ANALYSIS AND IMPLEMENTATION OF ENERGY EFFICIENT WIRELESS SENSOR NETWORKS

THESIS

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by

SONAM KHERA

Registration No. - YMCAUST/Ph 22/2011

Under the Supervision of

Dr. NAVDEEP KAUR
Professor
SGGSWU, Fatehgarh Sahib

Dr. NEELAM TURK
Professor
J.C. Bose UST, YMCA, Faridabad

DEPARTMENT OF ELECTRONICS ENGINEERING

Faculty of Engineering and Technology

J.C. Bose University of Science and Technology, YMCA

Sector-6, Mathura Road, Faridabad, Haryana, India

October, 2021

Dedicated

to

my children

Madhav and Manan

CANDIDATE'S DECLARATION

I hereby declare that this thesis entitled "**ANALYSIS AND IMPLEMENTATION OF ENERGY EFFICIENT WIRELESS SENSOR NETWORKS**" by **SONAM KHERA** being submitted in fulfilment of the requirements for the Degree of Doctor of Philosophy in ELECTRONICS ENGINEERING under Faculty of ENGINEERING AND TECHNOLOGY of J.C. BOSE University of Science and Technology, YMCA, Faridabad during the academic years 2012-21 is a bona fide record of my original work carried out under guidance and supervision of **Dr. NEELAM TURK, PROFESSOR, DEPARTMENT OF ELECTRONICS ENGINEERING,** J.C.BOSE UNIVERSITY OF SCIENCE AND TECHNOLOGY, YMCA, FARIDABAD and **Dr. NAVDEEP KAUR, PROFESSOR, DEPARTMENT OF COMPUTER SCIENCE,** SGGSW UNIVERSITY, FATEHGARH SAHIB, PUNJAB and has not been presented elsewhere.

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CERTIFICATE

This is to certify that this Thesis entitled "**ANALYSIS AND IMPLEMENTATION OF ENERGY EFFICIENT WIRELESS SENSOR NETWORKS**" by **SONAM KHERA,** being submitted in fulfilment of the requirement for the Degree of Doctor of Philosophy in **ELECTRONICS ENGINEERING** under Faculty of Engineering and Technology of J.C. BOSE University of Science and Technology, YMCA, Faridabad during the academic years 2012-2021, is a bona-fide record of work carried out under our guidance and supervision.

We further declare that to the best of our knowledge; the thesis does not contain any part of any work which has been submitted for the award of any degree either in this university or in any other university.

(Signature of Joint-Supervisor)

Dr. Navdeep Kaur
Professor
Department of Computer Science
Faculty of Engineering and Technology
SGGSW University
Fatehgarh Sahib, Punjab

Dated:

(Signature of Supervisor)

Dr. Neelam Turk
Professor
Department of Electronics Engineering
Faculty of Engineering and Technology
J.C. Bose UST, YMCA, Faridabad
Haryana.

Dated:

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(Sonam Khera)

Registration No. - **YMCAUST/Ph 22/2011**

ABSTRACT

Wireless Sensor Networks (WSN) have opened up a new arena of applications, which are not only giving more information about the environmental phenomenon but have also given better control to make life easy. These applications work on the basis of the data captured by a number of sensors with varied capabilities. Whether it is the latest development in the field of Internet of Things, monitoring large industrial units, precision agriculture, remotely operating power plants, monitoring long-distance transmission lines, distant medicinal diagnostics, controlling forest fires, monitoring volcanoes or keeping an eye on the climate change all such applications utilize sensor network technologies in one way or other.

The deployment of wireless sensor networks comprises of thousands of nodes spread across entire area under consideration with no or very less possibility of post deployment maintenance. Once deployed, the sensor nodes start operation in terms of sensing, capturing and transmitting data, for which the energy is consumed from limited power source installed in them. Due to inaccessibility, these power sources are non-replaceable, after their placement in the physical environment. Therefore, the phenomenon of energy consumption in individual sensor nodes plays significant role in determining the life of entire wireless sensor network. Improving energy efficiency has been the area of key interest in large number of research works under taken in the field of wireless sensor networks.

Special focus has been on hierarchical cluster-based schemes to reap the benefits like scalability, maintenance and reliability. Clustering not only simplifies the node management but also reduces the energy consumption and improves load balancing along with establishing robustness in the network. The node assigned the role of “Cluster Head” collects the data from the member nodes, aggregates it to forward the data to the base station directly or through some other intermediate Cluster Heads.

One of the first energy efficient hierarchical cluster based routing protocols for WSN was introduced by Heinzelman et al. in the form of LEACH. The protocol works on the principle of selecting the cluster head from among the number of nodes by rotation so that energy dissipation on account of communication can be shared by all nodes in the network. Though LEACH is still widely used and referred protocol, but still has certain disadvantages due to probabilistic selection of cluster heads and overhead of dynamic clustering and non-uniform distribution of cluster heads leading to increase in energy consumption.

In this research work, a new protocol *Hibernated Clustering Wireless Sensor Networks* (*HC-WSN*), based on improvements in existing protocols has been proposed. The proposed protocol tries to reduce the energy consumption in sensor nodes thereby increasing their period of operation and thus improving the overall life time of the wireless sensor network. This proposed protocol handles the issue of identification of cluster head through hierarchical clustering aided by inducing hibernation in sensor nodes for improving the energy efficiency and longevity of the network. The choice of node having maximum residual energy (higher than a threshold value) as cluster head eliminates the randomness and uncertainty regarding the cluster performance due to probabilistic selection as proposed in some of the existing protocols. Further the mobility and variation in location of sink has been considered to arrive at an energy efficient network.

The proposed protocol has been developed in phases which are simulated in MATLAB to assess the improvement over earlier phase. The proposed protocol HC-WSN has been compared with existing cluster-based routing protocols namely LEACH and Hybrid-LEACH, from the simulation results it has been found that HC-WSN performs better in terms of number of live nodes, average energy of the network and packets received at base station. Further the different scenarios in terms of variation in location of sink and mobility have been simulated to ascertain the scenario for an energy efficient network.

The proposed HC-WSN protocol has been implemented on an experimental hardware test-bed to know the validity of anticipated outcomes in near real time scenario. It has been found that the outcomes of the hardware test-bed are in line with the results received from MATLAB simulation. This test-bed has been provided with various parameters for user to test different scenarios considering the factors affecting the energy consumption in WSNs to gain hands on experience and better understanding in this field.

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LIST OF ABBREVIATIONS

CAMILS	Collision Avoidance Maximal Independent Link Set
CH	Cluster Head
DVS	Dynamic Voltage Scaling
E_{LTH}	Lower Threshold Energy
E_{UTH}	Upper Threshold Energy
FFDs	Full Function Devices
GTS	Guaranteed Time Slots
HC-WSN	Hibernated Clustering Wireless Sensor Networks
HEED	Hybrid Energy Efficient Distributed protocol
H-LEACH	Hybrid-Low Energy Adaptive Clustering Hierarchy
LEACH	Low Energy Adaptive Clustering Hierarchy
MAC	Media Access Control
MATLAB	MATrix LABoratory.
MIMO	Multi-Input-Multi-Output
PEGASIS	Power-Efficient Gathering in Sensor Information Systems
PHY	Physical Layer
RFDs	Reduce Function Devices
SDN	Software Defined Network
TDMA	Time Division Multiple Access
TEEN	Threshold Sensitive Energy Efficient Sensor Network protocol
WSN	Wireless Sensor Network
ZDOs	ZigBee Device Objects

CHAPTER I

INTRODUCTION

1.1 OVERVIEW

With the new and evolving technologies, human being tends to be omnipresent and intends to command control on everything that is going on in his accessible and inaccessible environs for better utilisation of resources. Although advances in the technology have equipped the world to communicate in a coherent manner, innovations in sensing technology aided with advancements in the field of networking have given an edge over natural senses and have made monitoring in hostile environments feasible. Wireless Sensor Networks [1] is the enabling technology which, with the help of a variety of sensors, provides control over inaccessible environments like ocean floors, active volcanoes, dense forests as well as in war zones during armed conflicts.

A wireless sensor network is a network of spatially distributed sensing devices called nodes that are specially designed to measure and monitor various physical parameters of interest such as temperature, pressure, humidity, vibration, sound, motion, etc. These devices are equipped with receiving, storing, processing and transmitting abilities to capture the data from the deployment environment, processing it and transmitting it across to the base station. The deployment of wireless sensor networks comprises of thousands of nodes spread across entire area under consideration with no or very less possibility of post deployment maintenance. Due to key factors like quantum of deployment, limited energy and unattended operation emphasis is laid on reducing the cost of sensor nodes, improving their energy efficiency and efficient utilization of limited available bandwidth. Lot of research work has been undertaken with focus on lowering cost of manufacturing, deployment in hostile environments, reducing hardware size, adaptive network topology, maximising fault tolerance, scalability, limiting power consumption, judiciously utilising available bandwidth, securing communication and improving energy efficiency.

On deployment, the sensor nodes start operation in terms of sensing, capturing and transmitting data, for which the energy is consumed from limited power source installed in them. Due to inaccessibility, these power sources are non-replaceable, after their placement in the area of focus. Therefore, the phenomenon of energy consumption in individual sensor nodes plays significant role in determining the life of a WSN. Improving energy efficiency has been the area of key interest in large number of research works under taken in the field of wireless sensor networks. But special focus has been on hierarchical cluster-based schemes to reap the benefits of scalability, maintenance and reliability. Clustering not only simplifies the node management but also reduces the energy consumption and improves load balancing along with establishing robustness in the network. The node assigned the role of "Cluster Head" collects the data from the member nodes, aggregates it to forward the data to the base station directly or through some other intermediate Cluster Heads.

