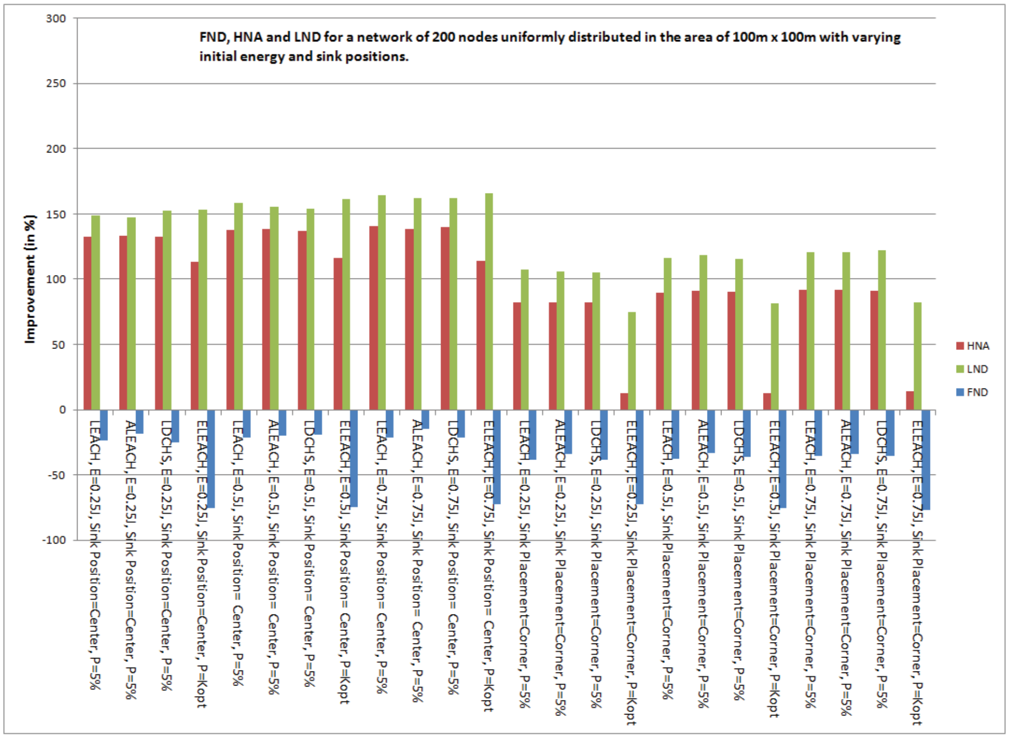


Figure 6.4: Percentage of improvement in FND, HNA and LND for a network of 200 nodes

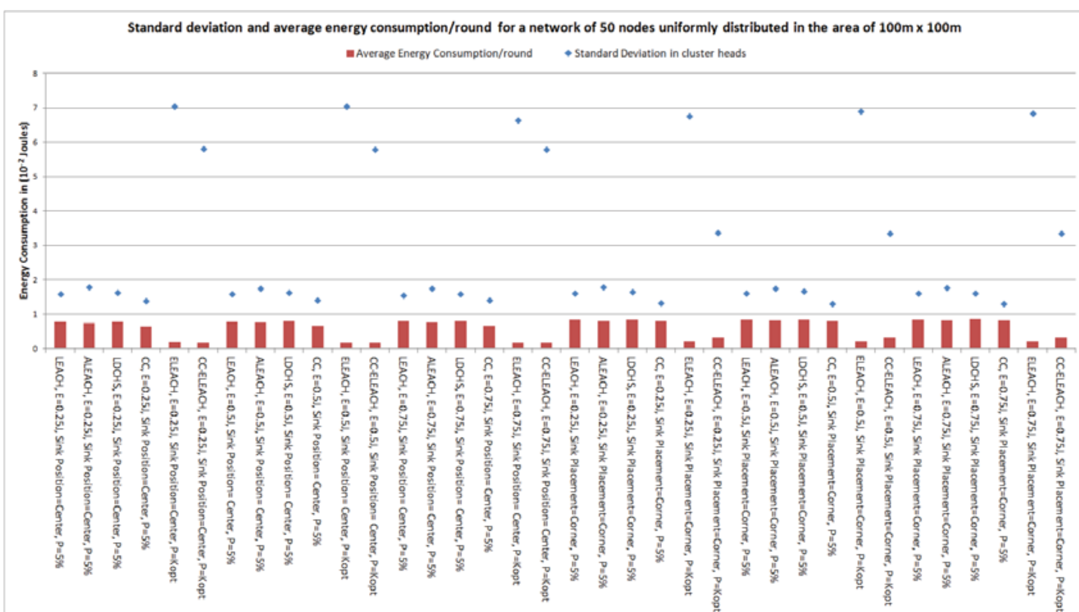


Figure 6.5: Effect of cluster heads on energy consumption/round for a network of 50 nodes

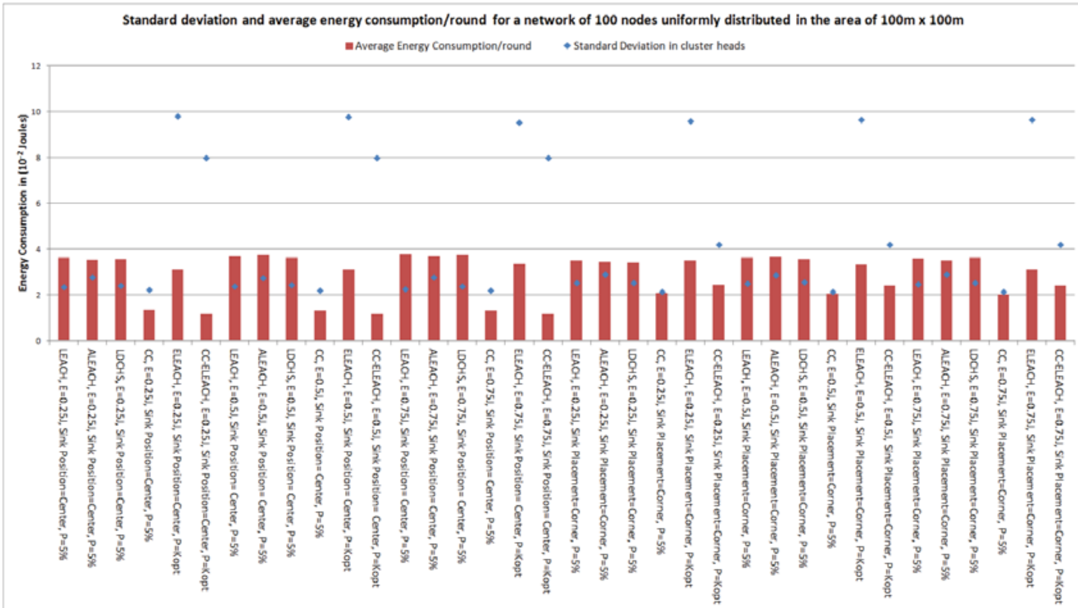


Figure 6.6: Effect of cluster heads on energy consumption/round for a network of 100 nodes

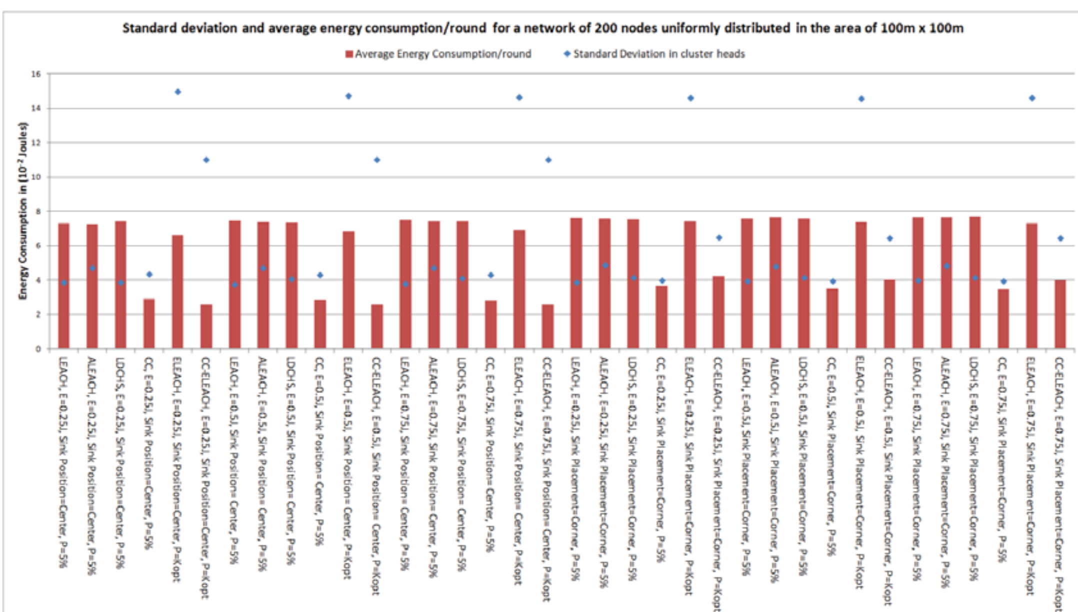


Figure 6.7: Effect of cluster heads on energy consumption/round for a network of 200 nodes

6.2.4 Energy Analysis

The average energy consumption per round is shown in Figures 6.5-6.7. It can be observed from the figures that average energy consumption per round increases with an increase in node density. The average energy consumption per round increases between 200% to 400% with an increase in node density for a given protocol and initial energy. However, the average energy consumption per round is not much affected with the increase in the initial energy for a given protocol and node density. The proposed approach reduces maximum energy consumption per round between 15% to 180% for ALEACH, 11% to 187% for E-LEACH, 22% to 181% for LDCHS and 20% to 185% for LEACH.

6.3 Summary

This chapter proposed a new Concentric Circle approach for cluster head election in wireless sensor network. It is energy efficient and distributed in nature. It selects radius of concentric circles by considering node density. It ensures that the desired number of cluster heads are to be maintained during each round. Also, it always selects highest energy node as cluster head from the set of eligible nodes during a particular round. It also minimizes the difference of the relative distances of the selected cluster heads with respect to sink, i.e. between 0 and farthest alive node from the sink. Simulation result shows that the proposed approach increases network lifetime compared to LEACH, LDCHS, ALEACH and E-LEACH. During the course of research, the effect of initial energy, node density and sink position is also manifested for the proposed approach.

In the next chapter, cluster head election method will be discussed inspired from Bollinger Bands. Also, a method will be discussed to enhance network lifetime by incorporating scheduling mechanisms with routing to avoid idle listening time. It also discusses that how proper duty-cycling improves the network lifetime.

Chapter 7

A new Bollinger Band based Energy Efficient Routing for Clustered Wireless Sensor Network

In this chapter, a new cluster based routing scheme based on Bollinger Bands is proposed, that uses "grid method" to route the packet without specifying the destination node's address. "Grid method" also helps to improve coverage (Luo, Tu, and Chen). The major objective of the proposed approach is to enhance the network lifetime. Extensive simulations are carried out to compare the proposed approach with existing cluster based routing algorithms. The brief summary of contributions is as under:

- It is shown that how "grid method" can be used for cluster formation for a given ROI.
- It is shown that how to compute the optimal grid size to route the packets using scheduled data path. This helps to reduce idle listening time and generates optimal duty-cycling for the radio to conserve energy of a node.
- A new approach is proposed to elect cluster heads once the clusters are formed. This approach is based on Bollinger Bands. It is a technical trading tool developed by John Bollinger in 1980 (Bollinger).
- It is also shown that how the selection of "next hop" should be done in multi-hop communication.

- The proposed approach is proven by extensive simulations with realistic radio parameters to get simulation results closest to the test bed. The proposed approach is also compared with other seven existing protocols.

The Bollinger Band (BB) based technique is not introduced by anyone to elect CH for WSN. This approach provides load balancing by rotating the role of CH and thus improves network lifetime. In addition, "Grid based" cluster formation technique helps to improve the network lifetime and provides better coverage.

7.1 Grid based Cluster Formation Technique

The node deployment area is virtually divided into smaller geographical regions called grids or clusters. Grid size depends upon the communication capability of the radio of a WSN node. In (Sim and Lee), authors have shown that as the cluster size increases, overall energy consumption of a network decreases; but the packet delivery ratio can become better or worse. The packet delivery ratio can be improved by relay nodes (Sim and Lee). Thus, smaller cluster size is not as energy efficient as the larger cluster size.

Communication range of any node is the function of transmission power of a radio and other parameters. For a given radio, if other parameters remain unchanged, then tight lower bound on cluster size can be given by the communication area covered with the minimum transmission power level of the radio. The largest possible cluster size is needed to get maximum energy efficiency (Sim and Lee). Also, inter-cluster communication must be possible with the largest cluster size. Hence, inter-cluster communication can be done with the maximum power level T_{max}. If a node can transmit up to L meters with T_{max} transmission power, for the proposed approach cluster size should be of $\frac{L}{\sqrt{5}}$ m x $\frac{L}{\sqrt{5}}$ m as the size of inter-cluster can be $\frac{L}{\sqrt{5}}$ m x $\frac{2L}{\sqrt{5}}$ or $\frac{2L}{\sqrt{5}}$ m x $\frac{L}{\sqrt{5}}$ m. Hence, for a given radio, if L meter distance is covered when transmitted with the maximum power level, then tight upper bound on cluster size should be of $\frac{L}{\sqrt{5}}$ m x $\frac{L}{\sqrt{5}}$ m. This is the maximum cluster size to get maximum energy efficiency. To improve the data delivery ratio, CHs are used as relay nodes. Scheduling of the data messages for CH nodes is shown in the Figures 7.1 and 7.2. This scheduling scheme ensures collision free data transmission. The transmission sequence of the grids (clusters) depends upon the location of the sink. The cluster formation is shown by dividing node deployment area into 5x5 grid and each grid area is $\frac{L}{\sqrt{5}}$ m x $\frac{L}{\sqrt{5}}$ m. However, this can be extended to any grid size. CH having same grid id as the sink is scheduled last as shown in Figures 7.1 and 7.2.

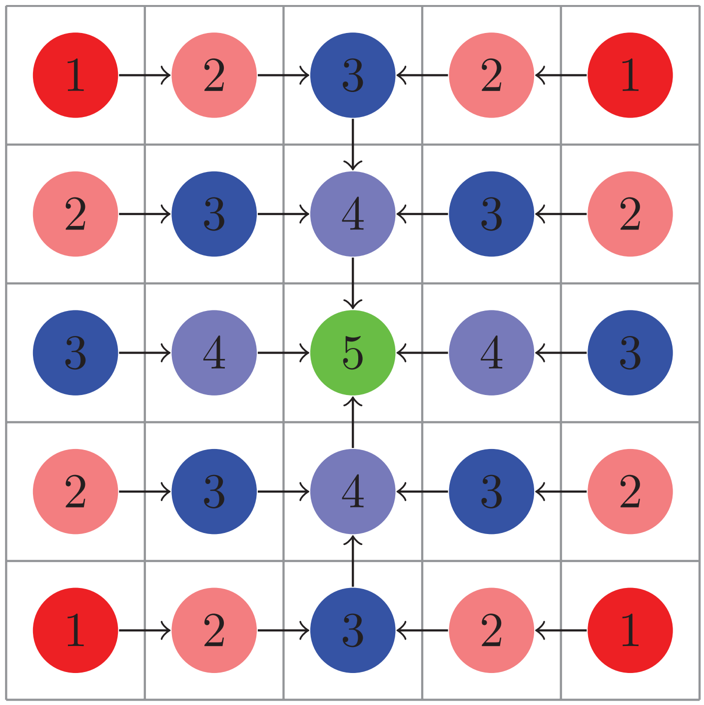


Figure 7.1: Scheduling of the CH nodes to send data to the sink. Sink is located at the center of the node deployment area

7.2 Introduction to Bollinger Bands

Bollinger Bands (BB) is the technical trading tool. BB is also known as standard deviation envelopes, developed by John Bollinger. His theory states that a trading envelope's distance from the mean (moving average) is a function of the market's volatility (Kahn).

Bollinger Bands consist of:

- A moving average (MA) calculated for N-period
- An upper band (UpperBB) at K times an N-period standard deviation above the moving average (MA + Kσ)
- A Lower band (LowerBB) at K times an N-period standard deviation below the moving average (MA - Kσ)

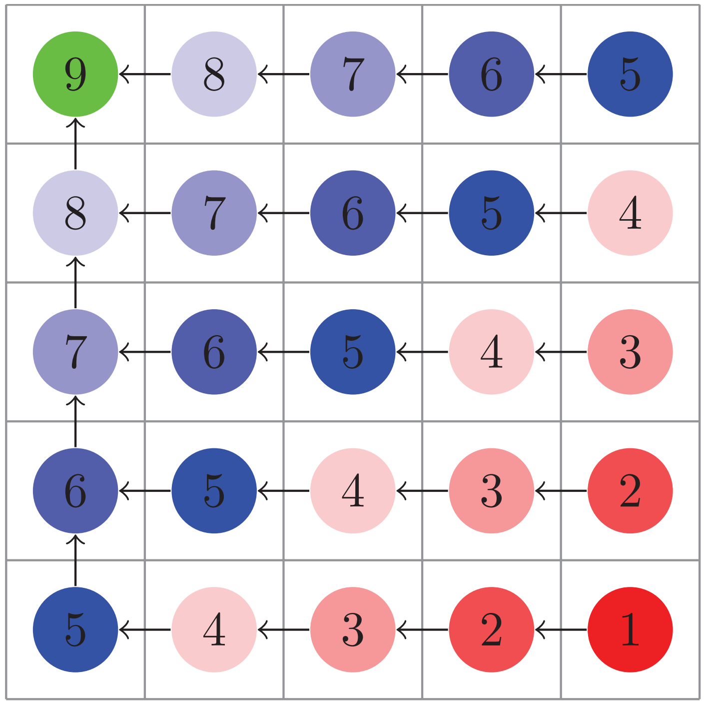


Figure 7.2: Scheduling of the CH nodes to send data to the sink. Sink is located at the corner of the node deployment area

Values of N and K are set to 20 and 2 respectively. Generally, simple moving average is used as MA; other choices like exponential moving average can also be used to calculate BB. Bandwidth for BB is calculated using Equation 7.1.

$$\text{Bandwidth} = \frac{\text{UpperBB} - \text{LowerBB}}{\text{MA}} \tag{7.1}$$

Bandwidth gives information about how wide are the Bollinger Bands on a normalized basis. This information can be used to elect CH. It is assumed that each node is able to remember their energy levels of last twenty rounds. Using these values, each node will calculate it's Bandwidth as per the Equation 7.1. If a node has been elected as a CH for a particular round, then it has wider Bandwidth. Each member node will send its Bandwidth information to the CH of their cluster. For the next round, each CH will elect one of their member nodes having minimum Bandwidth value as the CH; if more than one member of a particular cluster are having the same Bandwidth value, then a node with minimum (or maximum) node id will be elected as a CH.