Heinzelman et al. proposed one of the first energy efficient hierarchical routing protocols for WSN in the form of LEACH [2]. The protocol works on the principle of selecting the cluster head from among the number of nodes by rotation so that energy dissipation on account of communication can be shared by all nodes in the network. Though LEACH is still widely used and referred protocol, but has certain disadvantages due to probabilistic selection of cluster heads and overhead of dynamic clustering, also the non-uniform distribution of cluster heads leads to increase in energy consumption.

This research work proposes a new protocol *Hibernated Clustering Wireless Sensor Networks* (*HC-WSN*), based on improvements in existing protocols. The improvements have been made in terms of reduction in energy consumption in sensor nodes, so as to increase the period of operation and ultimately enhance the overall life time of WSN. The research work focuses on the issue of cluster head identification through hierarchical clustering and further inducing hibernation in member nodes for improving the energy efficiency and longevity of the network. The choice of node having maximum residual energy (higher than a threshold value) as cluster head, eliminates the randomness and uncertainty regarding the cluster performance due to probabilistic selection as proposed in some of the existing protocols. The mobility and variation in sink location has also been taken into account to arrive at an energy efficient network.

The proposed protocol has been developed in incremental phases which are simulated in MATLAB to assess the improvement over earlier phase. To analyse the performance of the proposed protocol HC-WSN has been compared with existing cluster based routing protocols namely LEACH and Hybrid-LEACH. The simulation results thus obtained indicate that HC-WSN performs better in terms of number of live nodes, average energy of the network and packets received at base station. Further, the impact of variation in location of sink and sink mobility has been examined using the proposed protocol to establish the sink condition for an energy efficient network.

To know the validity of anticipated outcomes in near real time scenario, the proposed HC-WSN protocol has been implemented on an experimental hardware test-bed. It has been found that the outcomes of the hardware test-bed are in line with the results received from MATLAB simulation. This test-bed has been provided with parameters for user to test different scenarios considering the factors affecting the energy consumption in WSNs and to gain hands on experience for better understanding.

1.2 RESEARCH CHALLENGES IN WIRELESS SENSOR NETWORKS

WSNs have unique characteristics, which make them useful for variety of applications. There are lots of constraints involved with WSNs, so implementation of real time applications is itself a challenging task. WSNs are specifically deployed to perform sensing operations in environments where human intervention is not possible, once deployed the WSN starts performing its functions and consumes the energy from the limited power source installed in sensor nodes. Due to inaccessibility of sensor nodes, these power sources are non-replaceable. Therefore, the phenomenon of energy consumption in sensor nodes plays significant role in determining life of the WSN. Apart from energy consumption various other research challenges in the field of WSNs are:

1) **Production Cost:** The wireless sensor networks comprise of deployment of large number of sensor nodes, due to the scale factor, cost of even a single node plays significant role in determining quantum of investment involved in setting up

complete network. It is understood that cheaper the solution, higher will be the no. of applications. With the advancements in electronics hardware design and manufacturing, efforts are being made to minimize the cost of sensor nodes.

2) **Operating Environment:** The nodes in sensor networks are densely deployed and they generally work unattended in inaccessible geographic locations and harsh terrains. They might be operating: in busy intersections, on the surface or at the bottom of oceans, in the interiors of machinery, in battlefields, attached to animals or fast-moving vehicles etc. In view of these scenarios the operating environment of sensor node should have following capabilities.

   i. Concurrency management
   ii. Platform independent and application driven
   iii. Intrinsic features to increase the energy efficiency/ energy harvesting
   iv. Should be priority based and enabled with easy programming paradigm

3) **Hardware Constraints:** A sensor node comprises of components with four key functions: sensing, processing, power supply, and transmission / reception. To enable prolonged and efficient operation of the sensor nodes (also called motes), there is limitation to these key components. Due to the limited memory of sensor nodes, only light weight program code can be loaded in the sensor nodes, Sensor nodes have 8 bit or 16 bit microprocessors, which are not capable of implementing complex algorithms. Due to limited power sources, it is therefore, necessary to limit the communication and computation cost. Wireless sensor Networks are deployed in hostile areas without any fixed infrastructure and it is difficult to perform continuous surveillance after network deployment therefore; fabrication of sensor nodes should ensure resistance to any sort of tempering or theft.

   There might be some application specific components required to be attached with sensor node like: a power generator, a location finding system, or a mobilizer. The signals captured by sensing unit are sent to processing unit. The processing unit carries out the specified tasks . Transceiver unit connects node to network. Power unit must be backed by energy scavenging unit like solar cell. Some other application dependent units are also part of the sensor node. Various routing schemes and sensing tasks have requirement of location awareness. A mobilizer may sometimes be required to furnish sensor mobility to carry out specific tasks.

4) **Network Topology**: Many of the wireless sensor network applications require environmental monitoring for which it is not possible to place each sensor node at a specific location or position and they are required to be scattered randomly in the field, leading to a network which is infrastructure less and self-organised. The remote and unattended sensor nodes are more prone to failures and make topology management a challenging job. The topology maintenance issues can be examined in following phases: deployment phase, Post-deployment phase and re-deployment of supplementary nodes. Due to limited energy source, some sensor nodes may cease operation leading to unpredictable arrangement of sensor node deployment.

5) **Unreliable Communication:** In Wireless Sensor Networks, sensor nodes communicate through radio interface configured at same frequency band. Such communication can be interrupted by external sources leading to data security issues. Moreover, due to limited communication range of sensor nodes, packets received at destination may get damaged due to errors in communication channel or lack of radio coverage.

6) **Latency:** Most of the applications require large scale deployment of sensor nodes, which cause multi-hop routing and processing at sensor node level, this may lead to latency in network and make the synchronisation among sensor nodes difficult.

7) **Transmission Media:** The nodes are connected via wireless medium in case of multi hop sensor networks. The wireless links are formed by radio or infrared media. For enabling network operations globally, the communication medium must be available worldwide. A low-cost and low-power transceiver is required by network. Due to constraints and trade-offs between antenna efficiency and power consumption limits, the choice of carrier frequency in such cases should be of ultrahigh range. Most of the existing sensor hardware is based on RF circuit design. Other possible mode of inter node communication is infrared which is license free and robust to interference but its dependency on line of sight is the key constraint.

8) **Fault Tolerance:** The network tasks must not be affected by node failures. Fault tolerance is the ability to maintain the functionalities of network without any interruption owing to node failures. Fault tolerance has to be high when sensed data are critical like in case of a WSN being used in a battlefield for surveillance. To strengthen fault tolerance of the network, issues like quick depletion of battery, buffer overflow due to low memory should be addressed at the time of designing the Wireless Sensor Networks.

9) **Scalability:** The number of nodes deployed in sensor field might be of the order of few numbers to few thousands in accordance with application. The new approaches must be capable to work with varying number of nodes. They should be able to exploit the dense nature of the network. The number of sensor nodes in a WSN is volatile due to number of reasons; the network should perform smoothly irrespective of addition / deletion of sensor nodes.

10) **Power Consumption:** The wireless nodes are equipped with limited power source. There are a few scenarios in which replacement of power resources is not viable. Therefore, the lifetime of nodes depends strongly on depletion rate of power source. In multi-hop networks each node plays the role of data originator and as well as data router. The failure of some of the nodes cause significant

changes in topology and may require network re-organization. Hence conservation and management of power takes an additional significance.

11) **Data Security Issues:** WSNs perform standard activities and most routing protocols are known publicly at the design stage itself. The security algorithms are complex in nature and heavy in terms of computation and communication, lot of research is being carried out to make such algorithms compatible with limited resources. The uncontrolled environment and broadcast nature of transmission medium pose additional security requirements like node authentication for establishing reliability of the message by identifying its origin. A sensor node has to prove its validity to other motes in the network and the base-station. The base-station confirms the authentication of the sensor nodes to avoid adversaries from sending malicious information in the network.

1.3 MOTIVATION FOR RESEARCH WORK

Wireless sensor networks, is a technology evolving for better control on environmental parameters. The ease of use due to wireless communication enabled with variety of sensors has opened abundant applications in coming future. The WSN technology also forms one of the building block of the much talked about field - The Internet of Things. For successful deployment and continued operation of a wireless sensor network it is desirable to overcome challenges especially in the field of energy efficiency and network security. Though much work has been done in the field of improving energy efficiency, there is further scope for improvement and exploring newer options. The research work proposes a protocol for energy consumption in the network. The proposed protocol has been simulated and to gain hands on experience in the nitty-gritty of hardware implementation of wireless sensor network, an experimental test bed has been prepared.

1.3.1 Problem Statement

Wireless sensor networks due to their small size, inaccessible deployment and limited energy source cannot be handled with routine networking protocols already in existence for wired and Wi-Fi networks. The routing protocols for WSNs should be capable of dynamic topologies without any IP based addressing schemes. They should efficiently manage resources on account of scarce energy, transmission power and energy. For ensuring prolonged operation, the sensor nodes operate at low processing speeds and many a times sense the same data due to close vicinity and redundancy. In such scenarios, cluster-based routing protocols are found to be most suitable for Wireless Sensor Networks. The clustering-based protocols not only make the organisation of the network manageable, but also optimise energy consumption among the sensor nodes. Clustering limits the quantum of data transmission to the destination through collaborative signal processing techniques viz. data fusion. But implementing clustering is itself a complex task with various parameters like span of cluster, cluster formation, number of cluster heads, eligibility of node to become a cluster head, number of iterations for which a node will remain cluster head, overheads of cluster head selection and cluster formation. This is further complicated with the dynamic nature of the network with frequent additions and removal of nodes. These conditions attribute to difficulty in handling clustering in wireless sensor networks through traditional techniques or by conventional mathematical modelling.

Several clustering based protocols have been proposed in this domain like LEACH, LEACH-C, HEED etc. The latest research work: HEED i.e. Hybrid Energy Efficient Distributed clustering suffers from unbalanced energy consumption and huge overhead formed due to multiple rounds. But probabilistic selection of cluster heads in LEACH and excess energy consumption in multiple rounds under HEED require further improvement. The proposed protocol decides upon the cluster head after taking into consideration the residual battery voltage of all the nodes in the network. The nodes having residual battery voltage less than a threshold value are also forced to hibernate or sleep, so as to be available when other nodes cannot become cluster heads. Further, to overcome energy loss due to collisions and to optimally utilize the available bandwidth, the field under consideration is divided into equal sized sections and redundant presence of nodes with in each section is utilised and only optimum number of nodes are maintained in active state at particular instant of time to preserve the energy of remaining nodes for maintaining continuity of the network. The proposed protocol supports multi-hop routing and data fusion at the level of cluster heads for limited transmission of data from the end nodes to the sink. The proposed protocol has been christened Hibernated Clustering – Wireless Sensor Networks (*HC-WSN)*. Apart from simulating the HC-WSN, an experimental hardware test-bed has been prepared to gain hands on experience of real time implementation.

1.4 SCOPE OF RESEARCH WORK

To gain the holistic and in depth knowledge of the subject, the research work has been undertaken with a much wider goal i.e. "Analysis and Implementation of Energy Efficient Wireless Sensor Networks". The work started with understanding the need and applications of wireless sensor networks to gain knowledge about specific characteristics of the technology. Further the challenges being faced in the implementation and prominent research trends in the field have been studied. Out of numerous constraints, the energy efficiency of the wireless sensor networks has been focused. The work then involves review of literature available regarding the research already undertaken. After evaluating the earlier works, a new protocol has been proposed to improve the energy efficiency of the network through cluster based routing protocol. The proposed protocol has been simulated on MATLAB and simulation results have been compared with the results available from earlier proposed protocols. Further, the proposed protocol has been implemented on the hardware test-bed and the outcomes have been analysed.

1.5 RESEARCH OBJECTIVES

Entire work has been divided into smaller research objectives which cover the step by step progress of the research work. These research objectives will be covered in detail to establish the understanding of entire work undertaken. These research objectives are:

a) Literature review of various factors affecting the energy efficiency of Wireless Sensor Networks.
b) Proposing a protocol to enhance the life time of Wireless Sensor Networks by improving the energy efficiency.
c) Performance analysis of proposed protocol.

d) To design an experimental multi-node wireless sensor network test-bed hardware
e) To implement proposed protocol on experimental wireless sensor network test-bed and analysis of performance.

1.6 RESEARCH PLAN

The strategy adapted to carryout research work has been depicted in the form of a Research Plan shown in Figure 1.1. As is evident from the research plan, extensive literature review has been carried out focusing mainly on the energy consumption perspectives and the routing protocols in Wireless Sensor Networks.

Based on the earlier research work in the area, it has been found that energy consumption in sensor nodes is the key factor influencing the overall lifetime of a wireless sensor network. Various routing protocols have been studied and clustering based hierarchical protocols have been found to meet the objective to certain extent. To further improve the energy efficiency a new approach HC-WSN has been proposed and the simulations have been undertaken using MATLAB. The proposed protocol has been evolved in phased manner. Simulations have been carried out to compare the proposed protocol with other existing routing protocols. Subsequently, an experimental hardware based test-bed has been prepared and the proposed protocol has been implemented along with features to customise the inputs for future experiments.

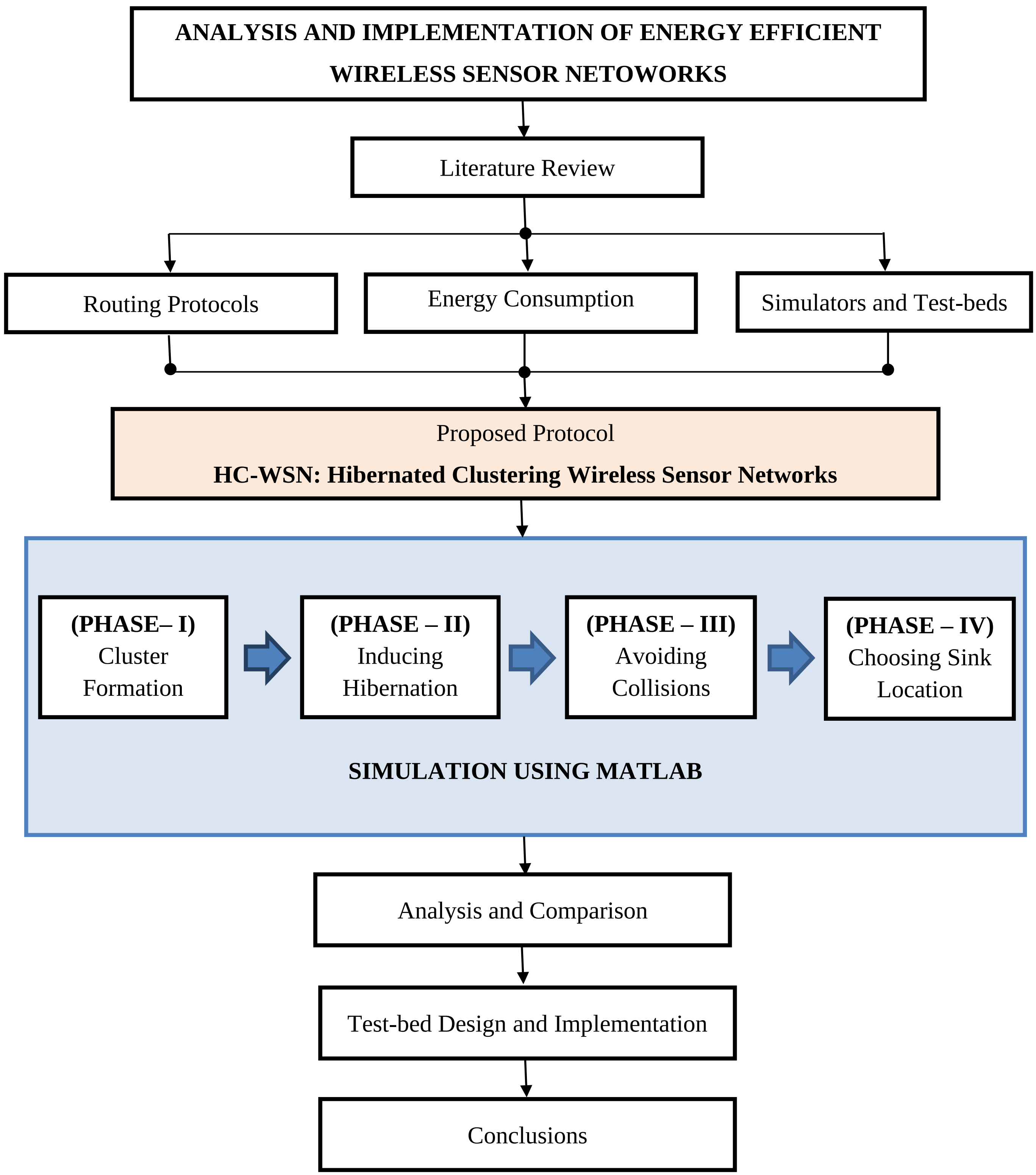


Figure 1.1: Research Plan

1.7 THESIS CONTRIBUTION

The domain of wireless sensor networks has been explored during the research work. The work has not only given an in depth understanding of the underlying principles of wireless sensor networks, but has also given hands on experience in simulation and implementation of the wireless sensor network test-bed. In this research work, some of the techniques for reducing power consumption in wireless sensor networks have been reviewed and new protocol for improving energy efficiency to enhance overall network lifetime has been proposed. The proposed protocol has also been implemented on hardware test-bed.

The experimental test bed prepared during the research work can be utilised to carry out further experiments and analysis in the field of Wireless Sensor Networks. The test-bed can be further programmed for simulating different scenarios for studying the rapidly emerging field of Internet of Things.

1.8 OUTLINE OF THESIS

To give an in-depth, in-sight into the research work undertaken, the thesis has been divided into seven chapters.

Chapter – I: Introduction

Chapter – I gives introduction to the thesis and research challenges in the field of Wireless Sensor Networks have been covered in detail. The chapter also covers in detail the motivation for the research, scope of work, contribution and objectives of the research. A pictorial representation of research plan has been given for better understanding.

Chapter – II: Literature Review

Chapter –II covers necessary background on fundamental concepts in Wireless Sensor Networks, their characteristics and applications, findings from the extensive literature review undertaken during the research work. It also reviews the published research in the field of improving energy efficiency of wireless sensor networks and provides details about the available simulation environments and test-bed technologies available for experiment with Wireless Sensor Networks.

Chapter –III: Energy Consumption Perspective of Wireless Sensor Networks

This chapter discusses the components of a WSN and elaborates constituents of a typical sensor node; it focuses on the various parameters of energy consumption and discusses in detail various factors influencing it. Aspects of useful power consumption and points of wasteful power consumption have been covered in detail.