7.3 Cluster Head Election based on Bollinger Bands

The process of data collection, fusion and delivery of data to the sink is divided into rounds. Round is the fixed duration for which a particular node within the cluster acts as a CH. Each round is divided into two phases: i) Cluster Head Election Phase and ii) Steady State Phase. A CH re-election process is to be carried out at the end of each round to achieve load balancing among the nodes. It is assumed that each node is aware with its location and they are time synchronized. However, both of these assumptions can be relaxed. Location information can be provided to the nodes using low powered GPS (Buchli, Sutton, and Beutel) and time synchronization between nodes can be achieved by one of the methods discussed in (Sundararaman, Buy, and Kshemkalyani) such as Reference Broadcast Synchronization (RBS) (Elson, Girod, and Estrin), Romer's protocol (Römer), Mock's protocol (Mock et al.), Network-wide Time Synchronization (Ganeriwal et al.), Delay Measurement Time Synchronization Protocol (Ping), the Probabilistic Clock Synchronization Service (PalChaudhuri, Saha, and Johnson), Sichitiu and Veerarittiphan's protocol (Sichitiu and Veerarittiphan), the Time-Diffusion Protocol (TDP) (Su and Akyildiz), the Asynchronous Diffusion protocol (Li and Rus). A detail working of these protocols can be found in the references mentioned along with protocol names.

7.3.1 Cluster Head Election Phase

During the first round, each node has to wait for T_{wait} time which is given by Equation 7.2.

$$\mathrm{T}_{wait} = \frac{\mathrm{Rnd(Id)}}{\mathrm{TotalNodes}} \tag{7.2}$$

where Rnd is a random integer number generator between [0,Id) and TotalNodes are the number of nodes deployed in ROI. A node will send *CH Announcement Message*, when its T_{wait} timer expires. CH Announcement Message consists of node id and grid id (Cluster Id) of the sender. Receiving nodes compare their grid id with the grid id received in the CH Announcement message. If both are same, then the receiving nodes cancel their T_{wait} timers and decide to be member nodes for the current round. Steady State Phase begins at the end of Cluster Head Election Phase and it is discussed in the following subsection.

7.3.2 Steady State Phase

At the end of Cluster Head Election Phase, each node knows its CH. Each node waits for a random amount of time between (0, maxTime); where maxTime is application dependent. A node sends a *Data Message* to the CH, after completion of the random wait period. *Data Message* carries information about the phenomenon of interest and its own Bandwidth value as discussed in section 7.2. After sending *Data Messages*, member nodes will go into the *Sleep* state to save their energy. CH fuses data over maxTime period. It sends fused data to the identified cluster as per schedule described in section 7.1. Since, the process of data transmission is scheduled in such a way that no CH will receive any data from nearby clusters, once the fused data is sent by it. CH will go into the *Sleep* state once it has transmitted data of its own cluster. This reduces idle listening time of the nodes and generates optimal duty-cycling for the CHs, that helps to conserve energy of CHs.

Just before the end of each round, all nodes are activated by self-timers. Since, CH has received Bandwidth value for all its members; it selects a member having the lowest bandwidth value as the CH for the next round. This is because a node with the lowest Bandwidth value from the set of nodes is the highest energy node. If more than one node is having the same bandwidth value, then the node with minimum (or maximum) id will be selected as the CH. CH for the current round does the CH announcement of the next round. This CH announcement message consists of CH id for the next round and cluster id. Receiving nodes records CH id for the next round and goes into the *Sleep* state until the commencement of the Steady State Phase of the next round.

7.4 Simulation Strategy and Result Discussion

The Bollinger Band based proposed approach is compared with ALEACH (Ali, Dey, and Biswas), CVLEACH (Thakkar and Kotecha, "CVLEACH: Coverage based energy efficient LEACH Algorithm"), ECBRP (Han et al.), LDCHS (Handy, Haase, and Timmermann), LEACH (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks"), MTANT (Thakkar and Kotecha, "Bio-inspired based optimized algorithm for Cluster Head election using RSSI and LQI") and TANT (Selvakennedy, Sinnappan, and Shang) algorithms. Castalia simulator is used to get energy consumption measurements for WSN nodes. Energy consumption results obtained with Castalia is closest to the test bed implementation (Pediaditakis, Tselishchev, and Boulis Stetsko, Stehlik, and Matyas). Energy consumption of a WSN node in Castalia is due to the three components of the node: i) Baseline Operating Power ii) Sensing Device and iii) Radio. Baseline Operating Power refers to constant minimum amount of energy drawn by the node. There is negligible energy consumption by sensing device. The major source of power consumption is different states observed by the radio during the lifetime of a particular node. Castalia supports realistic node behavior as far as access to the radio is concerned. A radio can be in one of the three states at any point of time: i) Transmit ii) Receive or iii) Sleep. To conserve the energy of the node, the radio should be in the Sleep state as and when possible (Thakkar and Pradhan Boulis, "Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User's manual").

Simulations are carried out by varying node densities between 100 to 500. These nodes are deployed in a simulation area of 250m x 250m. Each of these nodes was given 10 Joules of initial energy. The sink is positioned at the center of the deployment area and other nodes are deployed using three different node deployment patterns as mentioned in Table 7.1. Next, sink is positioned at (0,0) and simulations are repeated. Each simulation configuration was run five times and mean value of interested parameter is plotted. Simulation parameters are shown in Table 7.1.

To measure network lifetime, First Node Dies (FND), Half of the Nodes Alive (HNA) and Last Node Dies (LND) are used as a benchmark parameter (Bagci and Yazici Attea and Khalil Khalil and Attea Rashed, Kabir, Ullah, et al.). FND can also refer as the stability period (Smaragdakis, Matta, and Bestavros). Results for FND, HNA and LND are shown in Figures 7.3-7.5 respectively, with varying node density, node deployment pattern and sink positions. It can be easily visualized that proposed Bollinger Band based clustering algorithm outperforms other seven algorithms, two of which are based on Ant Colony Optimization (ACO); because CH selection is based on how a particular node's energy is normalized towards the mean value. If a node's energy is highly normalized (a narrow Bandwidth), that node has not become CH

Parameter Name	**Value**
Node Deployment Area	250m X 250m
Number of Nodes	1) 100 2) 200 3) 300 4) 400 5) 500
Initial Energy/Node	10 Joules
Simulation Time	1500 seconds
Transceiver	CC2420
Maximum Tx Power	0dBm
Baseline Node Power	6mW
Packet Size	30 Bytes
Algorithms	1) ALEACH[1] 2) BB 3) CVLEACH [2] 4) ECBRP[3] 5) LDCHS[4] 6) LEACH[5] 7) MTANT[6] 8) TANT[7]

[1] (Ali, Dey, and Biswas)
[2] (Thakkar and Kotecha, "CVLEACH: Coverage based energy efficient LEACH Algorithm")
[3] (Han et al.)
[4] (Handy, Haase, and Timmermann)
[5] (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks")
[6] (Thakkar and Kotecha, "Bio-inspired based optimized algorithm for Cluster Head election using RSSI and LQI")
[7] (Selvakennedy, Sinnappan, and Shang)

Table 7.1: Parameters used for the simulation of the Bollinger Band based approach

Parameter Name	**Value**
Sink Node Id	Node 0
Sink Location	1) Center of the deployment area 2) At location (0,0)
Node Deployment	1) [1..$totalNodes - 1$]->uniform [8] 2) [1..$totalNodes - 1$]->10x10[9,8] 3) [1..$totalNodes - 1$] ->randomized_10x10[10,8]
Simulation Runs	Repeated 5 times for each configuration and mean value is recorded for the parameter of interest

[8] (Boulis, "Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User's manual")
[9] This deployment pattern is shown as *Grid* in plotted results.
[10] This deployment pattern is shown as *RGrid* in plotted results.

Table 7.1: (Continued) Parameters used for the simulation of the Bollinger Band based approach

since long duration. When any node becomes CH for any round, its radio remains in receiving state for a long duration to receive data from its member nodes as well as nearby clusters. Hence, its Bandwidth becomes wider. Also, Bollinger Bandwidth makes tuse of 20-days moving average to calculate Bandwidth. It has advantage that node should require to remember their energy levels for the last 20 rounds only. The second reason for getting prolonged network lifetime is due to the scheduled path for data transfer. Hence, the proposed approach does not require to pass information about the elected CH to the neighboring clusters. Also, idle listening time is reduced and optimal duty-cycling is achieved for the radio of the CHs due to the schedule data path.

7.5 Summary

A new CH election protocol inspired from Bollinger Bands is proposed. Bollinger Bandwidth selects the maximum energy node as the cluster head. Use of grid to formulate clusters is also discussed in this chapter. This grid based method supports scheduling of messages as per grid id and thus no need to provide a destination node's address. It also helps to reduce idle listening time for the CHs. In addition, optimal

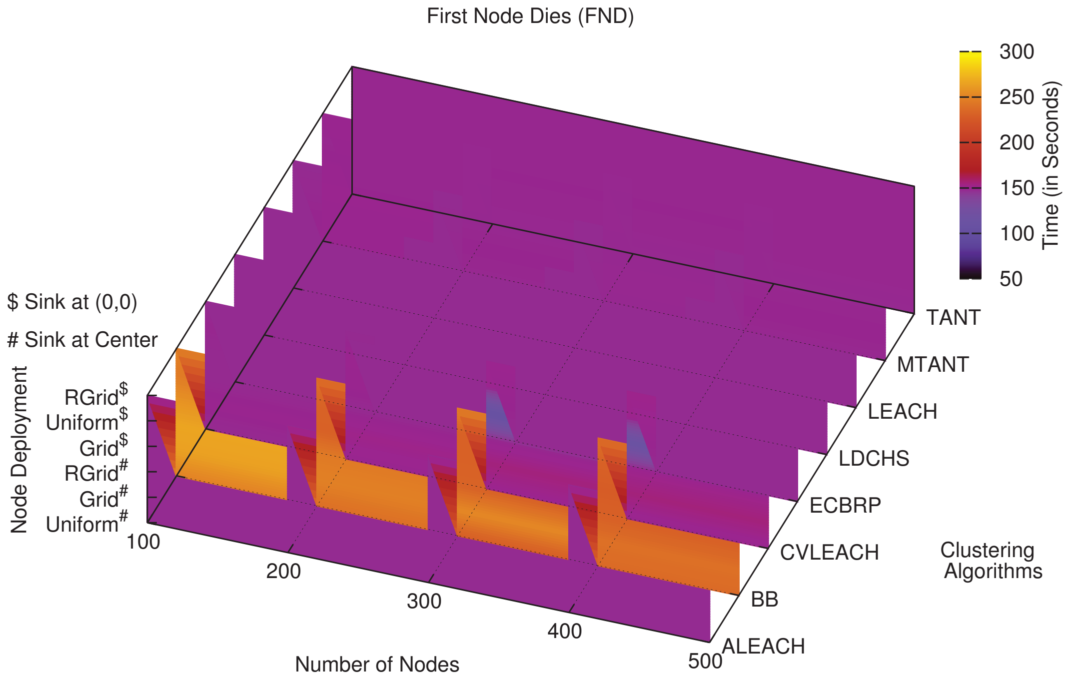


Figure 7.3: First Node Dies (FND) for varying node density between 100 to 500 nodes with initial energy 10 Joules/Node

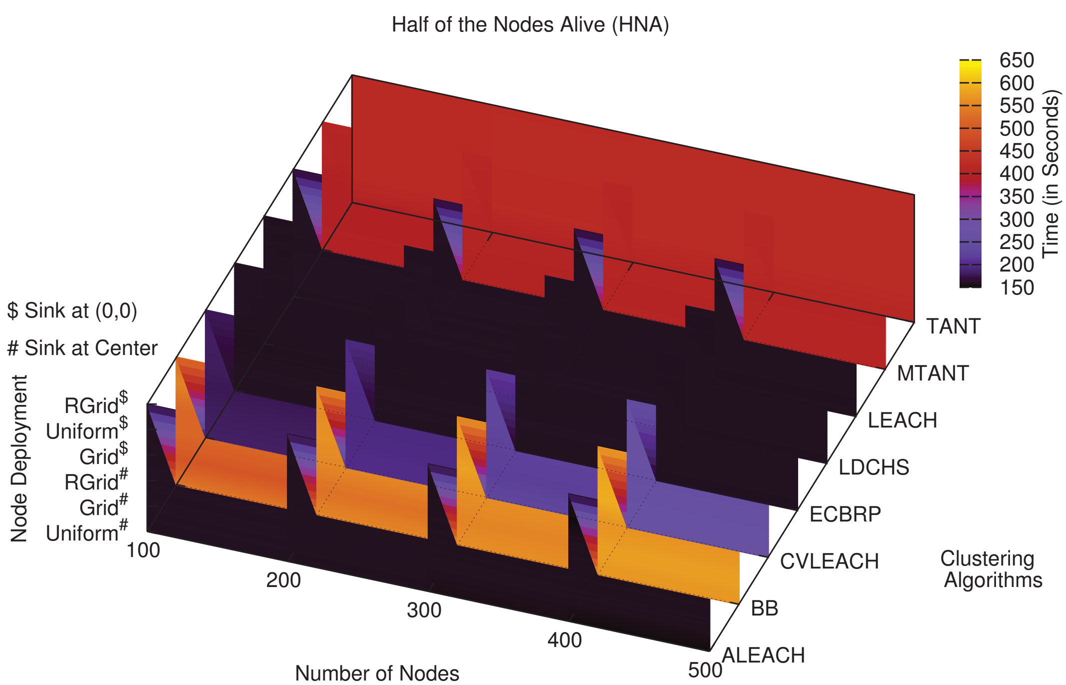


Figure 7.4: Half of the Nodes Alive (HNA) for varying node density between 100 to 500 nodes with initial energy 10 Joules/Node

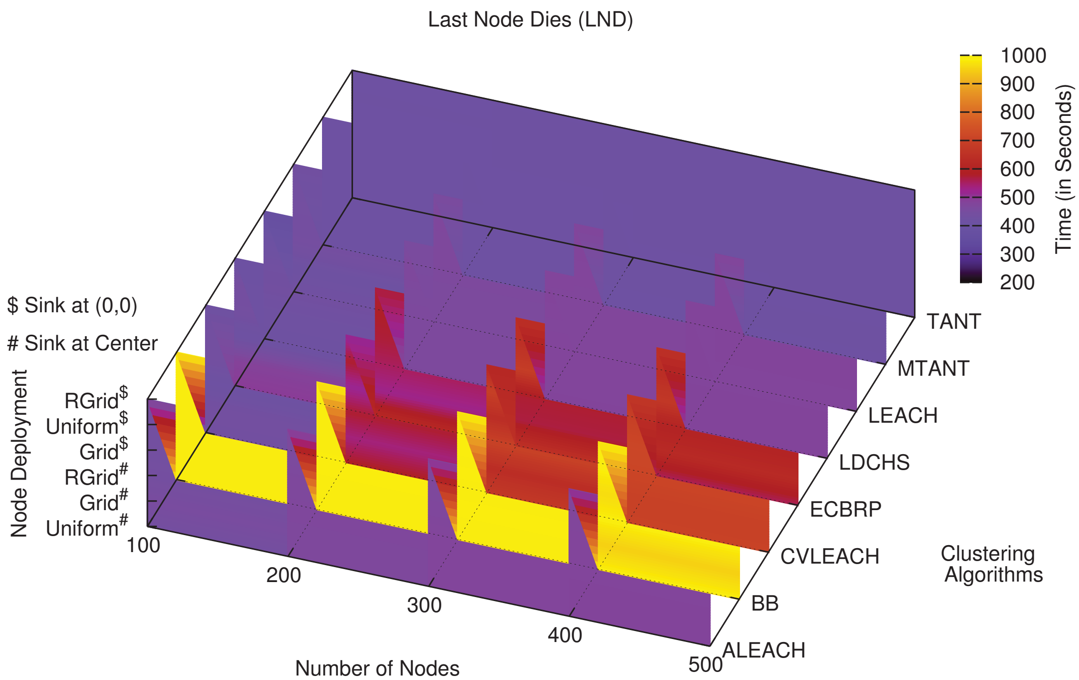


Figure 7.5: Last Node Dies (LND) for varying node density between 100 to 500 nodes with initial energy 10 Joules/Node

duty-cycling is also observed for the CHs. This results into improved network lifetime. The proposed approach is distributed in nature and energy efficient. The protocol has been tested using realistic radio model with three different node deployment patterns, two different positions of the sink and seven different algorithms named ALEACH, CVLEACH, ECBRP, LDCHS, LEACH, MTANT and TANT. Next chapter describes the use of scheduling mechanism for cluster head election process in WSN and its effect on the network longevity.

Chapter 8

Round Robin scheduling approach for Cluster Head election in Wireless Sensor Networks

Cluster Head (CH) election schemes presented so far are energy efficient and improve network lifetime. However, these algorithms suffer from overhead incurred during cluster setup phase as follows:

- Cluster Head Announcements are sent by CHs during each round. Also, these messages are listened by the receiving nodes. This makes energy expenditure for transmitting (CHs) as well as receiving nodes (members) both.

- Cluster Join messages are sent by member nodes to the CHs during each round. These messages are listened by CHs. This makes energy expenditure for transmitting (members) and receiving nodes (CHs) both.

- A TDMA schedule is announced by CHs to their members. This makes energy expenditure for transmitting (CHs) and receiving nodes (members) both.

In this chapter, Round Robin (RR) scheduling approach is proposed for cluster head election in WSNs, as RR is a fair scheduling scheme (Silberschatz et al.). In order to achieve load balancing between the WSN nodes, role of CH should be rotated and each node should get equal chance to become cluster head from the set of nodes belonging to the same cluster.

8.1 Overview of Round Robin Scheduling

Round Robin (RR) scheduling is used in the operating system to schedule the task using a fair share of CPU. This algorithm is governed by the time quantum which is maximum CPU time allocated to the process. After time specified by the time quantum elapsed, a task is preempted and next task from the ready queue is allotted CPU for the duration, which is minimum of CPU time needed by the task to complete its execution and time quantum specified for the RR scheduling. If there are n processes in the ready queue and the time quantum is q, each process gets $\frac{1}{n}$ of the CPU time in chunks of at most q time units at once. No process waits more than $(n-1)*q$ time units (Silberschatz et al.).

8.2 Round Robin scheduling approach for CH election in WSNs

8.2.1 Neighbor Discovery Phase

It is assumed that all nodes are time synchronized. Also, each node is aware with its position and position of the sink. However, both of these assumptions can be relaxed. Location information can be provided to the nodes using low powered GPS (Buchli, Sutton, and Beutel) and time synchronization between nodes can be achieved by one of the methods discussed in (Sundararaman, Buy, and Kshemkalyani).

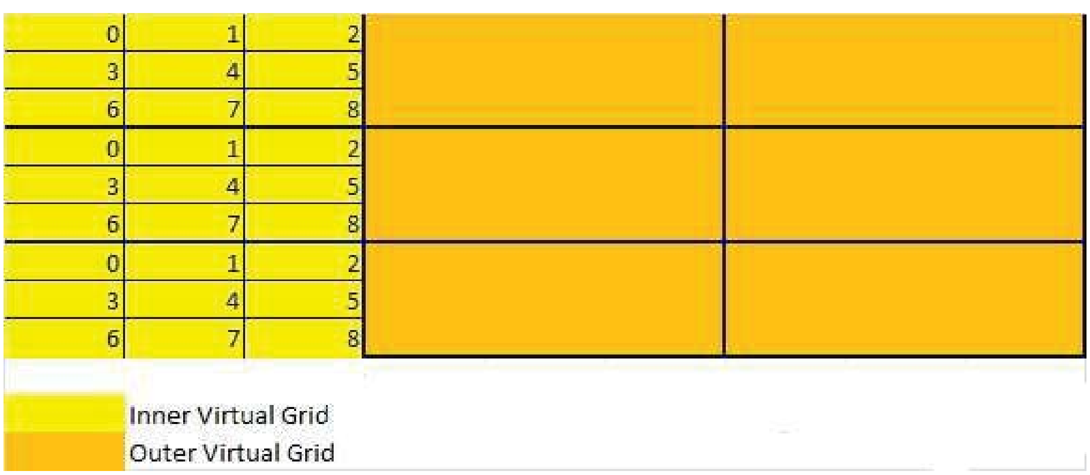


Figure 8.1: Example of Inner and Outer Virtual Grids

Neighbor discovery phase executes only once to prepare Round Robin queue and it works as follows: All nodes are grouped into clusters by dividing node deployment area into virtual grids as discussed in section 7.1. It will be referred as “outer virtual grid”. Each “outer virtual grid” is divided into the “inner virtual grids” that define resolution of a grid which is application dependent. Example of the inner and outer virtual grid is shown in Figure 8.1. To find neighbors in its own “outer virtual grid”, each node sends a *Hello Packet* after the expiration of $Wait$ timer, for which, wait time is set according to Equation 8.1; where *iRand* is the function that generates integer random numbers between 0 and parameter given to the function, $Self\ Id$ is the identifier of the node, *dRand* is the function that generates random number between 0 and 1, $inVGridId$ is the inner virtual grid id of the node itself, $Total\ Nodes$ are the number of nodes deployed in the ROI.

Hello Packet carries following information about the sender: Id, Wait Time, Inner Virtual Grid Id, Outer Virtual Grid Id. On the reception of *Hello Packet*, the node compares the outer virtual grid id of the packet with its own outer virtual grid id; if both are same, then the recipient node adds sender id in its own Round Robin queue.

$$Wait = \begin{cases} \frac{iRand(Self\ Id)}{Total\ Nodes} + dRand() & \text{if inner virtual grid id=0,} \\ \frac{1}{inVGridId} * \frac{Total\ Nodes}{100} + \frac{Self\ Id}{Total\ Nodes} & \text{otherwise} \end{cases} \tag{8.1}$$

8.2.2 Cluster Head Election Phase

At the end of neighbor discovery phase, each node adds its own id, inner virtual grid id, outer virtual grid id and wait time in its own Round Robin queue and then sorts it according to wait time. Each node examines its own Round Robin queue to decide whether it should work as CH or member node for the current round. If a node finds that a node id stored in the Round Robin queue returns its own id for a given *position*, then the node elects itself as CH, else it works as a member. Here, *position* is given by Equation 8.2

$$position = mod(r, length(RRQueue)) \tag{8.2}$$

where *mod* is an arithmetic modulo operation, r is the current round number, *RRQueue* represents the Round Robin queue managed by the node itself and *length* is a function which returns total elements in the Round Robin queue.

It may be possible that initially *RRQueue* of all nodes are not same and hence, initially for a few rounds, there are multiple CHs within the same outer grid. However, this problem can be overcome as follows: Whenever a node sends a data packet, it also sends the necessary information to form the RRQueue. The recipient nodes, i.e., multiple CHs during that round, check that sender node is part of their *RRQueue* or not. If it is, then, nothing is to be done; otherwise it adds sender into the *RRQueue* and sorts the queue as discussed earlier. This additional information sent by the sender is overhead for the algorithm for a few rounds only. After reception of data packets during the steady state phase, if CH node does not find any node whose information is not present in the *RRQueue*, that CH node sets a $flag$ in its data packets indicating that its *RRQueue* is synchronized for its outer virtual grid. These data packets are sent by the node when it acts as a member. Also, $flag$ carries only one bit information which is a negligible overhead compared to energy efficiency achieved by this protocol. Also, there is no need to send TDMA schedule. Each node sends data according to its position in its own *RRQueue*. When node energy level drops below the specified threshold, a node sets a *withdraw* flag in its data packet. This informs other nodes to remove its participation in the CH election process. This threshold value is application dependent.

8.2.3 Steady State Phase

During this phase, each member node sends data according to its position in its own *RRQueue*. Once data are sent by the member node, it goes into the *sleep* state to conserve its energy. CH performs data aggregation after it receives data from its neighbors and sends it to the other CH or sink according to the scheduled data path as discussed in section 7.1 depending upon the position of the sink. Once the CH sends its aggregated data packet, it goes into the *sleep* state till the commencement of the next round. After receiving data packet from neighbors, if CH has to wait as per the data forwarding method discussed in section 7.1, then CH goes into the *sleep* state till it turn comes. It helps to save energy of the CHs.

8.3 Simulation Parameters and Result Discussion

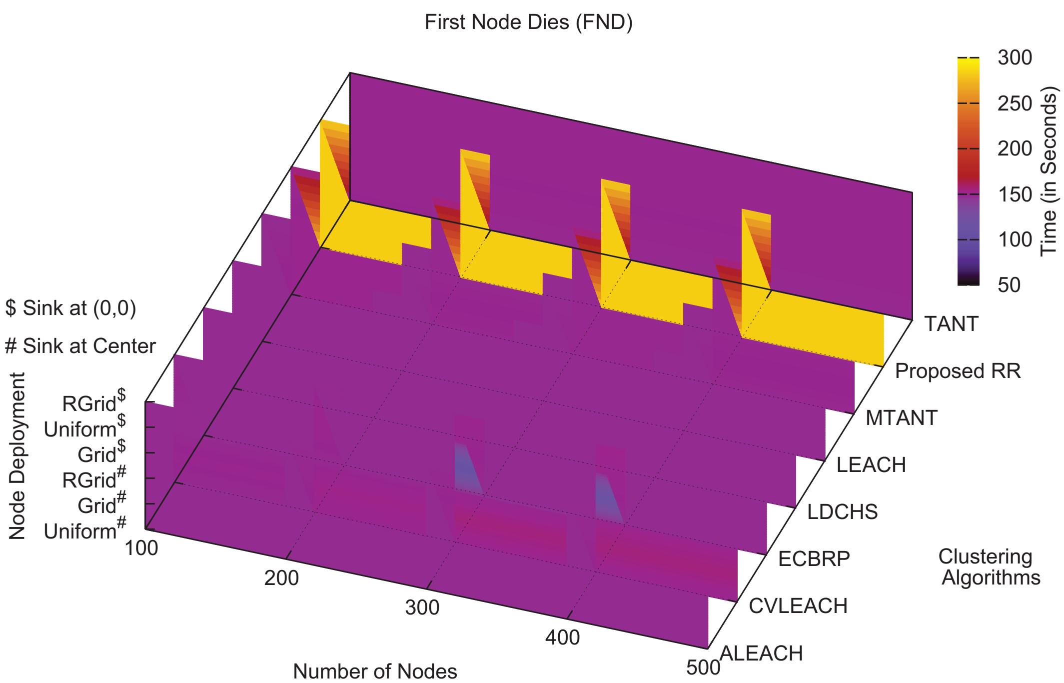


Figure 8.2: First Node Dies (FND) for varying node density between 100 to 500 nodes with the initial energy 10 Joules/Node

Simulation parameters are shown in Table 8.1. To measure network lifetime, First Node Dies (FND), Half of the Nodes Alive (HNA) and Last Node Dies (LND) are used as a benchmark parameter (Bagci and Yazici Attea and Khalil Khalil and Attea Rashed, Kabir, Ullah, et al.). FND can also refer as the stability period (Smaragdakis, Matta, and Bestavros). Results for FND, HNA and LND are shown in Figures 8.2 - 8.4 respectively, for varying node density, node deployment pattern and sink positions. It can be seen that the proposed Round Robin (RR) scheduling based clustering algorithm outperforms because it minimizes cluster formation overhead as discussed on page 130. The second reason for getting prolonged network lifetime is due to the scheduled path for data transfer. Hence, the proposed approach does not require to communicate information about the elected CH to the neighboring clusters as well as member nodes. Also, it reduces idle listen period and provide optimal duty-cycling time that helps to improve network lifetime.

Parameter Name	**Value**
Node Deployment Area	250m x 250m
Number of Nodes (N)	1) 100 2) 200 3) 300 4) 400 5) 500
Number of Ants [7,8]	10% of N
Rate of Sensory Data generation	Every 2 seconds
$RSSI_{sth}$ [7]	-87dBm
LQI_{min} [7]	50
Size of Control and Data messages	30 Bytes
TTL field for CHADV message [7,8]	3
Algorithms	1) ALEACH [2] 2) CVLEACH [3] 3) ECBRP [4] 4) LDCHS [5] 5) LEACH [6] 6) MTANT [7] 7) Proposed RR 8) TANT[8]

[2] (Ali, Dey, and Biswas)
[3] (Thakkar and Kotecha, "CVLEACH: Coverage based energy efficient LEACH Algorithm")
[4] (Han et al.)
[5] (Handy, Haase, and Timmermann)
[6] (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks")
[7] (Thakkar and Kotecha, "Bio-inspired based optimized algorithm for Cluster Head election using RSSI and LQI")
[8] (Selvakennedy, Sinnappan, and Shang)

Table 8.1: Parameters used for the simulation of the proposed RR approach

Parameter Name	Value
Sink Node Id	Node 0
Sink Location	1) Center of the deployment area 2) At location (0,0)
Node Deployment	1) [1..$totalNodes - 1$]->uniform [1] 2) [1..$totalNodes - 1$]->10x10[9,1] 3) [1..$totalNodes - 1$] ->randomized_10x10[10,1]
Simulation Time	1200 Seconds
Simulation Repeated	5 times
Neighbor Discovery Time	60 Seconds
CH status retain by CH node	20 Seconds
Tx Power	0dBm
Operating power of a Node	6mW
Operating power of a sensing device	0.02mW
Initial Energy	10 Joules

[1] (Boulis, "Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User's manual")
[9] This deployment pattern is shown as *Grid* in plotted results.
[10] This deployment pattern is shown as *RGrid* in plotted results.

Table 8.1: (Continued) Parameters used for the simulation of the proposed RR approach

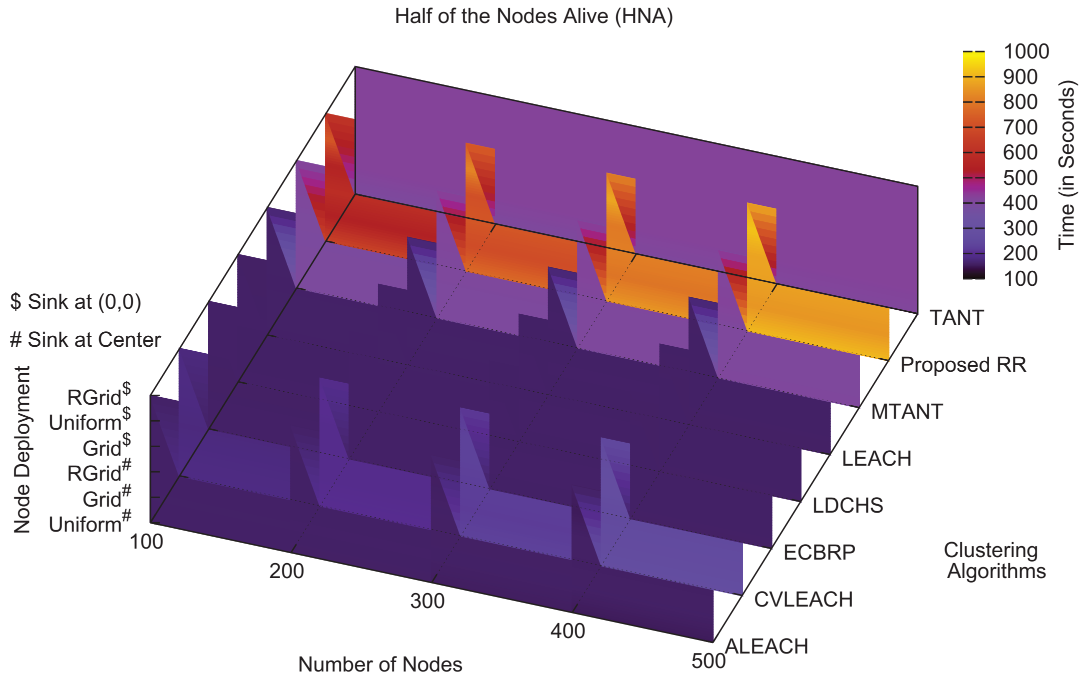


Figure 8.3: Half of the Nodes Alive (HNA) for varying node density between 100 to 500 nodes with the initial energy 10 Joules/Node

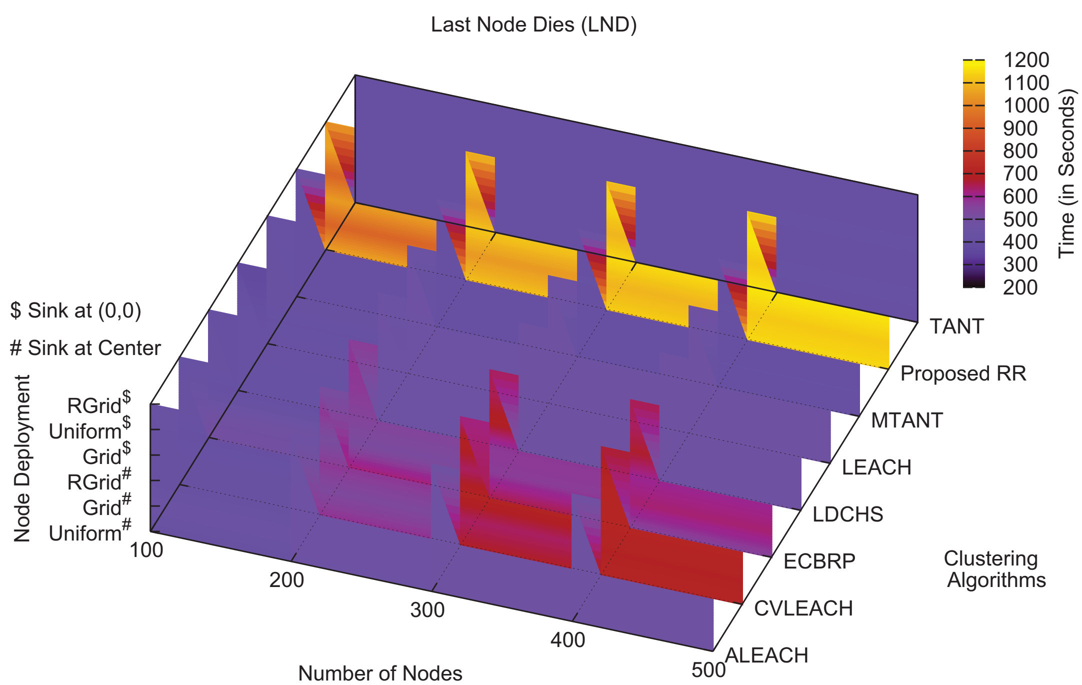


Figure 8.4: Last Node Dies (LND) for varying node density between 100 to 500 nodes with the initial energy 10 Joules/Node

8.4 Summary

A new CH election protocol is proposed for improving network lifetime by minimizing cluster formation overhead. It is based on Round Robin scheduling scheme, which is a fair scheduling method. Hence, the proposed approach gives equal chance to every node within the "outer virtual grid" or cluster. The protocol is distributed and energy efficient. It minimizes cluster formation overhead. The proposed protocol has been tested using a realistic radio model with three different node deployment patterns, two different positions of the sink and seven different algorithms named ALEACH, CVLEACH, ECBRP, LDCHS, LEACH, MTANT and TANT. In the next chapter, a novel method is discussed that dynamically compute the number of cluster heads for each round. This method depends upon time (i.e round), number of alive nodes and remaining energy of the network.

Chapter 9

A novel method to compute number of cluster heads in the wireless sensor network using stretched exponential function

The protocols discussed in Chapter 2 are energy efficient and improves network lifetime. However, the major improvement area in these protocols is the fixed number of cluster heads during each round, that does not change with the time. This number of cluster heads are also known to the algorithm in advance. In this chapter, a method is proposed to model percentage of cluster heads during each round as a function of time, current network energy and the number of alive nodes using stretched exponential function.

9.1 Proposed Approach using Stretched Exponential Function

9.1.1 Introduction to Stretched Exponential Function

The most commonly used empirical decay function for handling relaxation data affected by disorder is the Kohlrausch (or stretched exponential decay) function which is given by Equation 9.1 (Chou, Tu, and Wu). Study to parameterize the nonexponential decay of the electric polarization of Leyden jars (primitive capacitors) was done in 1854 by R. Kohlrausch using a phenomenological expression 9.1; his son F. Kohlrausch later used the same expression to analyze creep in galvanometer suspensions (Lemke and Campbell).

$$q_K(t) = exp[-(\frac{t}{\tau})^{\beta}], 0 \leq t < \infty, 0 < \beta < 1 \tag{9.1}$$

Later in 1951, Weibull has given Weibull statistical distribution function (Weibull). A simple relaxation function unifying the stretched exponential with the compressed hyperbola is derived in (Berberan-Santos). Avellaneda et al. (Avellaneda, Ryan, and Weinan) showed that the probability distribution solutions of the Burger's equation, with a random stationary Gaussian as the initial condition, have tails that take the form of Kohlrausch functions (Anderssen, Husain, and Loy).

9.1.2 Modeling percentage of cluster heads using Stretched Exponential Function

To decide the percentage of total nodes that can work as CHs during each round, the following extended model of stretched exponential function is designed.

$$p(r) = exp[-(r)^{rEnergy*rDead}], 0 \leq r < \infty, 0 \leq rEnergy * rDead < 1 \tag{9.2}$$

where r is the round number, $p(r)$ is the percentage of total nodes that can become cluster heads during a round r, $rEnergy$ and $rDead$ is given by Equations 9.3 and 9.4 respectively.

$$rEnergy = \frac{\text{Remaining Energy of the Network during round } r}{\text{Initial Energy of the Network}} \tag{9.3}$$

$$rDead = \frac{\text{Total Dead Nodes during round } r}{\text{Total Nodes}} \tag{9.4}$$

The percentage of cluster heads remain fixed until the death of first node; after that the number of cluster heads changes with the time depending upon the remaining energy of the network, number of alive nodes and time since network was set up. Equation 9.2 determines the percentage of cluster heads by considering current network energy, the number of dead nodes and the total time elapsed since network deployment.

9.2 Simulation Parameters and Result Discussion

9.2.1 Energy Model

The first order radio energy model is used for simulations (see page 28).

9.2.2 Simulation Environment

Simulations are carried out in MATLAB and the code for LEACH and SEP protocols are obtained from csr.bu.edu (Smaragdakis, Matta, and Bestavros). The parameters used for simulations are shown in Table 9.1. First order radio energy model is used as given in (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks" Smaragdakis, Matta, and Bestavros). Total 72 simulation runs are carried out by varying node density and initial energy to validate the robustness of the proposed approach, including 27 simulation runs for the LEACH protocol (initial energy/node * number of nodes * percentage of CH = 3*3*3), 27 simulation runs for the SEP protocol (initial energy/node * number of nodes * percentage of CH = 3*3*3) and 18 simulation runs for the proposed approach (initial energy/node * number of nodes * number of algorithms = 3*3*2). Percentage of cluster heads, p and p_{opt}, is also varied for LEACH and SEP protocols respectively.