Chapter – IV: IEEE 802.15.4: The Standard For Wireless Sensor Networks

It includes study of IEEE 802.15.4 standard for LR-PANs and covers the network architecture model of WSNs. The ZigBee standard for WSNs has also been discussed in detail.

CHAPTER –V: Proposed Protocol: Hibernated Clustering - Wireless Sensor Networks (HC-WSN)

This chapter takes inference from the works already under taken in the field of cluster based routing algorithms for improving energy efficiency by various researchers. A new protocol has been proposed to enhance the energy efficiency and network life time. Features of this proposed protocol have been discussed in detail along with simulation using MATLAB and analysis of results.

Chapter – VI: Test-Bed Design and Implementation

This chapter discusses in detail the available test-beds and sensor nodes; it focuses on the requirement and benefits of proposed experimental test-bed. The components used, their characteristics and mode of operation is discussed in detail. This chapter covers the different stages of implementation of proposed protocol including various experimental scenarios which have ultimately led to the proposition of HC-WSN. The network life time estimated on the basis of residual battery capacity of different sensor nodes in four different scenarios is discussed and analysed to validate simulation outcomes of HC-WSN.

Chapter – VII: Conclusions and Future Scope

This chapter covers the benefits that can be derived from the research work undertaken like development of applications for upcoming technologies like Internet of Things, Smart Metering for Energy Consumption and better understanding of practical aspects of WSNs. The chapter concludes the entire research work in terms of the protocol proposed, its analysis and immediate benefits. The chapter discusses the future scope of the work including improvement in data security of network with respect to proposed HC-WSN protocol.

CHAPTER II

LITERATURE REVIEW

2.1 INTRODUCTION

In different Wireless Sensor Network applications the constituent tiny sensor nodes are mostly deployed in unfriendly environments where replenishment of energy sources is not possible. The chapter gives a background of the wireless sensor networks with focus on applications and their unique characteristics.

Since evolution of Wireless Sensor Networks in the form of WINS i.e. Wireless Integrated Network of Sensor [3], efforts have been made to enhance the network life time by efficiently utilising the energy stored in the sensor nodes. During the research, various related works have been studied; same are being presented here some of these being the earliest ones and some from the recent times, to give complete idea regarding how the field of improving energy efficiency of Wireless Sensor Networks has evolved and what are the major research issues to be addressed.

Later in the chapter various simulation tools and test-beds which have evolved over time have been described.

2.2 WIRELESS SENSOR NETWORKS

Wireless Sensor networks are a rapidly evolving technology which provides an interface between the real world and the digital world. The technology promises to revolutionize the way we live, work and interact with the physical environment. A typical wireless sensor network (WSN) is a network of randomly distributed and spatially dispersed large no. of dedicated sensor nodes for monitoring and recording the physical conditions of the environment and transmitting the collected data to the base station.

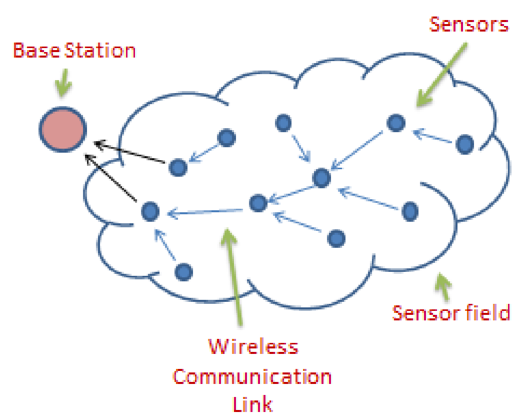


Figure 2.1: Layout of a Wireless Sensor Network

Various sensor and actuator networks have existed for decades. A Computer based control system is a typical hard wired sensor and actuator network, where sensors and actuators are connected with a central computer or control terminal via a data bus system or other networks and implements control and monitoring functions. This type of wired network is simple and reliable and is commonly found in various industrial control systems. Establishing such wired networks require lot of cabling and network infrastructure, which is difficult to extend and involves skilled manpower for its routine maintenance. Large scale deployment of wired sensors brings complexity to the system in terms of cabling, power supply, configuration and maintenance making the deployment in inaccessible and remote locations for applications like volcano monitoring, underwater ocean tracking, battlefield surveillance etc. almost impossible.

The sensor nodes are tiny devices equipped with capabilities of sensing, wireless communication, data and digital signal processing together in a single low cost package called sensor node. Group of such tiny sensor nodes form a wireless sensor network. These nodes are deployed in many kinds of areas to measure ambient conditions; the data thus measured is transformed into measurable signals. After necessary processing, the signals are sent to a predefined destination via radio transmitter. In such scheme of deployments, the wired/ grid connected sources of power supply may not be available therefore all activities of a sensor node are powered by batteries.

It can be summarised that basic goals of a Wireless Sensor Network are:

- To determine the value of physical variables at a given location.
- To detect the occurrence of events of interest, and estimate parameters of the detected events.
- To classify a detected object and track an object.

Wireless Sensor Networks find their utility in variety of applications. The scope depends upon the capability of sensing required. Various commonly available sensors are:

- Temperature
- Humidity
- Acoustics
- Pressure
- Illumination
- Soil Profile

- Noise Level
- Presence or absence of an object
- Vehicular Movement
- Mechanical stress levels on attached objects etc.

2.3 APPLICATIONS OF WIRELESS SENSOR NETWORKS

On the basis of nodes that have sensing and actuation faculties, in combination with computation and communication abilities, wireless sensor networks find their application in variety of areas (Figure 2.2):

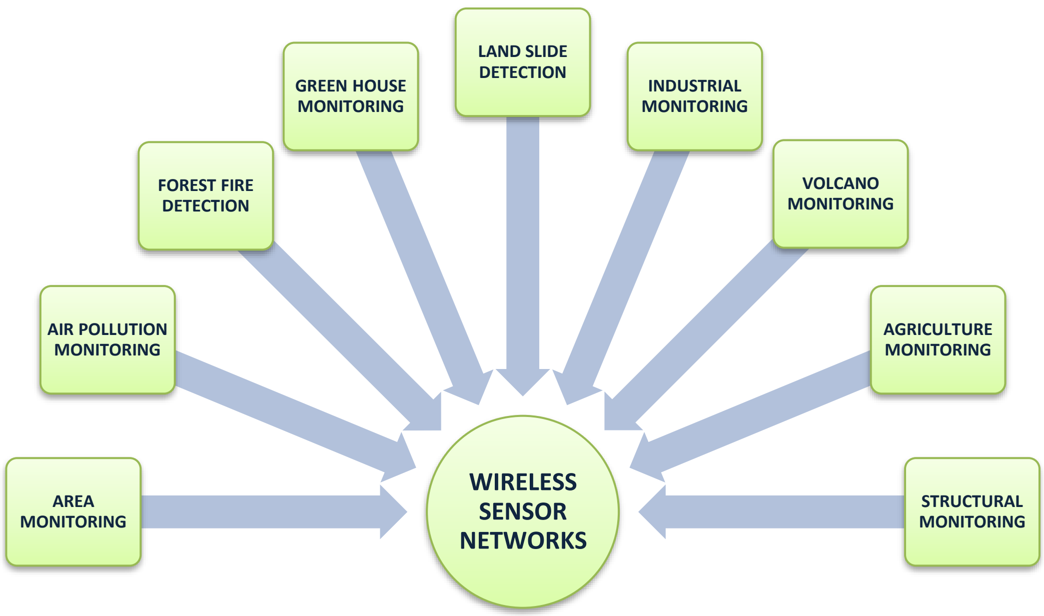


Figure 2.2: Variety of applications of Wireless Sensor Networks

1) **Area Monitoring:** WSNs are deployed in the surroundings where some specific activities are to be monitored. In military scenario, sensors are used for detecting intrusion by enemy; or for geo fencing of gas or oil pipelines in civilian areas.

2) **Agriculture:** WSNs relieve the farmers from the maintenance of wiring in open environment of fields. Gravity fed water systems can be monitored using pressure sensors to monitor water levels in tanks, pumps can be controlled using wireless controllers and water use can be measured and wirelessly transmitted back to a central control station for billing. Irrigation automation reduces wastage and enables efficient water use.

3) **Structural Monitoring:** Wireless sensors can be used to monitor the health of the buildings and vital public infrastructure such as bridges, flyovers, tunnels and embankments etc. enabling engineering staff to monitor these valuable assets remotely without the need for costly site visits, as well as having the advantage of daily data, whereas traditionally this data was collected weekly or monthly, using manual site visits, involving either road or rail closure in some cases.

4) **Forest Fires Detection:** A network of Sensor Nodes can be installed in a forest to control, when a fire has started (Figure 2.3). The sensor nodes are equipped with sensors to monitor temperature, humidity and gases which are produced by fire in the trees or vegetation. The early detection of fire is crucial for a successful action by the fire fighters.

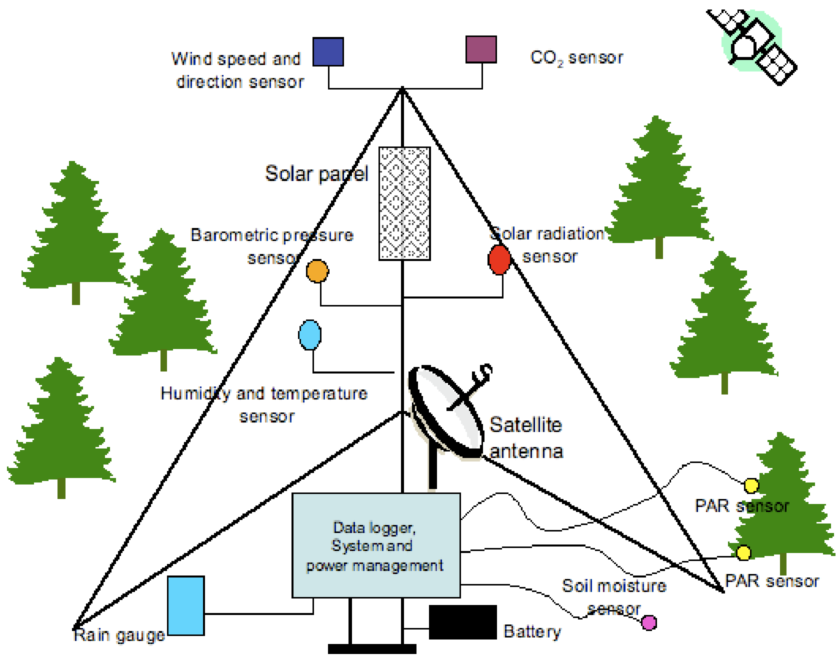


Figure 2.3: WSN for Monitoring of Forests

5) **Greenhouse Monitoring:** Wireless Sensor Networks are used to control temperature and humidity levels inside commercial greenhouses. When temperature and humidity drop below specific levels, the greenhouse manager can be notified via e-mail or cell phone text message, or host systems can

trigger misting systems, open vents, turn on fans, or control a wide variety of system responses.

6) **Landslide Detection:** A landslide detection system makes use of a WSN to detect the slight movements of soil and changes in various parameters that may occur before or during a landslide and makes it possible to know the occurrence of landslides long before it actually happens.

7) **Volcano Monitoring:** The low cost, size, and power requirements of wireless sensor networks have a tremendous advantage over existing instrumentation used in volcanic field studies (Figure 2.4). This technology[4],[5] permits deployment of sensor arrays with greater spatial resolution and larger apertures than existing wired monitoring stations.

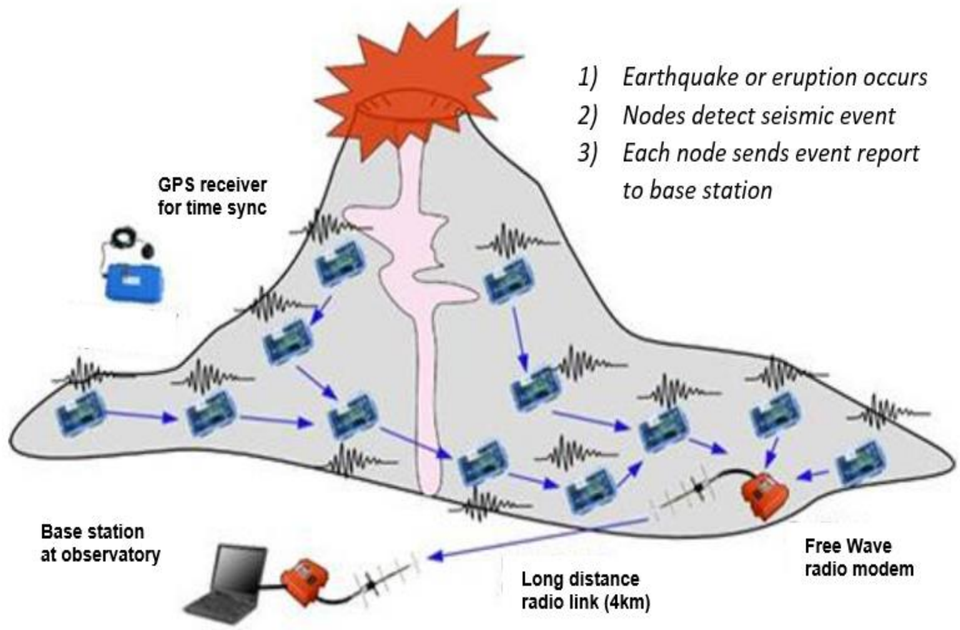


Figure 2.4: Deployment of sensor nodes for Volcano monitoring

8) **Water/wastewater Monitoring:** Water/ Waste water handling Facilities not wired for power or data transmission can be monitored using industrial wireless I/O devices and sensors powered using solar panels or battery packs.

9) **Industrial Monitoring:** Wireless Sensor Networks have been developed for machinery condition-based maintenance (CBM) as they offer significant cost

savings and enable new functionalities. In wired systems, the installation of enough sensors is often limited by the cost of wiring. Previously inaccessible locations, rotating machinery, hazardous or restricted areas, and mobile assets can now be reached with wireless sensors, which can further generate alerts for preventive / breakdown maintenance.

2.4 CHARACTERISTICS OF WIRELESS SENSOR NETWORKS

From the above discussed applications of Wireless Sensor Networks, their characteristics can be summarised as:

1) **Constrained Energy Sources:** These networks have power consumption constraints for wireless nodes due to use of batteries and utilize energy harvesting techniques wherever feasible.
2) **Node Failures:** These networks bear the responsibility of sensing the physical parameters and transmitting the data for some of the real time applications, they need to have the ability to cope with node failures for maximising over all network life and continuity of operation.
3) **Node Mobility:** Some of the applications require tracking of parameters related mobile objects like livestock, monitoring of wild life, school buses and transportation fleets etc. which involve wireless sensor networks to be designed with capabilities to handle the mobile nodes.
4) **Dynamic Network Topologies:** Due to frequent additions and ceasing of operation by certain sensor nodes, the network has a flexible arrangement of sensor nodes, hence wireless sensor network protocols should be able to accommodate dynamic network topologies.
5) **Communication Failures:** Due to hostile conditions of node deployment, many a times the key sensor nodes communicating with the sink or the destination ceases to operate, the wireless sensor networks are designed to handle such communication failures and ensure continuity of the network even in offline mode.
6) **Heterogeneity of Nodes:** For efficient use of energy sources, available nodes with in the network are assigned different functionalities some of the nodes with

bare minimum operating features are the end level nodes, some act as routers for routing the traffic to the coordinator which in turn transmit the collected data to the sink. Thus the network is required to handle heterogeneous nodes in terms of sleep patterns, data sensing and data gathering and communication operations.

7) **Scalability to Large Scale of Deployment:** The wireless sensor networks find their usage in variety of environment monitoring applications, which require dynamic expansion and reduction of the network in terms of addition and removal of sensor nodes, therefore these networks are capable of scaling up or down the operations depending upon span of deployment.

8) **Ability to withstand Harsh Environmental Conditions:** The sensor nodes are deployed in hostile and adverse climatic conditions or hazardous industrial situations such as nuclear power plants where wired connections are difficult to maintain. The autonomous nodes constituting the sensor networks are able to self-organize and self-heal the network in case of error or discontinuity, if any.

9) **Ease of Use:** Establishing Wireless Sensor Networks allows temporary deployment and no wiring or construction work. Such quick and easy deployments can add value to diagnosis of existing problems. After completion of tasks, WSNs can be easily removed and deployed at other locations.

10) **Unattended Operation:** Due to deployment in inaccessible environments, the networks are designed for capability with unattended or remote operation. Example of applications utilising this capability are volcano monitoring, forest fire detection and control etc.

11) **Self-organization Capability:** The nodes are deployed randomly and have no prior information of the network topology, time reference, location of other nodes or total number of nodes when the network is established. It is with the self-organization capability; the nodes collectively determine the connectivity matrix of the network and establish links for further communication.

12) **Collaborative Signal Processing:** Given the limited resources of nodes, a key constraint is to exchange the least amount of information between them to achieve desired performance. Classification of objects moving through the sensor field is

an important application that requires collaborative signals processing (CSP) between nodes.

2.5 REVIEW OF EXISTING ROUTING PROTOCOLS

The basic goal of a routing protocol for WSN can be divided into three categories: energy conservation, fast data delivery and fault tolerance. Review of some of the existing routing protocols is discussed here:

Number of routing protocols has been proposed by researchers in the field of WSN in recent past. Akyildiz et.al[1], Yan et.al.[6], Pantazis et.al.[7], Singh et.al.[8] and Al-Karaki et.al[9] have provided the surveys of various routing protocols and have discussed their strengths and weaknesses. As shown in Figure 2.5 below routing protocols have been classified initially into two broad categories based on network structure and protocol operations.