To compare the proposed approach with LEACH, approach given in (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks") is followed. For the proposed approach, each node assumes a random number between 0 and 1 and if the selected random number is less than threshold $T(n)$, then node elects itself as CH for the current round, where $T(n)$ is given by Equation 2.1. However, the proposed approach dynamically computes values of p using Equation 9.2 which is one of the parameters in Equation 2.1. The value of p is calculated every $\frac{1}{p}$ rounds for the proposed approach. Three different values of p, 5%, 10% and 20%, is used for LEACH protocol to compare it with the proposed approach.

To compare the proposed approach with SEP, the approach given in (Smaragdakis, Matta, and Bestavros) is followed. For the proposed approach, each node assumes a random number between 0 and 1. If the selected random number is less than the threshold value, the node elects itself as a cluster head for the current round. The threshold value for advanced nodes and normal nodes is given by Equations 2.22 and 2.19 respectively. The value of p_{adv} and p_{nrm} in Equations 2.22 and 2.19 is given by Equations 2.23 and 2.20 respectively. However, the value of p_{opt} for the proposed approach is computed dynamically using Equation 9.2 that can be used in Equations 2.23 and 2.20. Also, value of p_{opt} is calculated every $\frac{1}{p_{opt}}$ rounds for the proposed approach. Three different values of p_{opt}, 5%, 10% and 20%, is used for SEP protocol to compare it with the proposed approach.

9.2.3 Simulation Metrics and Result Discussion

- **Stability Period:** It refers to the time interval between the start of the network until the death of first node. It is also referred as a "stable region" (Smaragdakis, Matta, and Bestavros). It is shown as FND in Table 9.2 and Table 9.3 for LEACH and SEP based approaches. It can be concluded from the FND metric that the proposed approach achieves 77.77% times highest stability period.

- **Network Lifetime:** Network lifetime is measured using three metrics: First Node Dies (FND), Half of the Nodes Die (HND) (or Half of the Nodes Alive (HNA)) and Last Node Dies (LND). LND refers to the time when 90% of the total nodes die (Qiu et al.). Simulation results for FND, HNA and LND are shown in Table 9.2 and Table 9.3 for LEACH and SEP approaches. It can be concluded from these results that the proposed approach achieves 77.77% times highest value for FND metric, 100% times highest value for HNA metric and 72.22% times highest value for LND metric. In addition to that time is measured when 20% nodes die, 40% nodes die, 60% nodes die and 80% of the total nodes die. The results of these simulations metric are shown in Figures 9.1d-9.9d for LEACH based approach and Figures 9.10d-9.18d for the SEP based approach. Also, death of nodes over the time for the LEACH based approach is shown in Figures 9.1a-9.9a while for the SEP based approach is shown in Figures 9.10a-9.18a.

- **Number of Packets:** It indicates the number of packets received by BS from

Parameter Name	**Value**
Node Deployment Area	100m X 100m
Total Nodes (Excluding BS): N	1) 50 2) 100 3) 200
Percentage of Advanced Nodes: m	10%
Advanced Nodes: N_{adv}	$m * N$
Normal Nodes Nodes: N_{nrm}	$(1 - m) * N$
Relative Position of BS	(50,50)
α	1
Initial Energy/Node for N_{nrm} (in Joules)	1) 0.25 2) 0.50 3) 0.75
Initial Energy/Node for N_{adv}	$(1 + \alpha) * N_{nrm}$
Simulation Stopping Criteria	10000 Rounds
Transmitter Electronics ($E_{Tx-elec}$) Receiver Electronics ($E_{Rx-elec}$) ($E_{Tx-elec} = E_{Rx-elec} = E_{elec}$)	50 nJ/bit
Energy for Data Aggregation (EDA)	5 nJ/bit/message
Free Space (ϵ_{fs})	10 pJ/bit/m^2
Multi-path Fading (ϵ_{mp})	0.0013 pJ/bit/m^4
Packet Size	4000 bits
Proposed Approach Compared with	1)LEACH[1] 2) SEP[2]
Percentage of Cluster Heads for LEACH & SEP	1) 5% 2) 10% 3) 20%

[1] (Heinzelman, Chandrakasan, and Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks")
[2] (Smaragdakis, Matta, and Bestavros)

Table 9.1: Parameters used for the simulation of the proposed approach based on stretched exponential function

the network. More number of packet received indicates less die rate of the nodes and expenses of energy (Wang, Yang, and Sun). The number of packets received by BS is recorded at the end of the simulations and it is shown in Table 9.2 and Table 9.3 for LEACH and SEP based approaches respectively. It can be seen from these tables that proposed approach always gets the highest number of packets.

Total Nodes	**Energy** (J/Node)	**Protocol**	**FND** (rounds)	**HNA** (rounds)	**LND** (rounds)	**Packets received by BS**	**CI**
50	0.25	LEACH with P=0.05	476	641	**924**	2183	**1.72**
		LEACH with P=0.1	430	614	761	3646	0.8
		LEACH with P=0.2	**520**	642	817	7302	**1.72**
		Proposed Approach	516	**680**	882	**11909**	1.23
	0.5	LEACH with P=0.05	977	1294	**2034**	4357	**2.33**
		LEACH with P=0.1	926	1212	1566	7395	1.24
		LEACH with P=0.2	1024	1276	1602	14588	1.29
		Proposed Approach	**1039**	**1347**	1782	**23865**	1.41
	0.75	LEACH with P=0.05	1514	1981	**2770**	6270	**1.69**
		LEACH with P=0.1	1445	1827	2329	10955	1.31
		LEACH with P=0.2	1521	1895	2434	21848	1.44
		Proposed Approach	**1575**	**2017**	2658	**35585**	1.45
		LEACH with P=0.05	406	601	801	3672	1.03

Table 9.2: (Continued) Network Lifetime for the Proposed Approach and LEACH

Total Nodes	**Energy** (J/Node)	**Protocol**	**FND** (rounds)	**HNA** (rounds)	**LND** (rounds)	**Packets received by BS**	**CI**
100	0.25	LEACH with P=0.1	498	617	749	6909	1.11
		LEACH with P=0.2	502	632	786	14026	1.18
		Proposed Approach	**520**	**670**	**940**	**23171**	**1.8**
	0.5	LEACH with P=0.05	833	1204	1564	7213	0.97
		LEACH with P=0.1	955	1216	1439	13846	0.85
		LEACH with P=0.2	1012	1264	1637	28020	1.48
		Proposed Approach	**1031**	**1325**	**1833**	**46148**	**1.73**
	0.75	LEACH with P=0.05	1309	1794	2293	10588	1.03
		LEACH with P=0.1	1414	1837	2193	20666	0.84
		LEACH with P=0.2	1528	1908	2417	41786	1.34
		Proposed Approach	**1550**	**1980**	**2655**	**68978**	**1.57**
200	0.25	LEACH with P=0.05	415	606	777	6800	0.9
		LEACH with P=0.1	493	619	844	13514	**1.79**
		LEACH with P=0.2	509	648	854	27804	1.48
		Proposed Approach	**519**	**674**	**877**	**46412**	1.31
	0.5	LEACH with P=0.05	897	1205	1529	13586	1.05
		LEACH with P=0.1	1014	1233	1613	27020	**1.74**

Table 9.2: (Continued) Network Lifetime for the Proposed Approach and LEACH

Total Nodes	**Energy** (J/Node)	**Protocol**	**FND** (rounds)	**HNA** (rounds)	**LND** (rounds)	**Packets received by BS**	**CI**
		LEACH with P=0.2	1024	1295	1703	55463	1.57
		Proposed Approach	**1043**	**1338**	**1778**	**91941**	1.49
		LEACH with P=0.05	1434	1804	2271	20291	1.26
	0.75	LEACH with P=0.1	1508	1851	2458	40236	**1.77**
		LEACH with P=0.2	1558	1931	2563	83185	1.69
		Proposed Approach	**1583**	**2008**	**2651**	**137329**	1.51

Table 9.2: Network Lifetime for the Proposed Approach and LEACH

- **Energy Analysis:** Energy consumption of all nodes is measured and remaining energy of the network is calculated after each round and it is shown in Figures 9.1b-9.9b for the LEACH based approach and Figures 9.10b-9.18b for the SEP based approach. It can be seen from these figures that energy consumption curve for the proposed approach is straight, which indicates balanced energy consumption during each round. Also, energy consumption of the proposed approach is lower than that of the LEACH and SEP protocols.

- **Convergence Indicator (CI):** It is given by Equation 3.2 (Qiu et al.), where FND, HND and LND refer to the time when First Node Dies, Half of the Nodes Die and 90% of the total node die. It is used to measure network convergence. Higher the value of CI, the more balanced energy consumption of the network. The CI is shown in Table 9.2 and Table 9.3. It can be seen from these tables that the proposed approach got ten times highest values and five times second highest values out of eighteen different simulation groups.

- **Percentage of Cluster Heads:** Percentage of cluster heads, p, for LEACH (see Equation 2.1) and optimal probability of a node to become CH, p_{opt} for SEP (see Equations 2.20 and 2.23), is set to 5%, 10% and 20% for varying node density and initial energy. However, these values are calculated dynamically for

Total Nodes	**Energy** (J/Node)	**Protocol**	**FND** (rounds)	**HNA** (rounds)	**LND** (rounds)	**Packets received by BS**	**CI**
50	0.25	SEP with P=0.05	540	673	**885**	1826	**1.59**
		SEP with P=0.1	474	635	746	3334	0.69
		SEP with P=0.2	**566**	656	741	6533	0.94
		Proposed Approach	538	**690**	864	**13448**	1.14
	0.5	SEP with P=0.05	1111	1356	1546	3843	0.78
		SEP with P=0.1	1024	1271	1438	6807	0.68
		SEP with P=0.2	**1121**	1315	1458	13081	0.74
		Proposed Approach	1072	**1368**	**1740**	**26796**	**1.26**
	0.75	SEP with P=0.05	**1686**	2011	2446	5640	**1.34**
		SEP with P=0.1	1586	1925	2124	10063	0.59
		SEP with P=0.2	1679	1959	2157	19574	0.71
		Proposed Approach	1622	**2064**	**2623**	**40098**	1.26
	0.25	SEP with P=0.05	439	632	716	3319	0.44
		SEP with P=0.1	537	640	745	7253	1.02

Table 9.3: (Continued) Network Lifetime for the Proposed Approach and SEP

Total Nodes	**Energy** (J/Node)	**Protocol**	**FND** (rounds)	**HNA** (rounds)	**LND** (rounds)	**Packets received by BS**	**CI**
100		SEP with P=0.2	539	669	774	13032	0.81
		Proposed Approach	**560**	**700**	**872**	**26788**	**1.23**
	0.5	SEP with P=0.05	927	1253	1411	6807	0.48
		SEP with P=0.1	1093	1269	1432	14414	0.93
		SEP with P=0.2	1096	1325	1563	26044	1.04
		Proposed Approach	**1133**	**1384**	**1720**	**53429**	**1.34**
	0.75	SEP with P=0.05	1439	1865	2120	9847	0.6
		SEP with P=0.1	1634	1910	2159	21593	0.9
		SEP with P=0.2	1662	1991	2292	38891	0.91
		Proposed Approach	**1699**	**2086**	**2564**	**79781**	**1.24**
200	0.25	SEP with P=0.05	526	636	741	6619	0.95
		SEP with P=0.1	524	659	765	14044	0.79
		SEP with P=0.2	531	669	804	26021	0.98
		Proposed Approach	**545**	**703**	**900**	**53581**	**1.25**
	0.5	SEP with P=0.05	1064	1259	1438	13123	0.92
		SEP with P=0.1	1062	1297	1519	28005	0.94
		SEP with P=0.2	1075	1342	1608	51960	1

Table 9.3: (Continued) Network Lifetime for the Proposed Approach and SEP

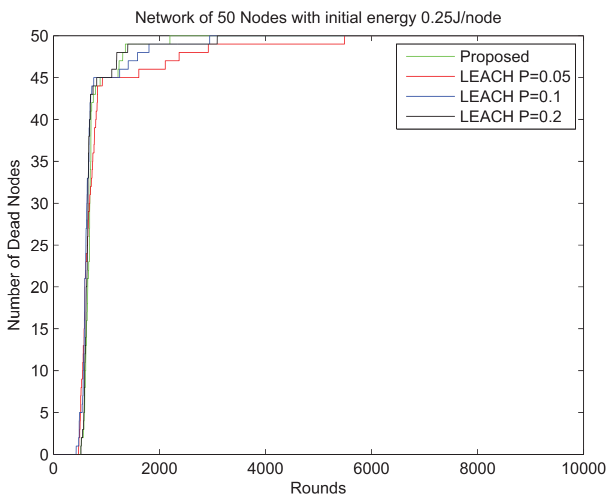
Total Nodes	**Energy** (J/Node)	**Protocol**	**FND** (rounds)	**HNA** (rounds)	**LND** (rounds)	**Packets received by BS**	**CI**
		Proposed Approach	**1112**	**1405**	**1789**	**106505**	**1.31**
	0.75	SEP with P=0.05	1605	1883	2138	19619	0.92
		SEP with P=0.1	1612	1934	2273	42041	1.05
		SEP with P=0.2	1599	2010	2374	77790	0.89
		Proposed Approach	**1679**	**2103**	**2689**	**159327**	**1.38**

Table 9.3: Network Lifetime for the Proposed Approach and SEP

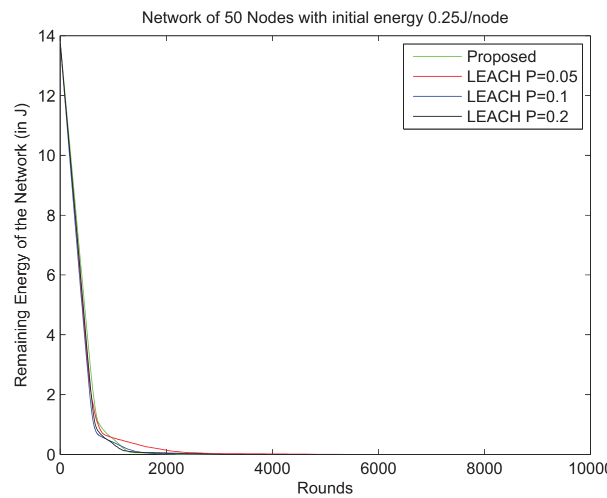
the proposed approach. The values of p for the proposed approach with LEACH are shown in Figures9.1c-9.9c; and the values of p_{opt} for the proposed approach with SEP are shown in Figures 9.10c-9.18c.

9.3 Summary

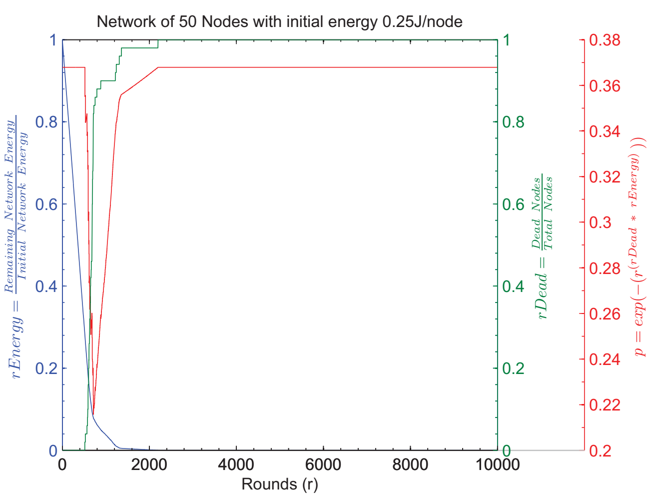
A novel method is proposed to calculate percentage of cluster heads during each round using stretched exponential function. The proposed approach derives percentage of cluster heads by considering three important parameters: i) time since the network has been deployed, ii) number of alive nodes in the network and iii) remaining network energy. The proposed approach is also compared two prominent clustering protocols LEACH and SEP by varying node density, initial energy given to the nodes and percentage of cluster heads for LEACH and SEP protocols. Simulation results show that the proposed approach outperforms LEACH and SEP.



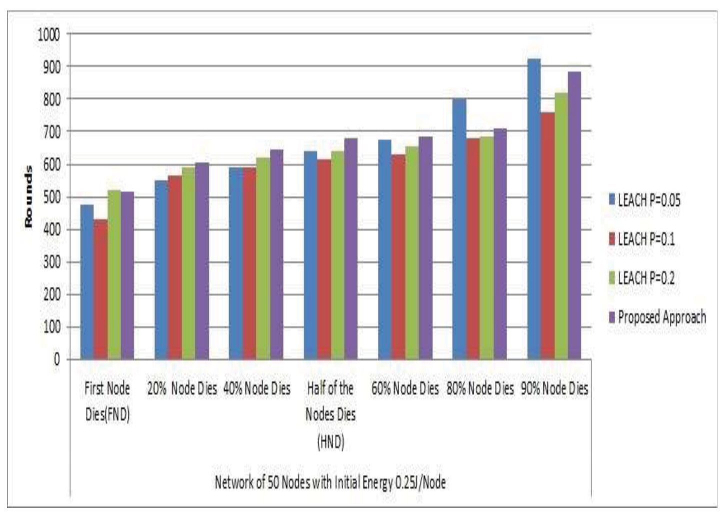
(a) Death of Nodes



(b) Remaining Network Energy

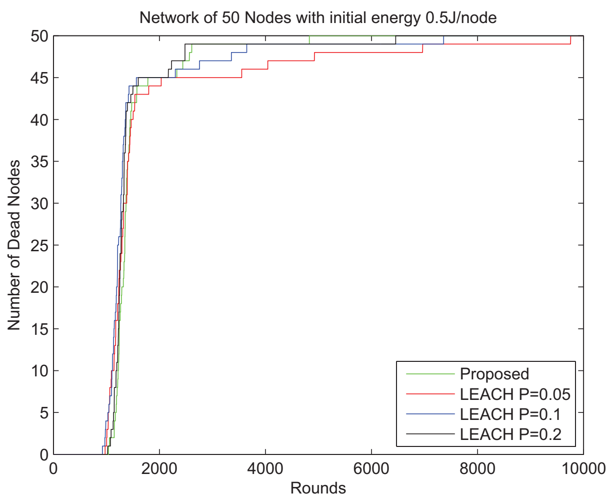


(c) Value of p using stretched exponential function

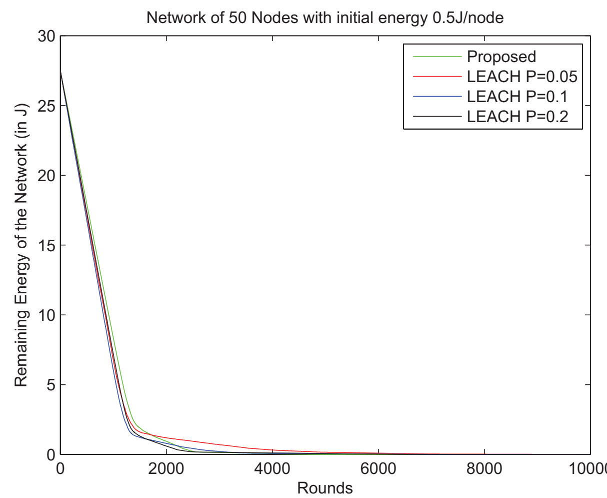


(d) Percentage of Nodes Dies

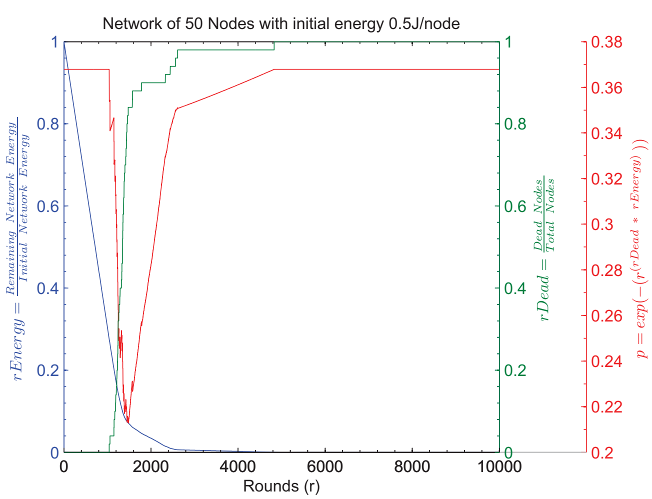
Figure 9.1: Comparison of proposed approach with LEACH protocol for a network of 50 nodes with initial energy 0.25J/node



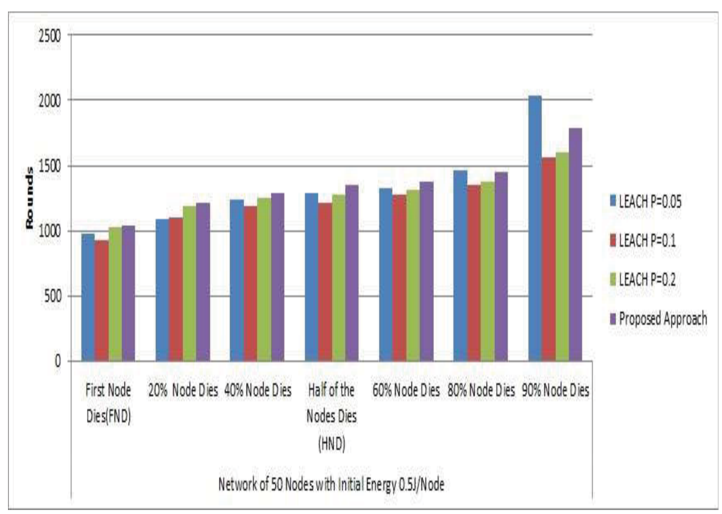
(a) Death of Nodes



(b) Remaining Network Energy

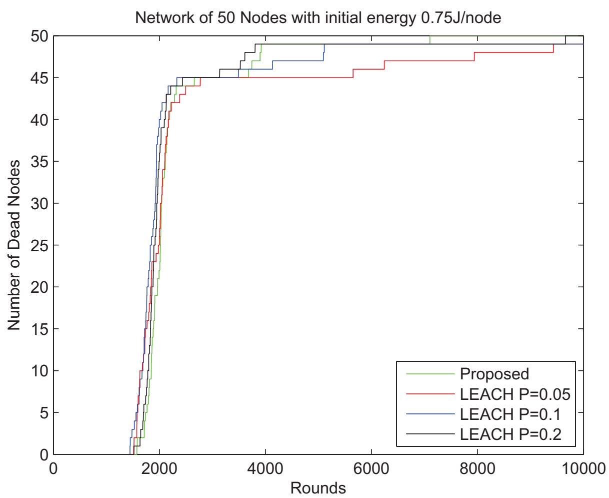


(c) Value of p using stretched exponential function

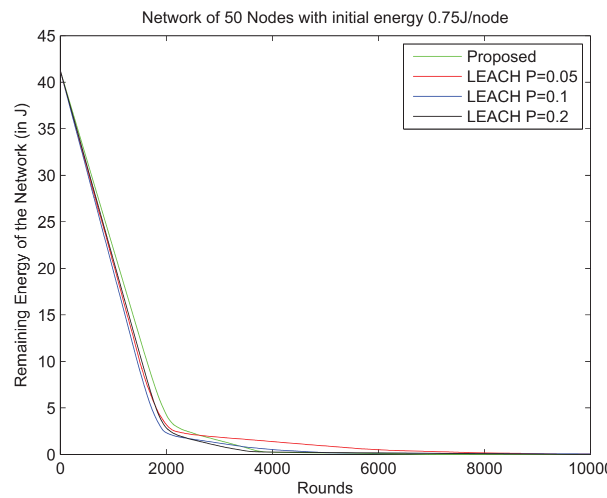


(d) Percentage of Nodes Dies

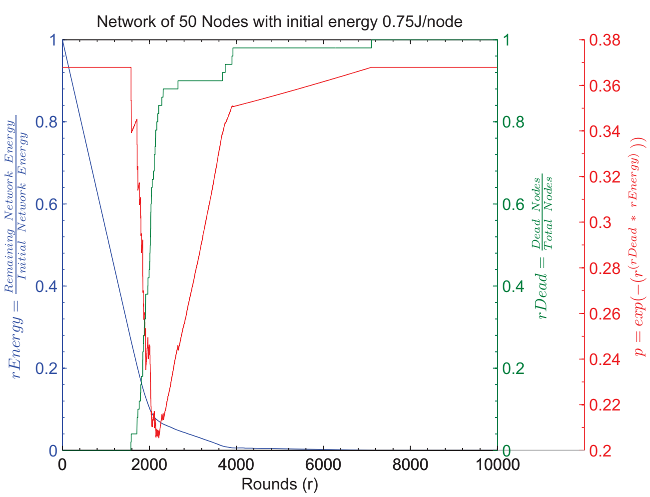
Figure 9.2: Comparison of proposed approach with LEACH protocol for a network of 50 nodes with initial energy 0.5J/node



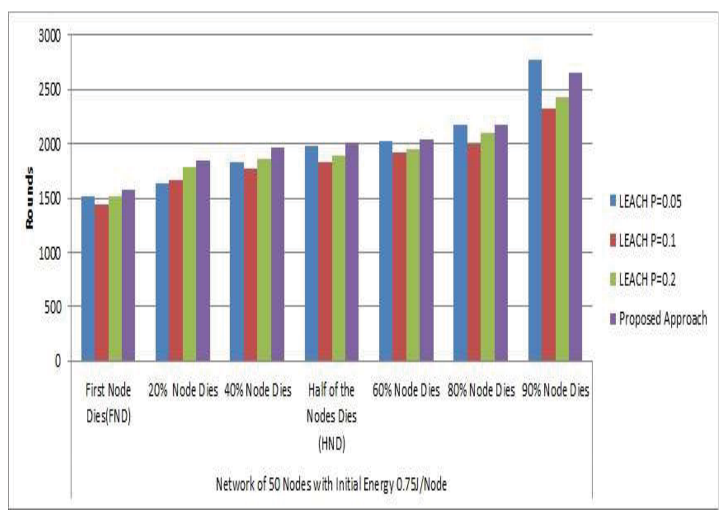
(a) Death of Nodes



(b) Remaining Network Energy

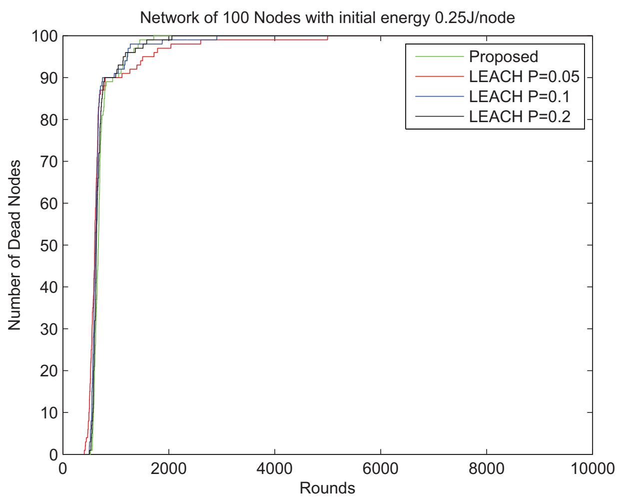


(c) Value of p using stretched exponential function

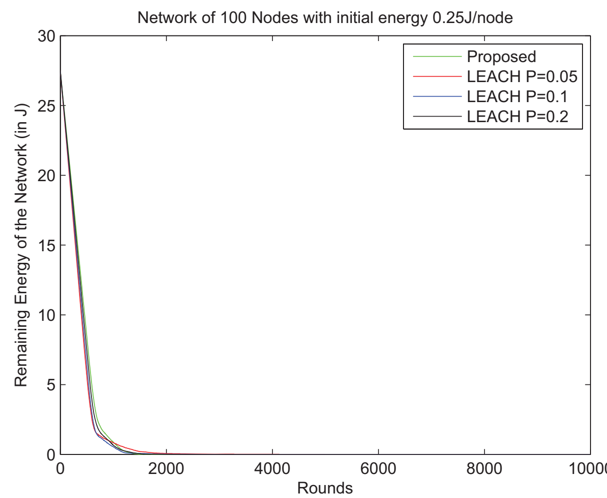


(d) Percentage of Nodes Dies

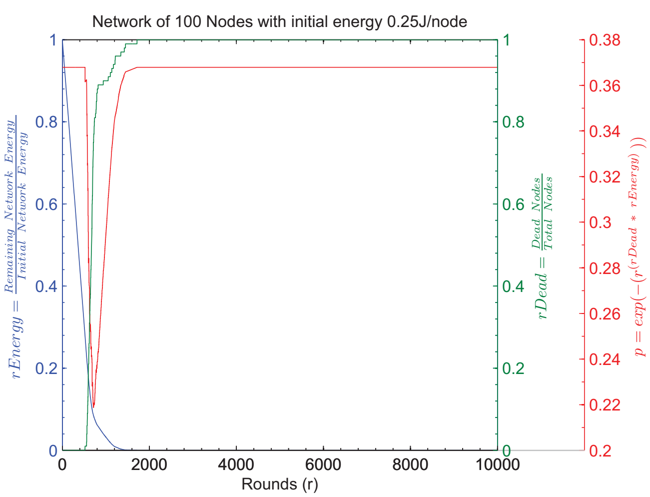
Figure 9.3: Comparison of proposed approach with LEACH protocol for a network of 50 nodes with initial energy 0.75J/node



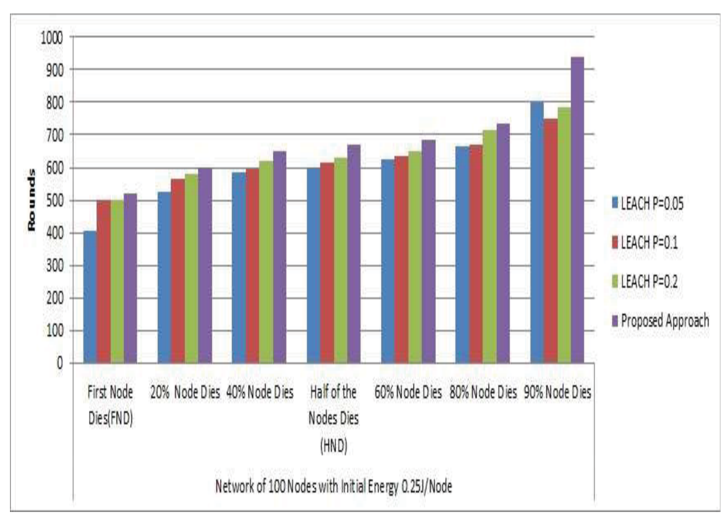
(a) Death of Nodes



(b) Remaining Network Energy

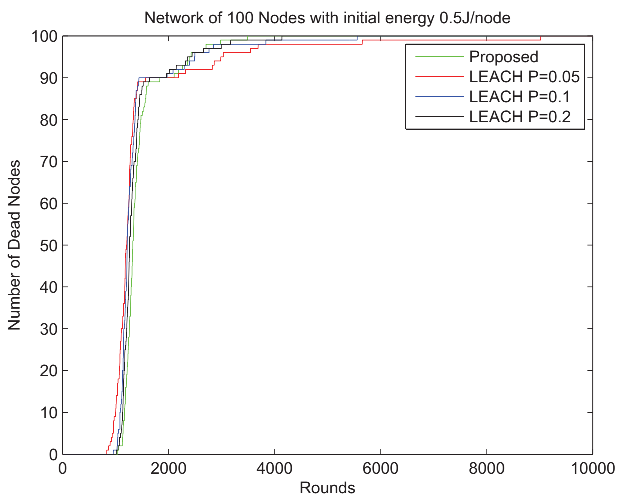


(c) Value of p using stretched exponential function

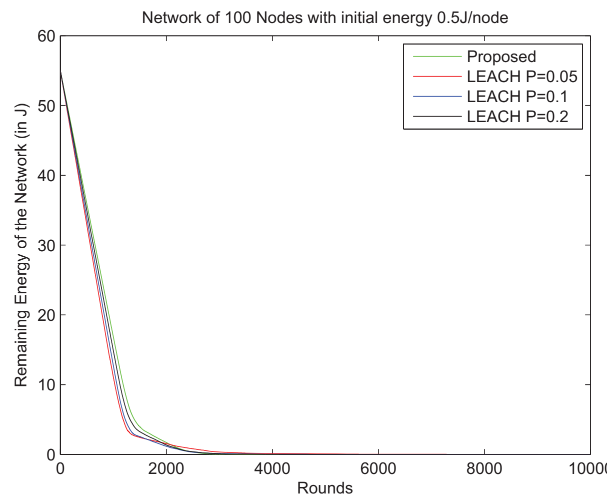


(d) Percentage of Nodes Dies

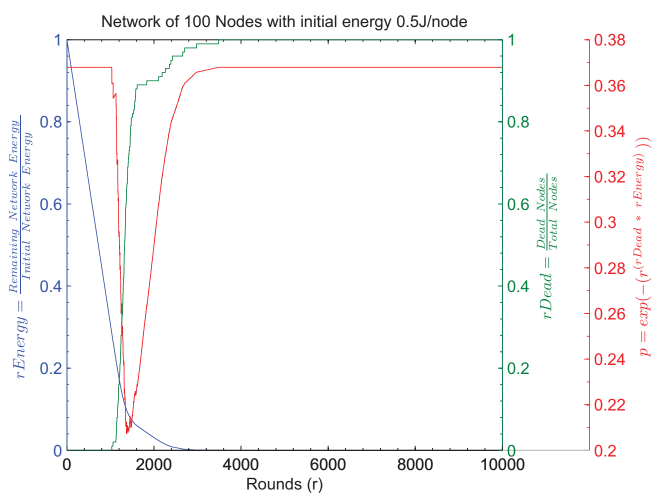
Figure 9.4: Comparison of proposed approach with LEACH protocol for a network of 100 nodes with initial energy 0.25J/node



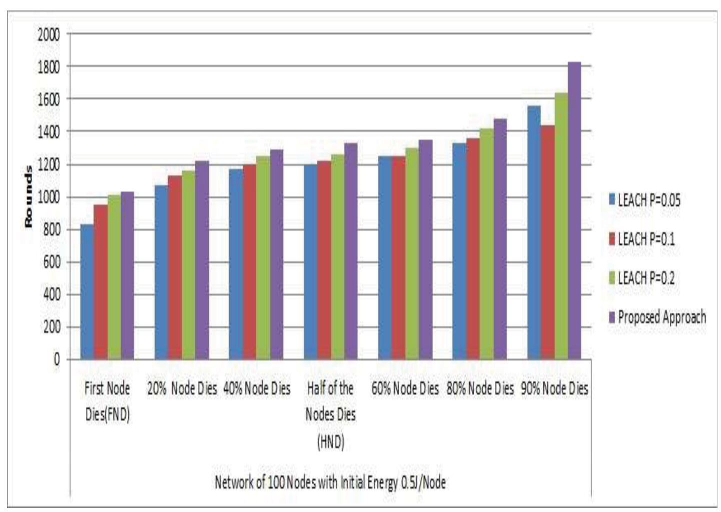
(a) Death of Nodes



(b) Remaining Network Energy

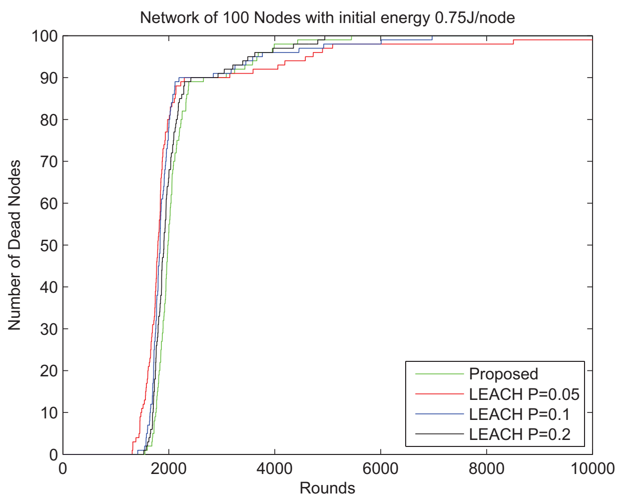


(c) Value of p using stretched exponential function

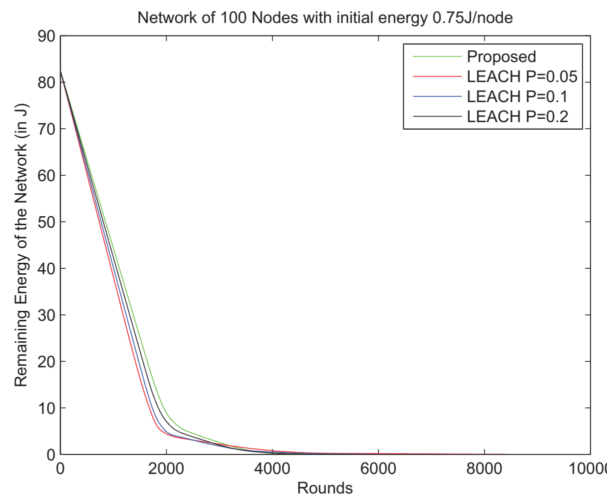


(d) Percentage of Nodes Dies

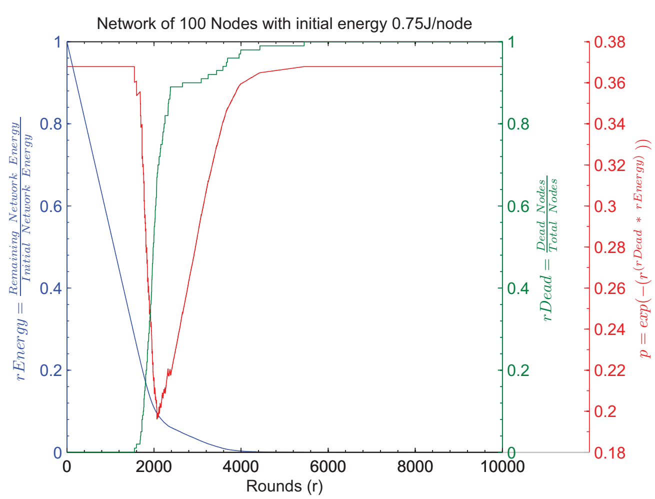
Figure 9.5: Comparison of proposed approach with LEACH protocol for a network of 100 nodes with initial energy 0.5J/node