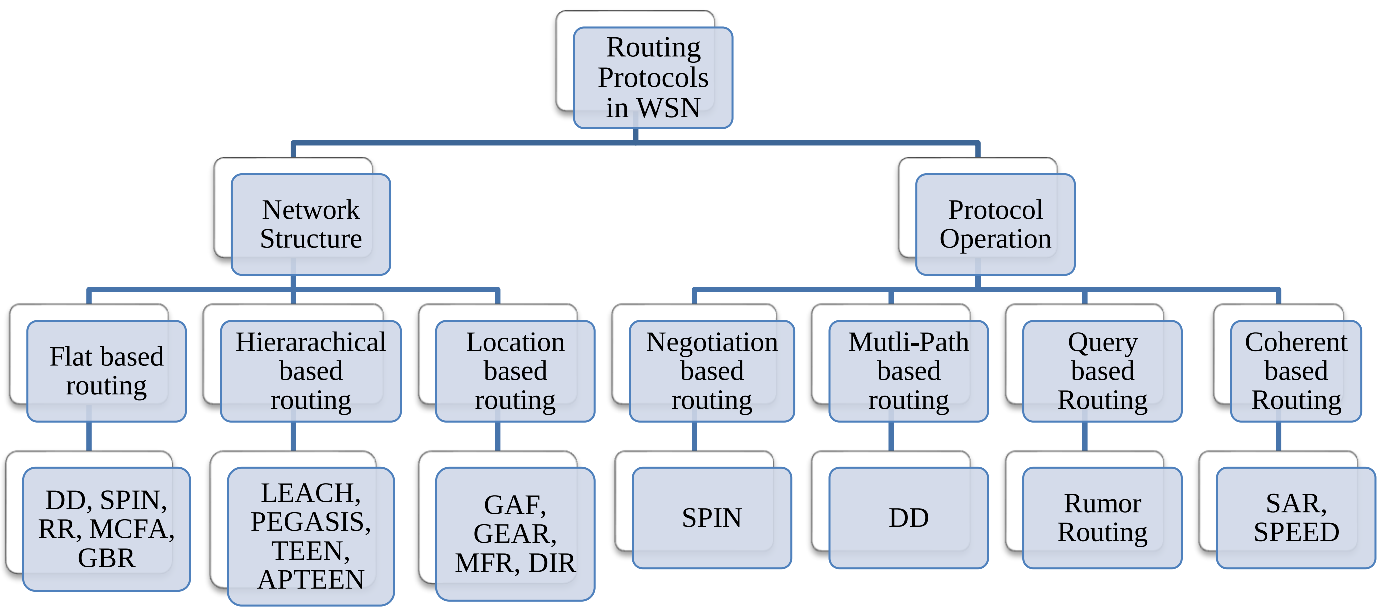


Figure 2.5: Classification of Routing Protocols[9]

Further, the protocols under Network structure are classified as Flat based or data centric, Hierarchical based and Location based protocols. Depending upon mode of protocol operation, the protocols are divided as Negotiation based, multi-path based, Query based and Coherent based routing techniques. These routing paradigms are discussed in detail in following sections.

Network Structure Based Routing Protocols: The structure of the network in a WSN plays significant role in operation of routing protocols. Different network structure based routing protocols are:

2.6 FLAT / DATA CENTRIC ROUTING

Data centric or flat routing protocols are applied in the networks where all sensor nodes play the same role and collaborate to perform the common sensing task. Such networks have large number of identical nodes, due to which it is not feasible to assign a global identifier to each node. Hence address-based routing protocols are not preferred for such networks and this has led to data centric routing where the base station or the sink sends queries to the sensor nodes and waits for data from sensor nodes located in specific region. The data queries are made using the attribute-based naming to specify the properties of data.

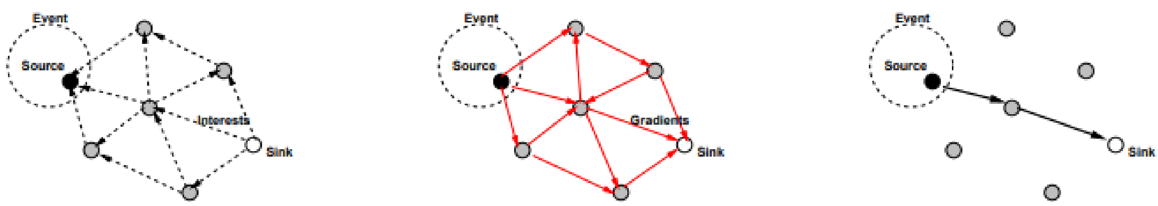
SPIN[10] and Directed Diffusion[11] are some of the early works of data centric routing and have been shown to save energy through elimination of redundant data using aggregation and negotiation. Data centric schemes operate by combining the data arriving from different sensor nodes to eliminate redundancy by employing some aggregation-based functions like average, maximum and minimum etc. Thus, total volume of data transmission to the base station is minimized which reduces energy consumption and increases network life time. For attribute-based naming, rather than querying individual node users are more interested in querying an attribute related to the phenomenon.

If in case the user at base station is interested in knowing the areas where temperature is higher than 40^0C, the nodes with sensor readings matching this request are addressed. This causes a single data-centric query to address, multiple nodes even in distant locations.

2.6.1 Directed Diffusion

Directed Diffusion[11] is a sink initiated protocol proposed by Intanagonwiwat et al. where the sink queries the sensor nodes for specific data. The protocol works in three phases - Interest propagation, Gradient setup and Data dissemination through path reinforcement. The sink sends out the interest to query for data to all its neighbours. The interest can be defined as attribute-value pairs. Each sensor node that receives the interest sets up a gradient towards the sensor nodes from which it receives the interest. The gradient can be defined as data rate, duration and expiration time derived from the received interest message. This process continues until gradients are setup from the sources back to the sink. When interests fit gradients, multiple paths of information flow are formed; the best paths are reinforced so as to prevent further flooding. The data is aggregated on the way in order to reduce communication costs. To reinforce a path, the sink resends the original interest through the selected path with smaller interval for source node to send data more frequently on that path.

In the Data dissemination phase, the source node receives the interest for the second time from the sink; the source node sends the data to the sink along the best path. The goal is to find an aggregation tree for routing the data from source to sink. When a path between a source and the sink fails, a new or alternative path is identified and reinforced. This process is repeated after frequent intervals to ensure continuity of data transmission. Being query-driven, this protocol cannot be applied to applications with continuous data flow towards sink. Below Figure 2.6 shows the three phases of Directed Diffusion.



(a) Interest propagation (b) Initial gradients set up (c) Data delivery along reinforced path

Figure 2.6: A simplified schematic of Directed Diffusion [11]

2.6.2 Sensor Protocols for Information via Negotiation (SPIN)

W. Heinzelman et al[10] proposed a data centric routing protocol named as Sensor Protocols for Information via Negotiation (SPIN). SPIN overcomes the deficiencies of classic flooding by high-level negotiation using meta-data descriptors and resource adaptation. It is a three-stage protocol and uses three types of messages for negotiation like ADV, REQ and DATA. ADV is used to advertise about new data in each node, REQ is for requesting the advertised data and DATA is used to send the actual information in the node. For ADV and REQ messages, any SPIN node uses a meta-data. Therefore, before any actual data transmission a meta-data negotiation is performed. Using SPIN routing algorithm, sensor nodes can conserve energy by sending the meta-data that describes the sensor data instead of sending all the data. The protocol starts when a node has any new data and is willing to share it with other neighbour nodes in the network. So the node broadcasts the meta-data of the sensed data as ADV message. If any neighbour node of the source node is interested in that data, then it replies with an REQ message. After receiving the REQ, the source node sends the actual data using DATA message to this particular neighbour node. Then the neighbour node repeats this procedure with its neighbours until the interested nodes in the entire network receive a copy of the data. Because of the meta-data negotiation there is no redundant data in the network. Figure 2.7 below describes the operation of the SPIN protocol.

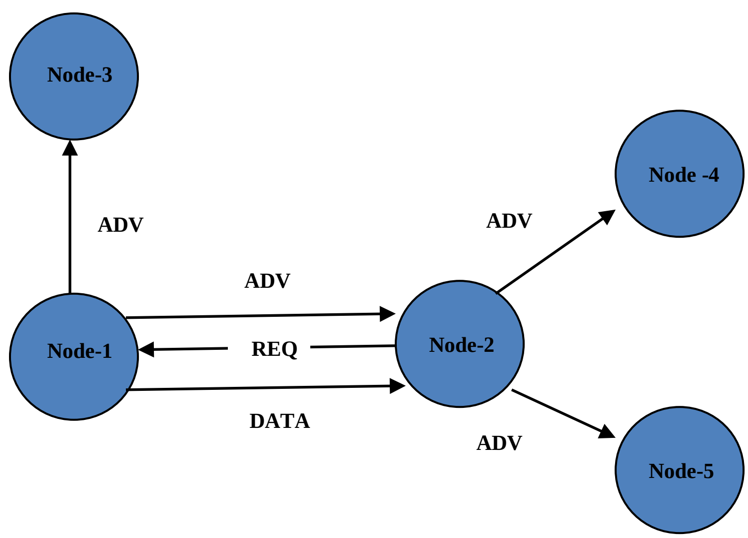


Figure 2.7: SPIN Protocol

2.7 HIERARCHICAL ROUTING

Hierarchical or cluster-based routing was originally proposed in wired networks. These techniques have significant relevance in real time scenarios with special advantages related to scalability and efficient communication. The concept of hierarchical routing is also utilized to perform energy-efficient routing in WSNs. In a hierarchical architecture, nodes with higher energy can be used to process and transmit the data while remaining nodes can perform the sensing operations. This implies that creation of clusters and assigning specialised tasks to high energy nodes called cluster heads can greatly contribute to overall system scalability, lifetime, and energy efficiency. Hierarchical routing is an efficient way to reduce energy consumption within the cluster and also decreases overall data transmitted to the sink by performing data aggregation and fusion. Hierarchical routing is mainly two-step process where in the first step, the clusters are formed and cluster heads are chosen and the second step is used for sensing and routing or transmitting the data collected by member nodes to the cluster heads and ultimately to the sink or base station. However, most techniques in this category do not focus only on routing, rather importance is given to "who and when to send or process/aggregate" the data, channel allocation etc., which can be orthogonal to the multi-hop routing function.

Over the last two decades lot of research has been undertaken in the field of improving the energy efficiency of Wireless Sensor Networks by utilising Hierarchical or cluster-based routing techniques. Some of these research works have been referred here in the later part of this section.