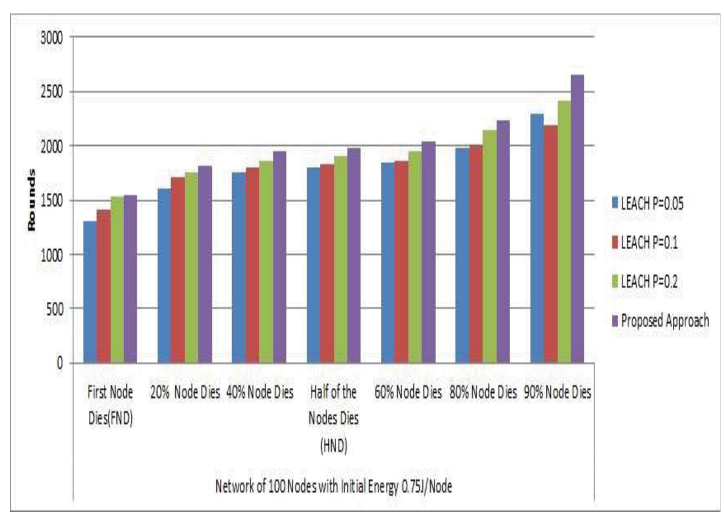
(a) Death of Nodes



(b) Remaining Network Energy

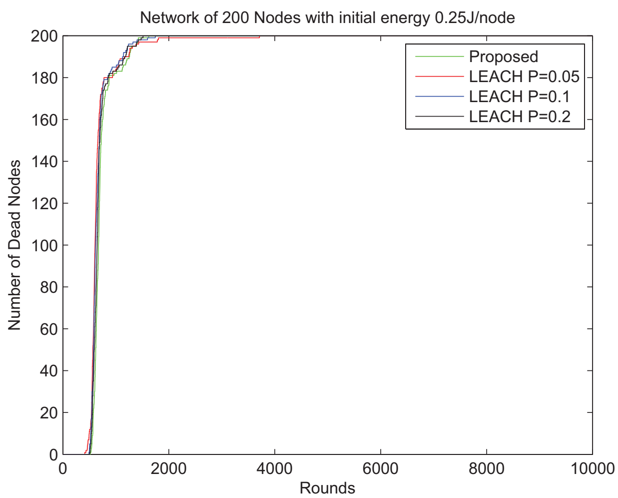


(c) Value of p using stretched exponential function

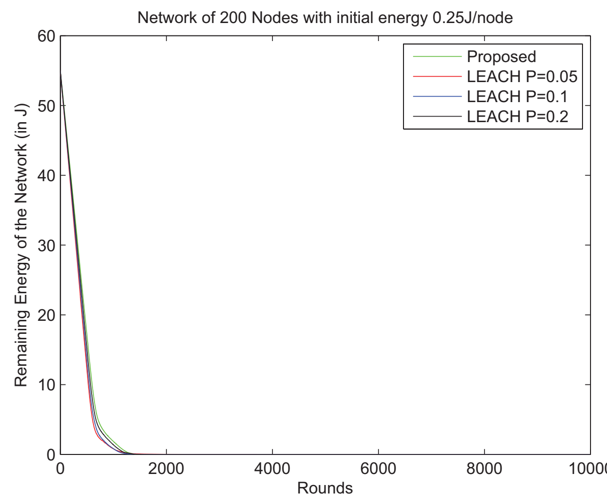


(d) Percentage of Nodes Dies

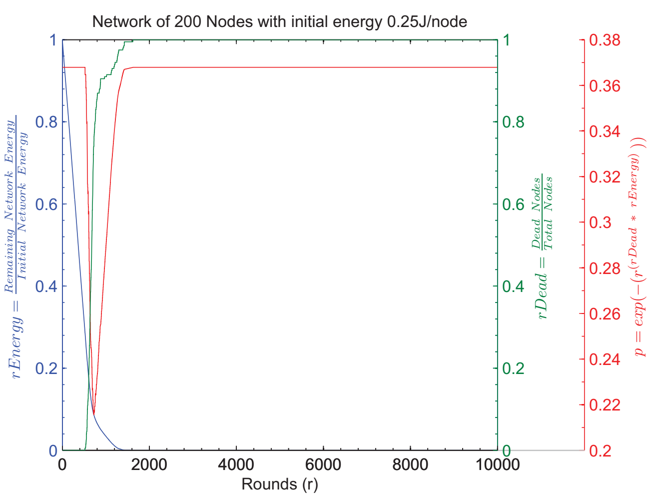
Figure 9.6: Comparison of proposed approach with LEACH protocol for a network of 100 nodes with initial energy 0.75J/node



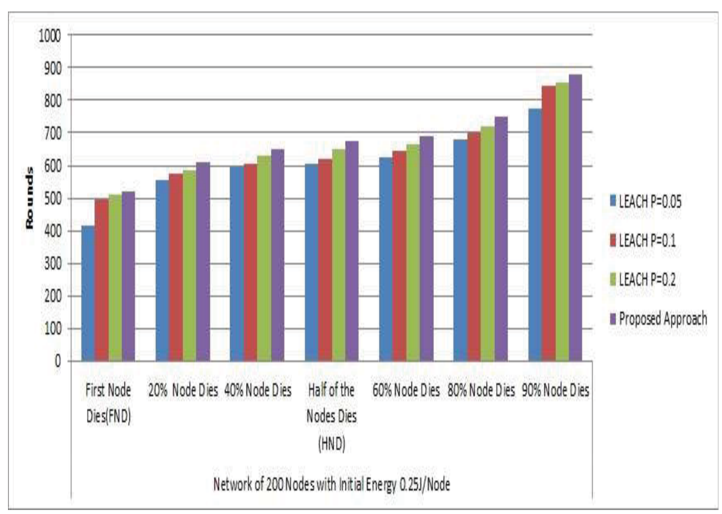
(a) Death of Nodes



(b) Remaining Network Energy

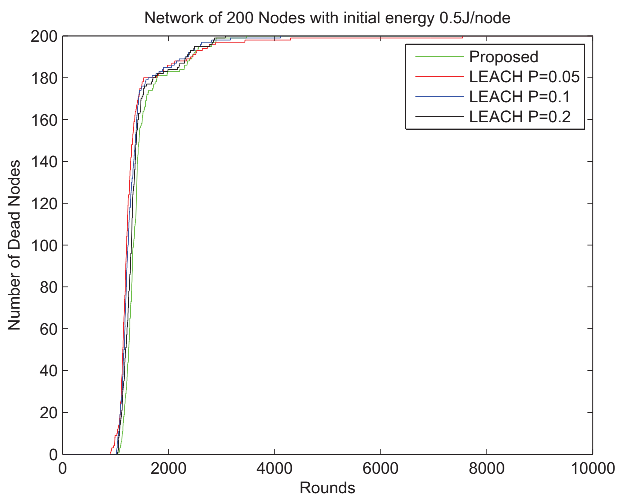


(c) Value of p using stretched exponential function

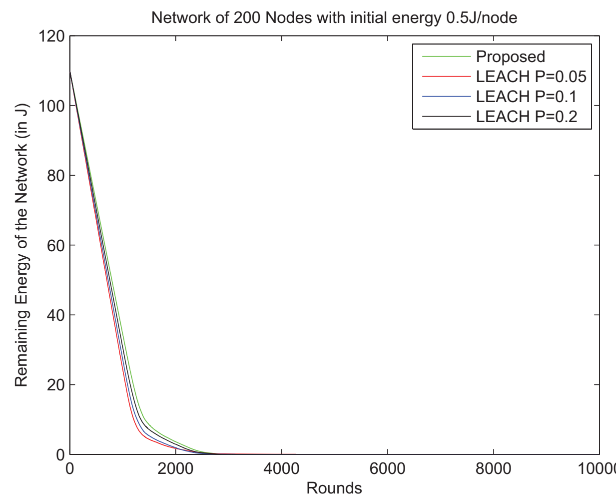


(d) Percentage of Nodes Dies

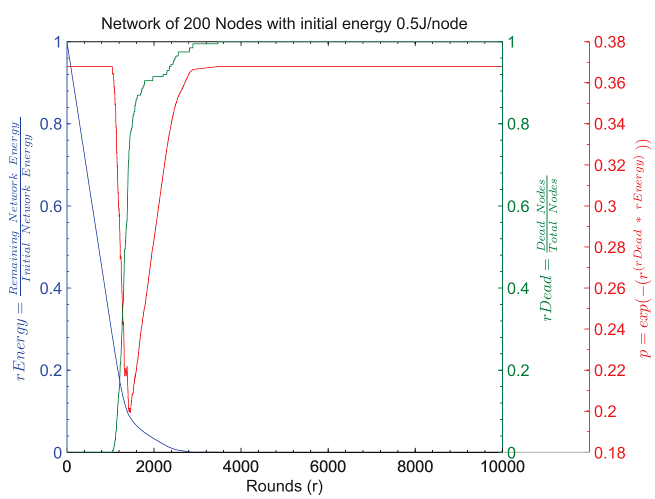
Figure 9.7: Comparison of proposed approach with LEACH protocol for a network of 200 nodes with initial energy 0.25J/node



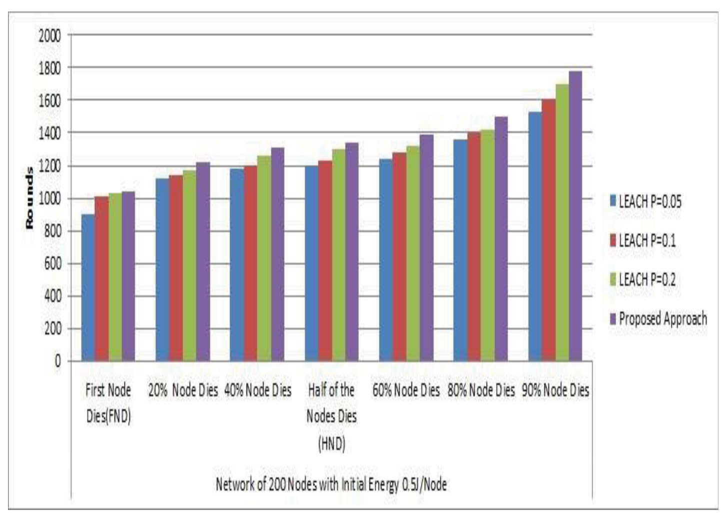
(a) Death of Nodes



(b) Remaining Network Energy

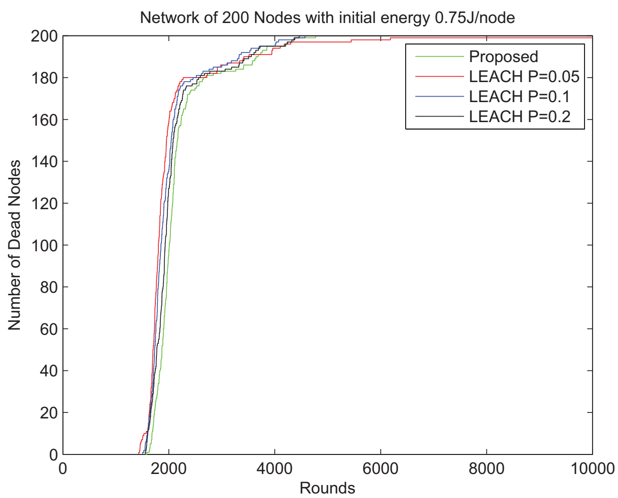


(c) Value of p using stretched exponential function

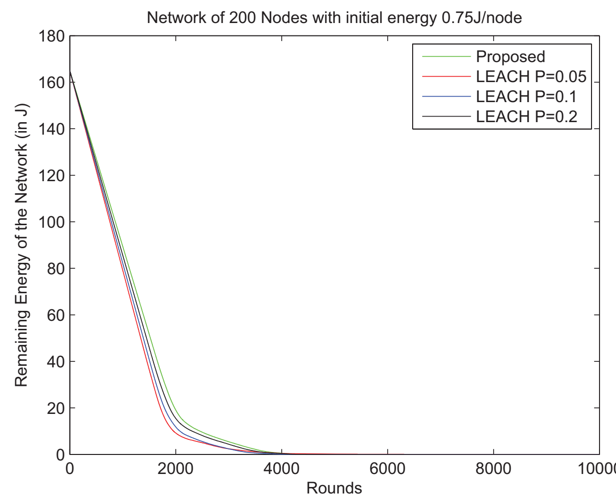


(d) Percentage of Nodes Dies

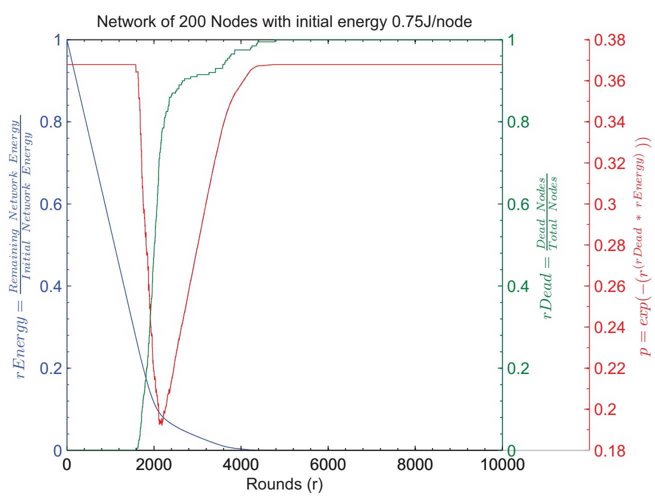
Figure 9.8: Comparison of proposed approach with LEACH protocol for a network of 200 nodes with initial energy 0.5J/node



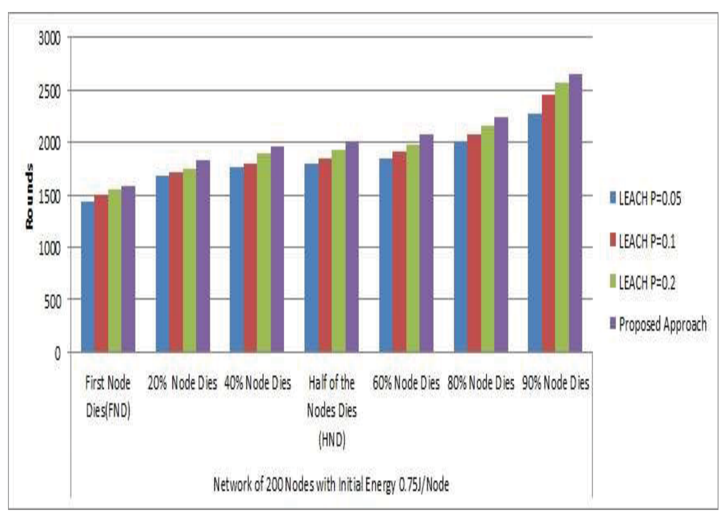
(a) Death of Nodes



(b) Remaining Network Energy

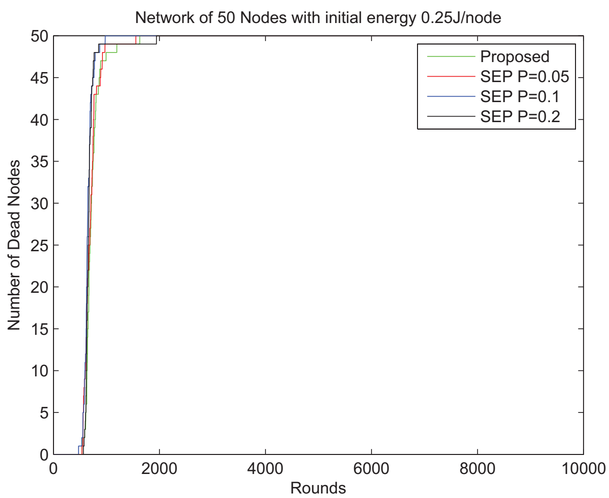


(c) Value of p using stretched exponential function

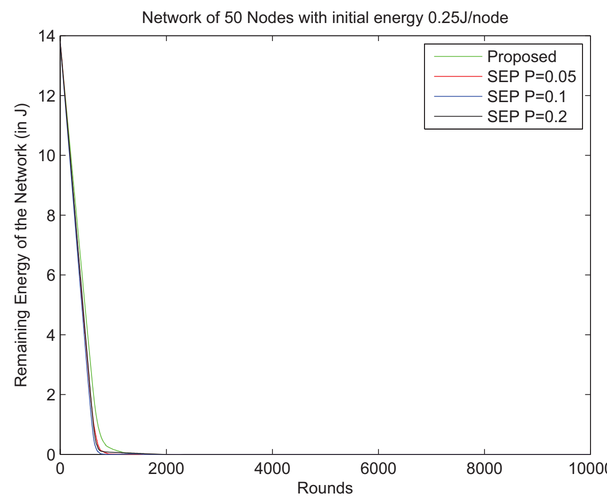


(d) Percentage of Nodes Dies

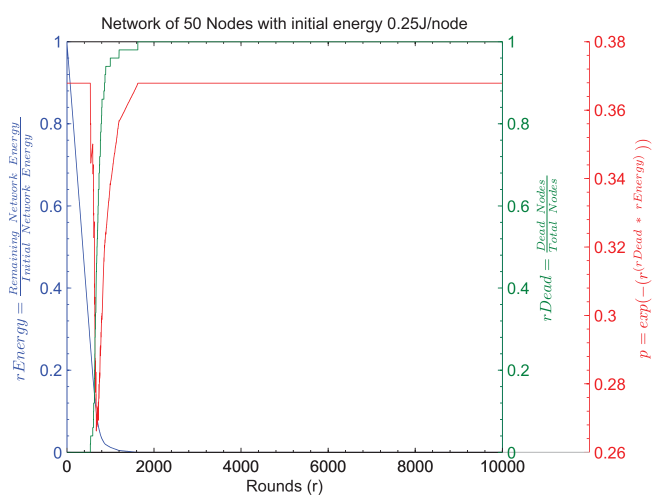
Figure 9.9: Comparison of proposed approach with LEACH protocol for a network of 200 nodes with initial energy 0.75J/node



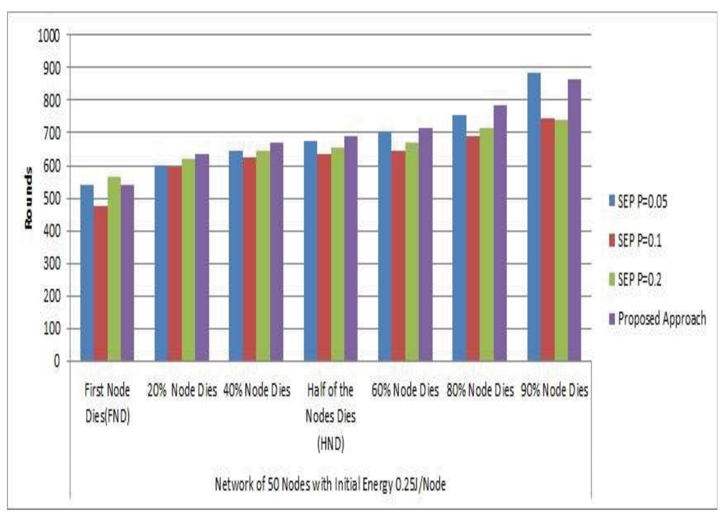
(a) Death of Nodes



(b) Remaining Network Energy

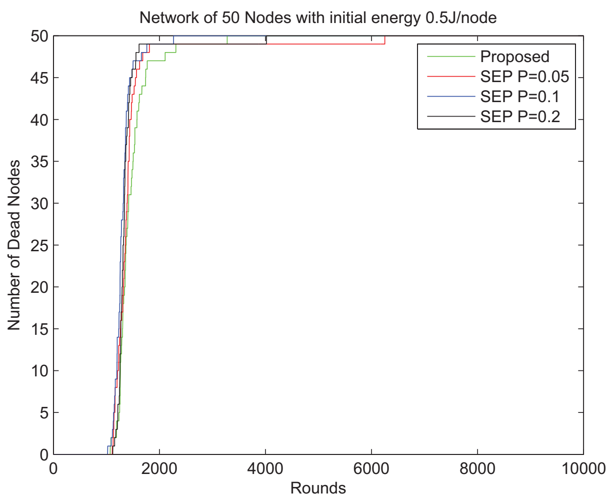


(c) Value of p using stretched exponential function

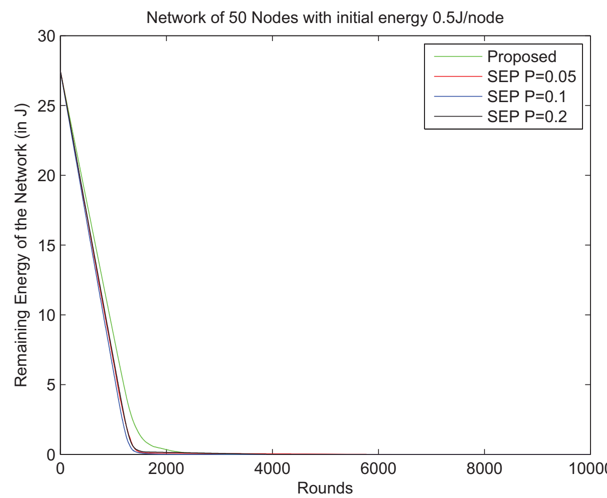


(d) Percentage of Nodes Dies

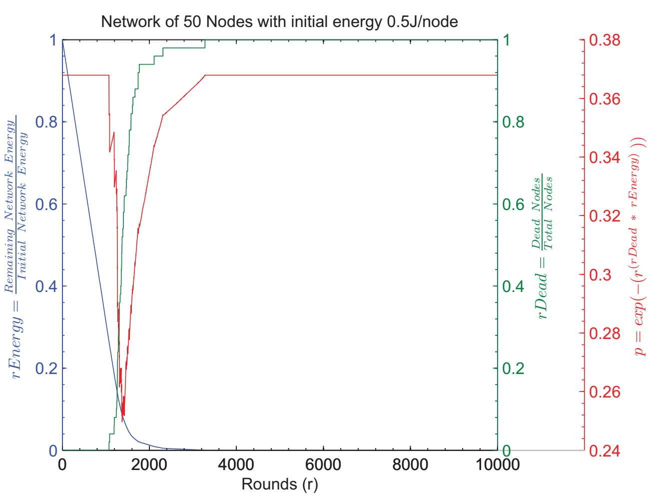
Figure 9.10: Comparison of proposed approach with SEP for a network of 50 nodes with initial energy 0.25J/node



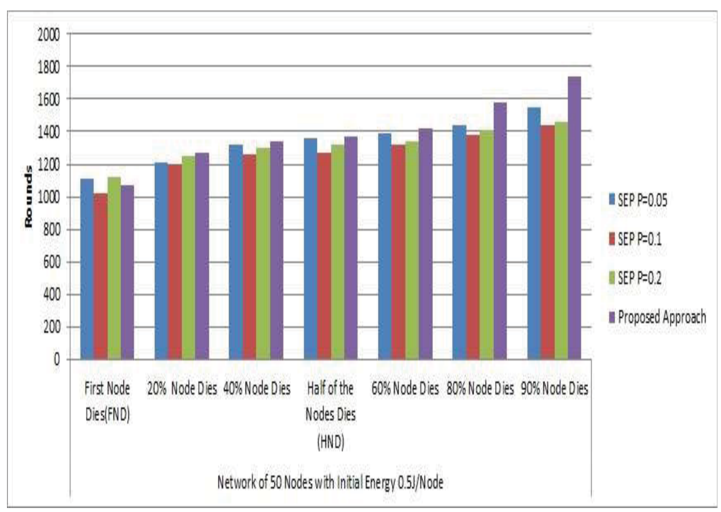
(a) Death of Nodes



(b) Remaining Network Energy

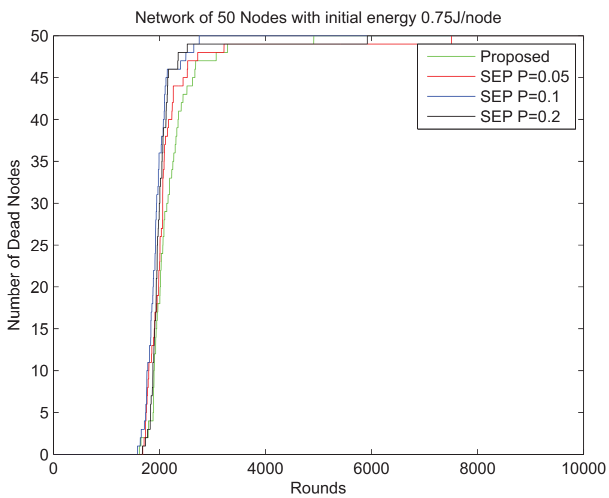


(c) Value of p using stretched exponential function

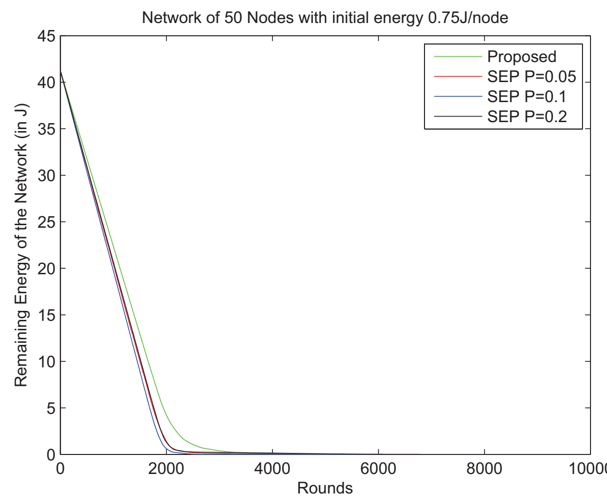


(d) Percentage of Nodes Dies

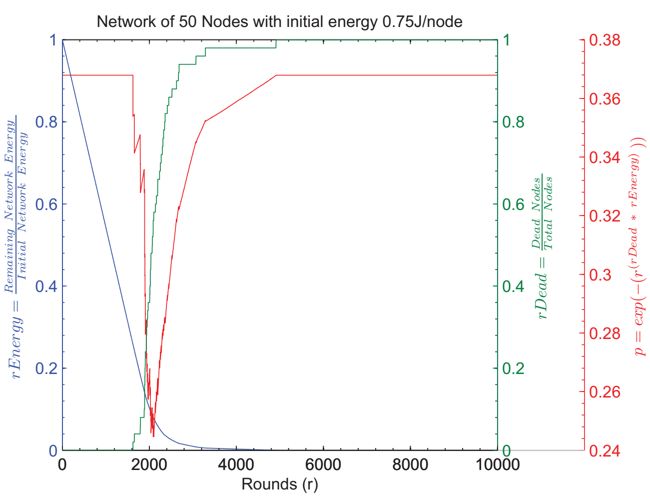
Figure 9.11: Comparison of proposed approach with SEP for a network of 50 nodes with initial energy 0.5J/node



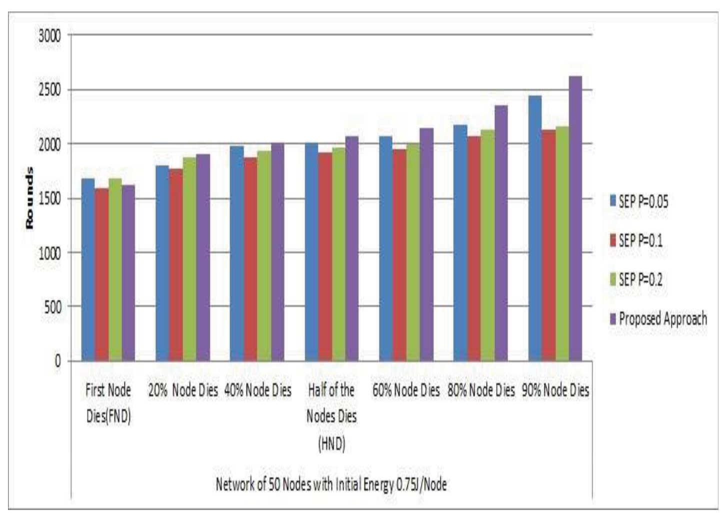
(a) Death of Nodes



(b) Remaining Network Energy

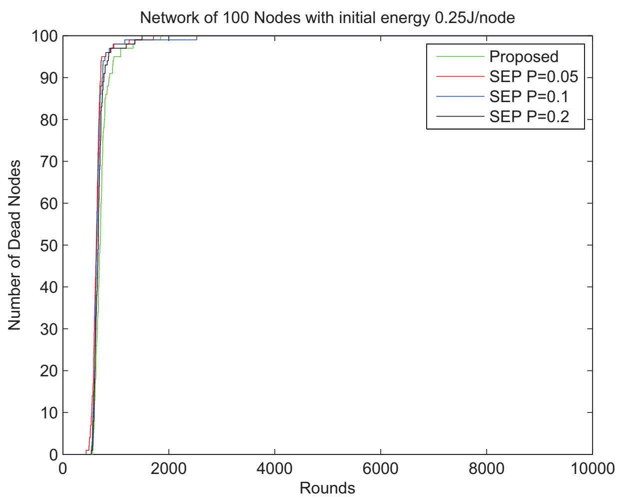


(c) Value of p using stretched exponential function

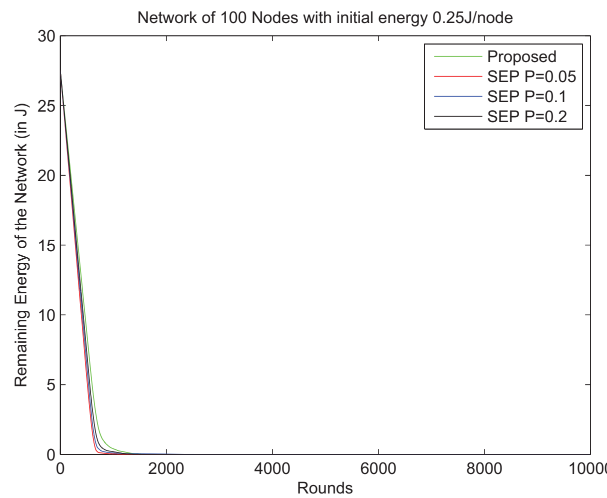


(d) Percentage of Nodes Dies

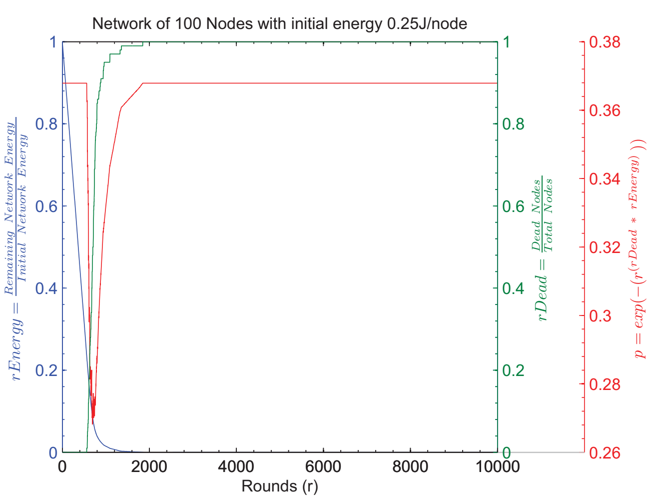
Figure 9.12: Comparison of proposed approach with SEP for a network of 50 nodes with initial energy 0.75J/node



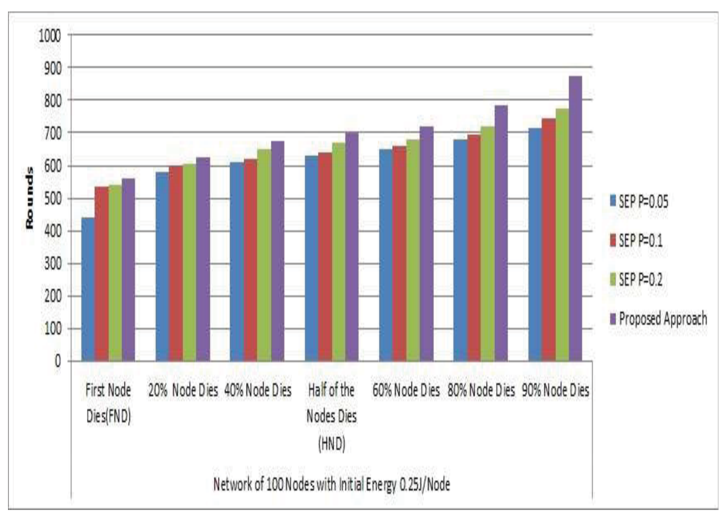
(a) Death of Nodes



(b) Remaining Network Energy

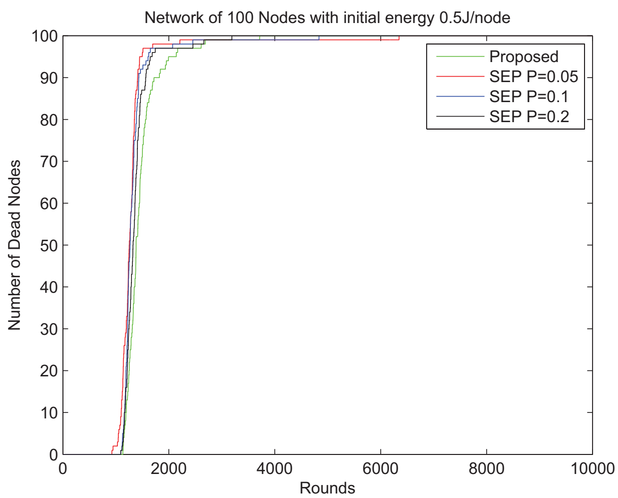


(c) Value of p using stretched exponential function

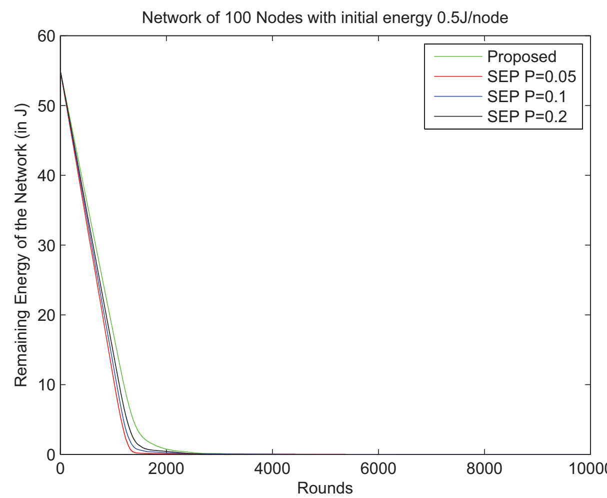


(d) Percentage of Nodes Dies

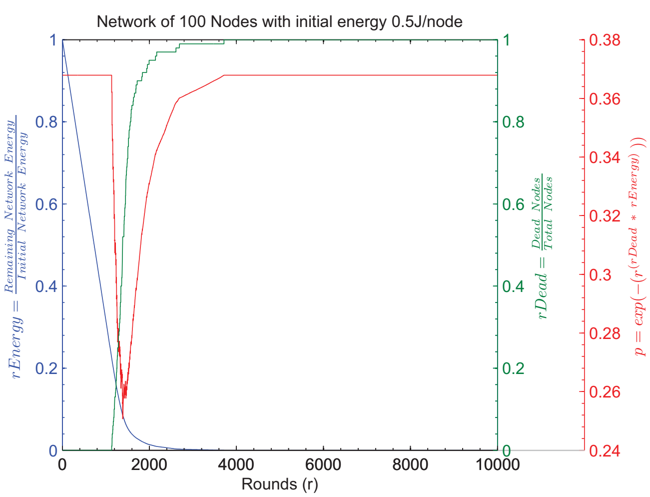
Figure 9.13: Comparison of proposed approach with SEP for a network of 100 nodes with initial energy 0.25J/node



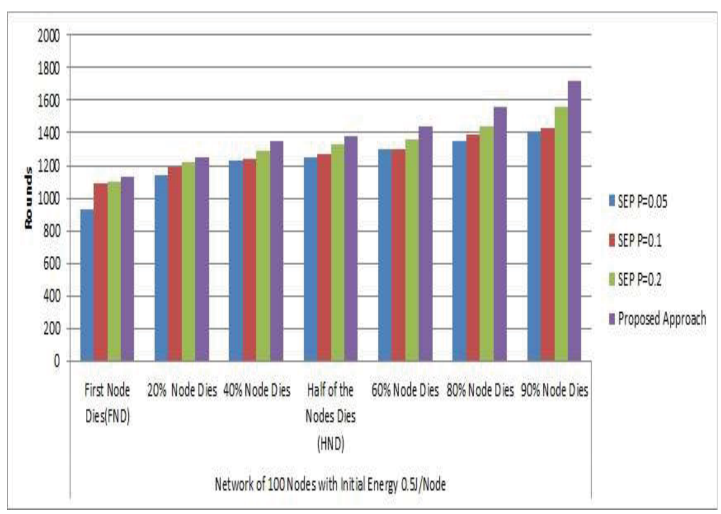
(a) Death of Nodes



(b) Remaining Network Energy

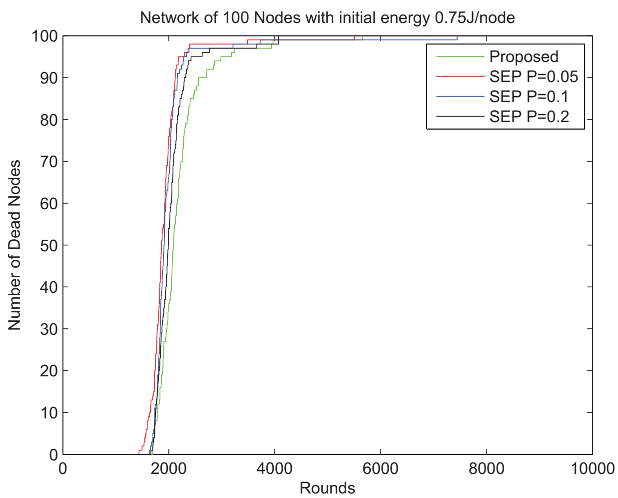


(c) Value of p using stretched exponential function

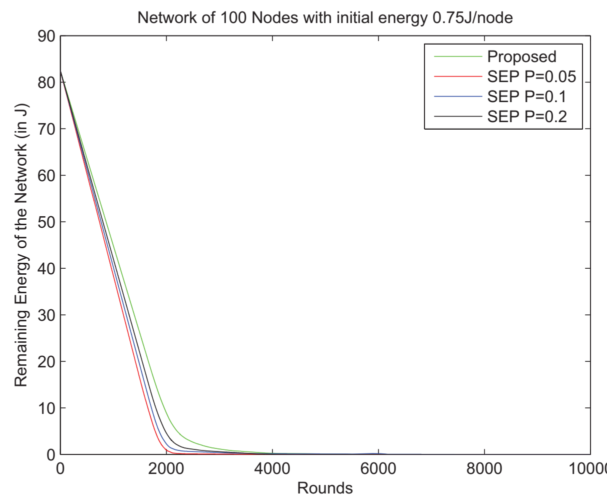


(d) Percentage of Nodes Dies

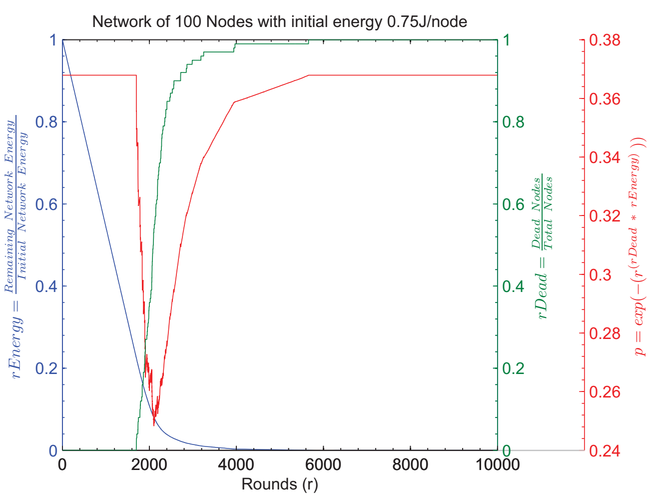
Figure 9.14: Comparison of proposed approach with SEP for a network of 100 nodes with initial energy 0.5J/node