2.7.1 LEACH (Low-Energy Adaptive Clustering Hierarchy)

Heinzelman et al. [12] stated that the conventional protocols of direct transmission, minimum-transmission-energy, multi-hop routing, and static clustering may not be optimal for sensor networks, they proposed LEACH (Low-Energy Adaptive Clustering Hierarchy), a clustering-based protocol. The protocol utilizes randomized rotation of local cluster base stations (cluster-heads) to evenly distribute the energy load among the constituting nodes of the wireless sensor network. LEACH has been based on localized coordination to enable scalability and robustness for dynamic networks. Data fusion algorithms have been incorporated in the routing protocol to reduce the amount of data transmitted to the base station. Distribution of energy dissipation evenly throughout the nodes in the network almost doubles the useful system lifetime for the network. Further, Heinzelman et al[13] developed protocol architecture of LEACH, that enables self-organization of large numbers of nodes, algorithms for adapting clusters and rotating cluster head positions to evenly distribute the energy load among all the nodes, and distributed signal processing to save communication resources. LEACH uses TDMA/CDMA MAC to reduce inter-cluster and intra-cluster collisions. In LEACH, the data collection is centralized and is performed periodically; therefore, it is most appropriate for constant monitoring applications.

LEACH operates into two phases, the setup phase and the steady state phase. In setup phase, formation of clusters and selection of cluster heads takes place. The steady state phase covers the actual data transfer to the sink. In order to minimize overhead of the setup phase, the steady state phase has longer duration. During setup phase, a predetermined fraction of nodes, p, elect themselves as Cluster heads. The sensor node chooses a random number, r, between 0 and 1. If this random number is less than a threshold value, T(n), as shown in equation (1) below, the node becomes a cluster-head for the current round. The threshold value is calculated based on an equation that incorporates the desired probability to become a cluster-head, the current round, and the set of nodes that have not been selected as a cluster-head in the last (1/P) rounds, denoted by G. It is given by:

$$T(n) = \frac{p}{1-p(r \, mod\left(\frac{1}{p}\right))} \; if \; n \in G \qquad (1)$$

Where, G is the set of nodes that are involved in the cluster head selection. Each elected cluster head broadcasts an advertisement message to rest of the nodes in the network. The non-cluster head nodes, after receiving the advertisement, decide on the basis of signal strength of the advertisement regarding the cluster to which they intend to join. The non-cluster head nodes inform respective cluster head regarding the association. After the cluster formation, the cluster-head node creates a TDMA schedule and assigns each node a time slot for transmitting data. The schedule is broadcasted to all the nodes in the cluster.

During steady state phase, sensor nodes begin sensing and transmitting data to the cluster-heads. The cluster-head node, after receiving all the data, aggregates it before sending it to the base-station. After predefined interval of time, the network enters into setup phase again to select the new cluster head. The results show that LEACH can improve system lifetime by an order of magnitude compared with general-purpose multi-hop approaches and through simulations, it has been shown that LEACH can achieve reduction in energy dissipation over the conventional routing protocols by as much as a factor of 8.

Although LEACH is able to increase the network lifetime, there are still a number of issues in this protocol on account of assumptions regarding initial energy of nodes and probabilistic approach for cluster head selection.

2.7.2 HEED (Hybrid Energy-Efficient Distributed Clustering)

Younis et al. [14] have stated that topology control in a wireless sensor networks balances the load on sensor nodes, and increases network scalability and lifetime. To effectively control the topology, they have suggested the approach of distributed clustering of sensor nodes. In this approach they have not made any assumption regarding node capabilities or presence of infrastructure, though the availability of multiple power levels in sensor nodes has been taken into consideration. They have presented a protocol, HEED (Hybrid Energy-Efficient Distributed clustering) which works by periodically selecting cluster heads based on combination of the node residual energy and proximity of node to its neighbours or node degree. HEED terminates in O(1) iterations, incurs low message overhead, and achieves fairly uniform cluster head distribution across the network. With appropriate bounds on node density and intra-cluster and inter-cluster transmission ranges; HEED can asymptotically almost surely guarantee connectivity of clustered networks. The proposed protocol has been simulated and results indicate prolonging of network life time and scalable data aggregation.

2.7.3 H-LEACH

Razaque et al. [15] have discussed about H-LEACH, to solve problems of energy considerations while electing channel head. The proposed algorithm considers residual and maximum energy of nodes for every round while electing channel head using threshold condition. The algorithm has been compared with LEACH and HEED protocols, and has been proved as more efficient than both these methods. In H-LEACH, during selection of channel heads, the average energy and residual energy of the nodes play significant role. H-LEACH, being combination of HEED and LEACH overcomes node energy related issues. They have also proposed to find threshold value based on the average energy of node. The energy consumed by the node for transmitting and receiving data is reduced in every round to keep track of the alive nodes in every round. Node is declared dead when its energy falls below the minimum energy required to continue transmit/ receive operation. The proposed approach has improved substantial energy in the network, this is evident from the simulation, when both LEACH and H-LEACH protocols are applied and number of alive nodes has been compared in both the cases. It has been found that the last node died in much later round using H-LEACH than in the case of LEACH protocol.

2.7.4 PEGASIS (Power-Efficient Gathering in Sensor Information Systems)

Lindsey et al. [16] have described PEGASIS (Power-Efficient Gathering in Sensor Information Systems), a protocol based on greedy chain algorithm that provides near optimal solution for data-gathering problem in wireless sensor networks. PEGASIS performs better than LEACH by eliminating the overhead of dynamic cluster formation, minimizing the distance non header-nodes must transmit, limiting the number of transmissions and receives among all nodes, and using only one transmission to the sink per round. Each node communicates only with a close neighbour and takes turns to transmit the fused data to the sink to balance the energy depletion in the network and preserve robustness of the sensor web as nodes die at random locations. Distributing the energy load among the nodes increases the lifetime and quality of the network. The simulation results show that PEGASIS performs better than LEACH by about 100 to

300% when 1%, 20%, 50%, and 100% of nodes die for different network sizes and topologies. It has also been shown that with the increase in network size there is further improvement using PEGASIS.

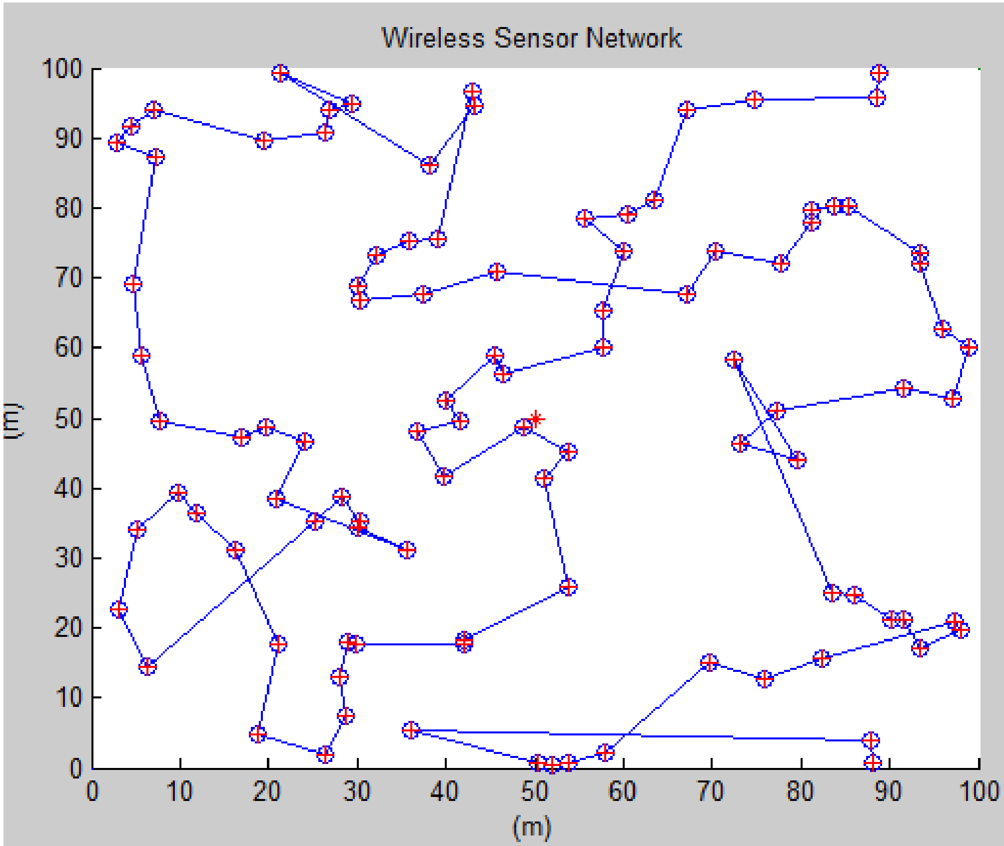


Figure 2.8: PEGASIS protocol in operation

Luo et al. [17] stated that the limited energy of sensor nodes and the huge number of nodes with dynamic network topology information have always been the important concerns in designing Wireless Sensor Networks (WSN). Clustering of nodes is an effective way to tackle the two issues by grouping the nodes into hierarchies. Such grouping not only reduces communication distance but also the amount of data to be transmitted. The approach focuses on unification of energy consumption at nodes in WSN. The distribution of the energy consumption for various scenarios in the hierarchical network has been analysed and two main reasons are found leading to the asymmetry of energy consumption among nodes. One is the energy consumption from the communications between nodes and base station, and the other is that from the cluster head for receiving data from other nodes. It is concluded that the probability of the node acting as cluster head should depend on the distribution of the head's energy consumption, and a variable sampling space oriented to the potential number of cluster heads is established thereafter. They have proposed a new clustering algorithm, the Segment Equalization Clustering based on Cluster Head Energy Consumption (SECHEC), which can effectively improve the network lifetime and ensure the availability of the system within its entire lifespan.