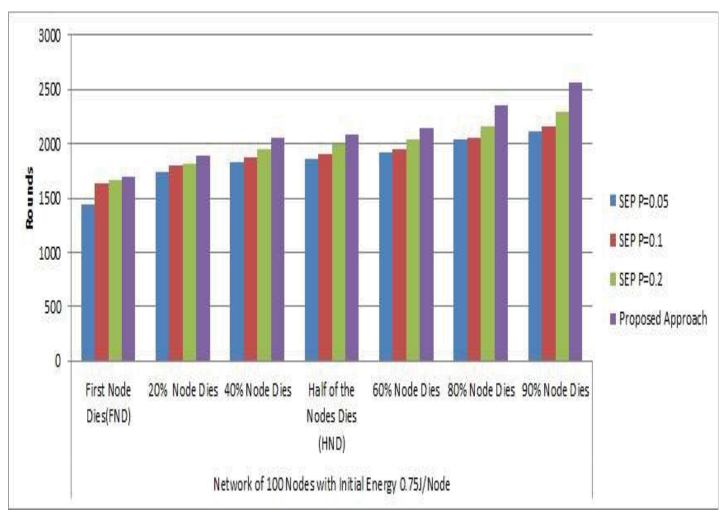
(a) Death of Nodes



(b) Remaining Network Energy

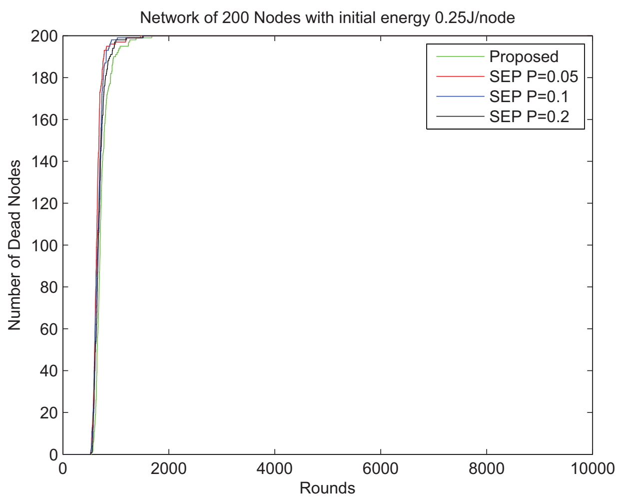


(c) Value of p using stretched exponential function

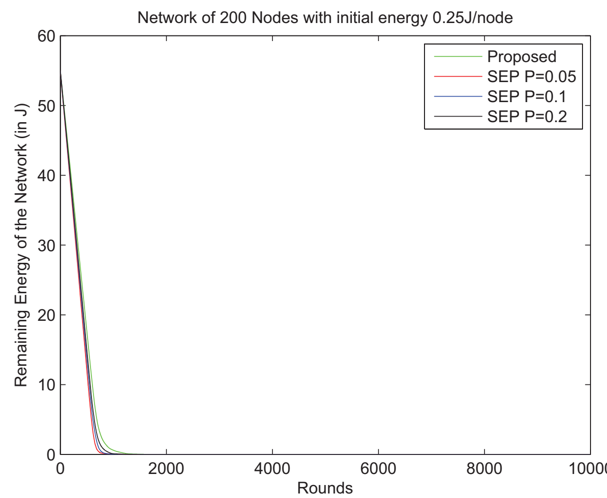


(d) Percentage of Nodes Dies

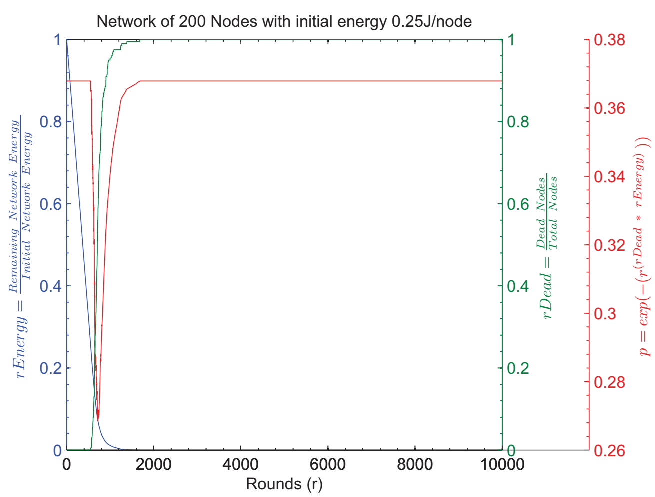
Figure 9.15: Comparison of proposed approach with SEP for a network of 100 nodes with initial energy 0.75J/node



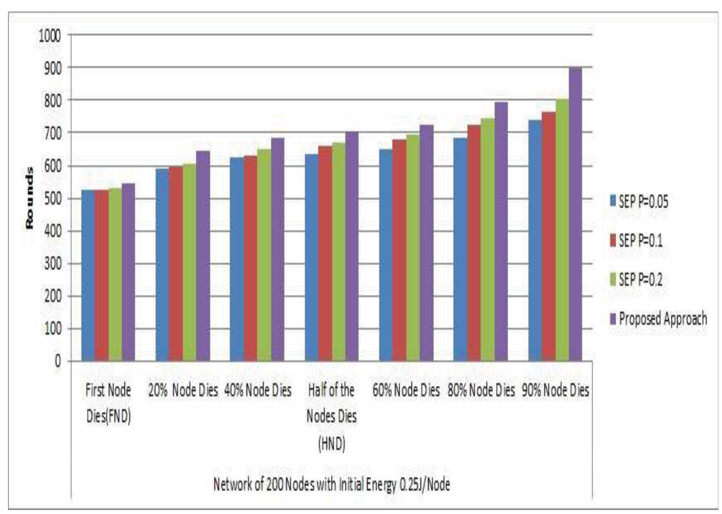
(a) Death of Nodes



(b) Remaining Network Energy

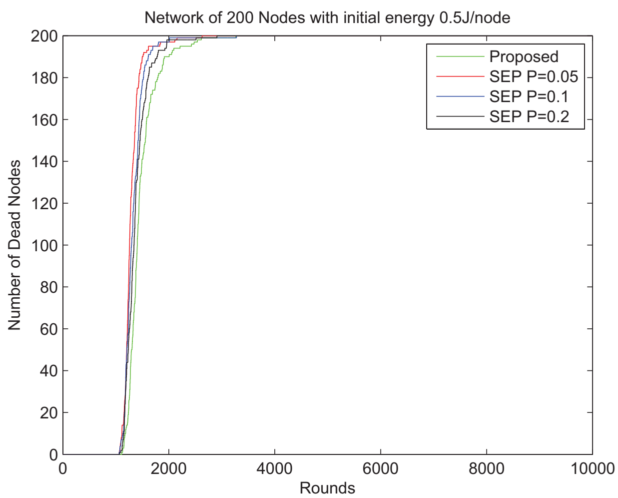


(c) Value of p using stretched exponential function

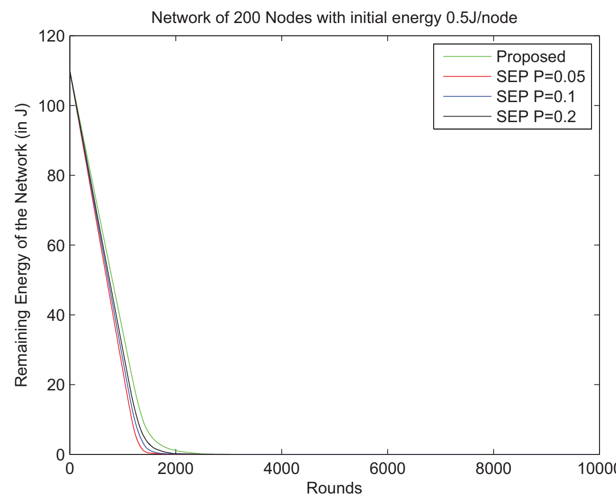


(d) Percentage of Nodes Dies

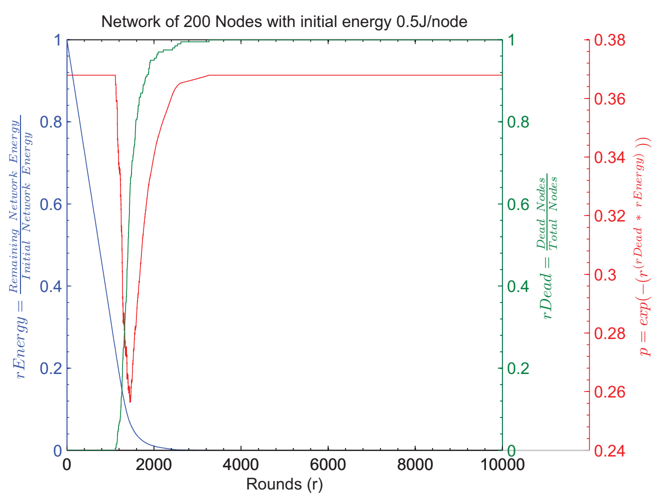
Figure 9.16: Comparison of proposed approach with SEP for a network of 200 nodes with initial energy 0.25J/node



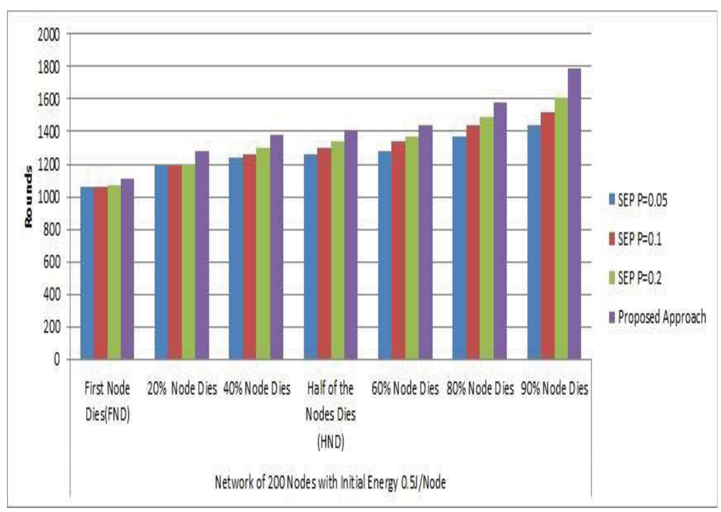
(a) Death of Nodes



(b) Remaining Network Energy

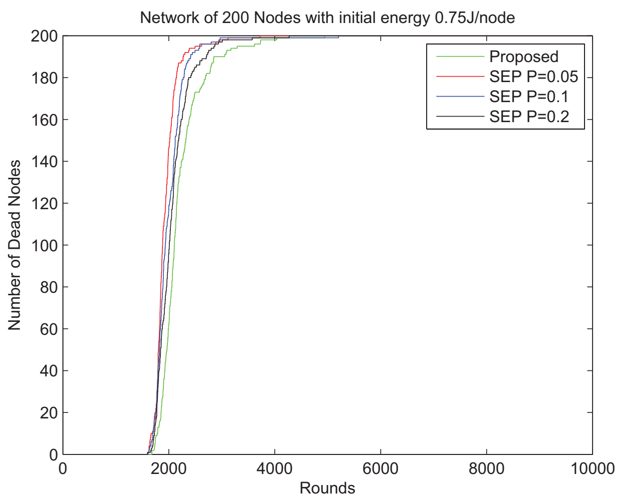


(c) Value of p using stretched exponential function

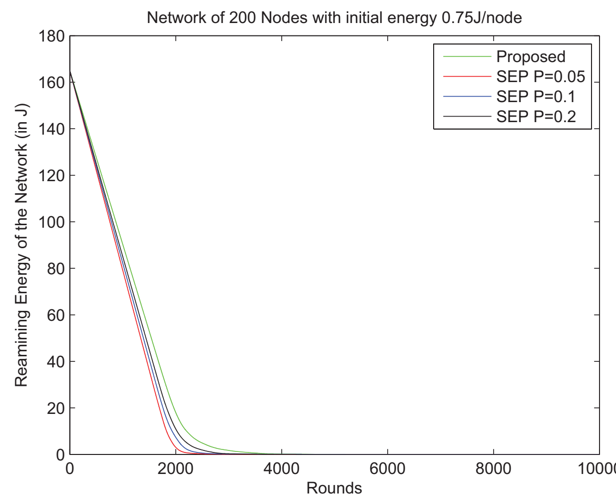


(d) Percentage of Nodes Dies

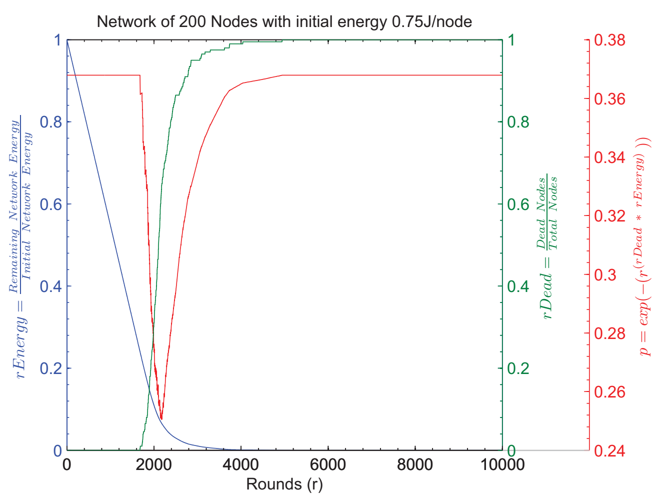
Figure 9.17: Comparison of proposed approach with SEP for a network of 200 nodes with initial energy 0.5J/node



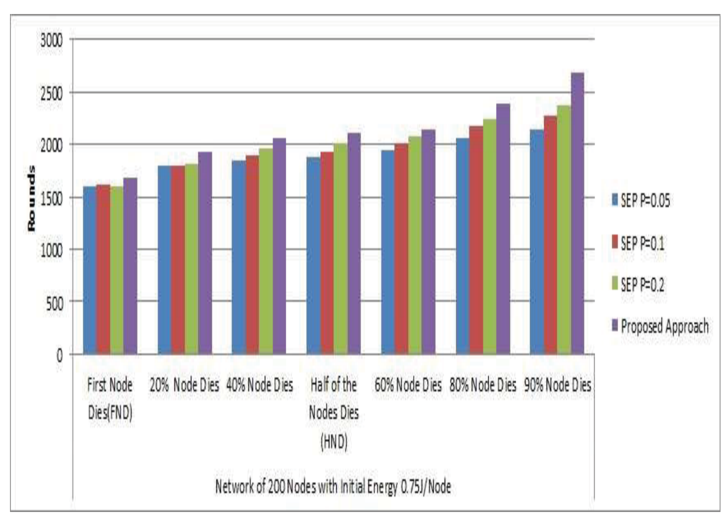
(a) Death of Nodes



(b) Remaining Network Energy



(c) Value of p using stretched exponential function



(d) Percentage of Nodes Dies

Figure 9.18: Comparison of proposed approach with SEP for a network of 200 nodes with initial energy 0.75J/node

Summary and Conclusion

The Summary of the work presented and the Conclusions derived therein is mentioned as under:

Summary and Conclusion

- There are four key points for energy consumption of a WSN node: i) Communication energy is propositional to the distance between the communicating nodes. ii) Communication energy is proportional to the number of bits exchanged between the nodes. iii) A node can deplete its energy during the idle listening period to detect any event. iv) A node can deplete its energy in the absence of the proper management of the duty-cycling time.

- The network lifetime can be improved by effective clustering mechanisms. The conclusion of the techniques developed during the course of research is as under:

  – Cluster Head election algorithms are stochastic in nature, which are affected by the methods used to generate random numbers.

  – The network lifetime can be improved by assigning weight to the random numbers according to the number of alive nodes in the network.

  – The network lifetime can be improved by sequential selection of the cluster heads.

  – The network lifetime can be improved by creating non-overlapping cluster regions. This results in the increase in the number of member nodes per round with the desired percentage of cluster heads, and thus improves network lifetime.

  – A weighted clustering scheme helps to improve the network lifetime. However, the weight value is a tuning parameter that depends upon the system parameters.

– Network lifetime can also refer to the energy/delay trade-off for the delay sensitive applications. In the course of research, the Energy Delay Index for Trade-off (EDIT) is derived for the delay sensitive applications by considering two different types of distances: Euclidean distance and Hop-count.

– Cross-layer Design helps to improve clustering mechanisms that results in improved network lifetime.

– The Cluster Head election method can be improved by minimizing cluster formation overhead. This can be achieved by relaxing maximum energy criteria (within the certain bound) used to elect cluster head. Enforcing a node to work as a CH also helps to improve the network lifetime, if the node has not decided to become CH or member within the stipulated time duration.

– Network lifetime is sensitive to the standard deviation observed in the number of cluster heads, i.e. network lifetime can be improved by minimizing the variance in the number of cluster heads.

– A technical trading tool, Bollinger Band, can be used to elect cluster head in the WSN by dividing node deployment area in the virtual grid. This method selects a node as CH that had not been elected as CH since long duration within the cluster. This method has advantage that a CH can send data to other clusters without knowing id of the receiving CHs. Data transfer along the scheduled path also helps to improve the network lifetime.

– A fair scheduling approach such as Round Robin scheduling can be used to elect cluster heads. To create round robin queue of each node, a double virtual grid based strategy is presented.

– A stretched exponential function based method is presented that dynamically compute the number of cluster heads during each round. It is also shown that number of cluster heads during the round affects the network lifetime. Also, dynamically computed cluster heads are more preferable compared to the fixed number of cluster heads.

Future Scope

The protocols have been tested under the assumption that the nodes, including sink, are stationary once they are deployed in the Region of Interest. Designing of the energy efficient routing with effective clustering mechanisms becomes a challenging task with the multiple static and/or mobile sink nodes, and it becomes more complex with moving nodes. These future protocols can be affected by the mobility models being used, mobility speed of nodes and/or sink, and pause time. Hence, tuning of these parameters is a challenging task as it depends upon the requirements of the underlying application.

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