2.7.5 OP-LEACH

Gambhir et al. [18] stated that LEACH uses localized coordination to enable scalability and robustness for dynamic networks, and incorporates data fusion into the routing protocol to reduce the amount of information that must be transferred to the base station. But LEACH is based on the assumption that each sensor node has equal amount of energy but in real world scenario, this is not the case. In order to maintain balanced energy consumption, LEACH uses a TDMA based MAC protocol, but when the nodes have random data distribution many TDMA slots are wasted. Therefore, in order to use the slots corresponding to nodes that do not have data to send at its scheduled slot, a modification to existing LEACH protocol is needed. A new version of LEACH protocol called OP-LEACH has been presented which aims to reduce energy consumption within the wireless sensor network, without making any changes in the TDMA schedule, by utilising the TDMA slots of the sensor nodes that don't have data to transmit. Using OP-LEACH, sensor nodes get more than one slot per frame, thus reducing the waiting time for sensor nodes. This causes reduction in data transmission delay and subsequently, increases throughput of the network. The proposed algorithm has been evaluated using OMNET++ simulator. The simulation work shows improvements in terms of data sent, time delay and hence the throughput of network. The throughput of the network is improved in terms of data sent per frame and the average data sent per slot.

2.7.6 CAMILS (Collision Avoidance Maximal Independent Link Set)

Byungseok et al. [19] stated that overall network delay is increased due to the retransmissions caused by collision and interference during communication among sensor nodes. This causes overall reduction in network performance on account of increase in waiting time at nodes. The requirement is for a link scheduling scheme for communication among nodes free from collisions and interference. Due to highly constrained and distributed environment, a sensor node has limited knowledge about its neighbouring nodes in a Wireless Sensor Network. To overcome this, a comprehensive link scheduling scheme is required for distributed WSNs. Many schemes use TDMA to prevent collisions and interference; however, TDMA-based schedule also increases the delay time and decreases communication efficiency. They have proposed the distributed degree-based link scheduling (DDLS) scheme, based on the TDMA.

The DDLS scheme achieves the link scheduling more efficiently than the existing schemes and has the low delay and duty cycle in the distributed environment. Communication between sensor nodes in the proposed DDLS scheme is based on collision avoidance maximal independent link set (CAMILS), through which primary and secondary collisions are avoided while assigning the timeslot to the link. It enables to assign collision-free timeslots to sensor nodes, and meanwhile decreases the number of timeslots needed and has low delay time and duty cycle. Only one timeslot is assigned per link regardless of the transmission requirement of the node. Simulation results show that the proposed DDLS scheme reduces the scheduling length by average 81%, the transmission delay by 82%, and duty cycle by over 85% in comparison with distributed collision-free low-latency scheduling scheme.

Jurdak et al. [20] have talked about radio as contributor to overall node energy consumption. They proposed adaptive radio low-power sleep modes based on current traffic conditions in the network. They have explained that an inherent trade-off exists as fixed low-power modes involve deep sleep mode and have low current draw but high energy cost on account of latency for switching the radio to active mode, on the other hand, light sleep mode have quick and inexpensive switching to active mode with a higher current draw. They have introduced a comprehensive node energy model, which includes energy components for radio switching, transmission, reception, listening, and sleeping, as well as microcontroller energy component for determining the optimal sleep mode and MAC protocol to use for given traffic scenarios. Further they have proposed a RFIDImpulse protocol, which is very low power radio wake-up scheme for sensor networks. RFIDImpulse is based on off-the-shelf RFID tags and readers. All network nodes turn off their radios, including voltage regulator and oscillator, as long as they have no packets to send or receive. During this idle period, the nodes also put their MCUs in power down mode. A node that wishes to send a packet uses a built-in RFID reader to trigger an RFID tag that is located at the remote sensor node. The impulse from the sender causes the RFID tag at the intended receiver, connected to the external interrupt pin of microcontroller at that node, to generate an interrupt to wake up the MCU. The MCU wakes up and in preparation for the incoming packets, activates the radio voltage regulator and oscillator. After a short start-up time, the radio at the receiver becomes fully active and sends a short acknowledgment message through the standard radio to the sender, indicating successful RFID wake-up. Upon receiving acknowledgment from receiver, sender commences the transmission. On completing packet transmissions, both sender and receiver again turn off their radios and MCUs, though the RFID tag remains in its low- power idle mode for triggering future remote wake-ups.

The model proposed has been used for evaluating energy related performance of RFIDImpulse protocol enhanced with adaptive low-power modes, and comparing it against BMAC and IEEE 802.15.4. The comparative analysis confirms that RFIDImpulse with adaptive low power modes provides up to 20 times lower energy consumption than IEEE 802.15.4 in low traffic scenario.

They have covered in detail the Microcontroller Unit Energy, Listening Energy, and Switching Energy i.e. the energy consumed for switching the radio state between states, including normal, power down and idle modes. The following equation (2) defines the energy consumed for switching the radio from sleep mode α to active mode:

$$E_{switch}^{\propto} = \frac{(I_{active} - I_{\propto}) \times T_{\propto} \times V}{2} \tag{2}$$

I_{active} - indicates the current draw of the radio in active mode, $I_{\propto}$ - is the current draw in sleep mode α, and $T_{\propto}$ is the time required by radio to switch from sleep mode α to active mode.

The sleep time energy consumption is the energy consumed when the radio is in low power mode and has been expressed as equation (3) be:

$$E_{sleep} = T_{rf}^{off} \times I_{\propto} \times \mathrm{V} \tag{3}$$

2.7.7 TEEN (Threshold sensitive Energy Efficient sensor Network protocol)

Manjeshwaret. al. [21] have classified sensor networks, based on their mode of functioning, as proactive and reactive networks. Reactive networks, in contrast to passive data collecting proactive networks, respond immediately to changes in the relevant parameters of interest. They presented a new energy efficient protocol, TEEN (Threshold sensitive Energy Efficient sensor Network protocol) for reactive networks. They evaluated the performance of the protocol for a simple temperature sensing application. TEEN has been found well suited for time critical applications and is also quite efficient in terms of energy consumption and response time. It also allows the user to control the energy consumption and accuracy to suit the application.

2.7.8 Other Variants of LEACH protocol

SHAN et al. [22] have proposed an improved LEACH protocol which takes into account the energy and distance of nodes and adds energy factor and distance factor while calculating the threshold T(n). Accordingly, the modified equation for T(n) is given as equation (4) below:

$$T(n) = \begin{cases} \frac{p}{1-p*(r*mod\frac{1}{p})} * \left(1 - \frac{d_n}{E_n} * \frac{E_{ce}}{R_c}\right) & if\ n \in G \\ 0 & else \end{cases} \tag{4}$$

Where $\frac{d_n}{E_n}$ acts an important factor to affect the probability of a node to become cluster head. Here E_{ce} is the minimum value of the remaining energy of every node in the cluster and Rc is the radius of the circle which contains all nodes within the cluster.

They have also proposed the multi hop routing algorithm based on the hop count and remaining energy. Further investigations have been performed to see if the improved LEACH protocol operates more effectively than the traditional LEACH protocol. The simulation data suggests that the death rate of nodes of the improved protocol is lower than the original LEACH protocol and it is concluded that the improved LEACH protocol can balance network load and extend the life-cycle of network.

Ghasemzadeh et al. [23] stated that a Wireless Sensor Networks (WSN) consist of large number of sensor nodes which have constraints of computation, energy and memory resources. Limited energy resources affect the lifetime of the WSNs. Hence many protocols have been proposed to reduce energy consumption. LEACH is one of the most popular clustering protocols which aims at reducing energy consumption and controls energy dissipation. Almost all revisions of LEACH protocol give no guarantee that cluster-heads are uniformly distributed in the network. They have proposed a protocol named BN-LEACH to select cluster-heads using Bayesian Network (BN) model based on three factors - distance to the Base Station (BS), remaining energy and density. This model calculates the probability of becoming cluster-head for each sensor node. Appropriate cluster-heads are chosen according to a dynamic zoning method and a greedy approach in order to distribute cluster-heads uniformly. By comparison with LEACH, LEACH-C and WEEC protocols, which are improvements on LEACH, simulation results show that BN-LEACH protocol balances energy consumption of sensor nodes, improves the network lifetime and extends the First Node Death (FND) further more from above-mentioned protocols. The number of cluster-heads in LEACH protocol is unpredictable and in some cases is far more than its initial assumption, while in BN-LEACH protocol the number of cluster-heads relies on the number of alive nodes and the proposed zoning method.

Tan et al. [24] stated that to efficiently utilise the energy of the sensor nodes, they proposed sleep scheduled and tree-based clustering approach routing algorithm (SSTBC). SSTBC preserves energy by turning off radio of either impossible or unnecessary nodes, which observe almost the same information, based on their location information to remove redundant data. In addition, to further reduce energy dissipation of communication in network, minimum spanning tree is built with the root as the cluster head (CH) from active nodes in a cluster to forward data packets to base station (BS). Simulation results show that the network lifetime with using of our proposed protocol can be improved about 250% and 23% compared to low energy adaptive clustering hierarchy (LEACH) and power efficient gathering in sensor information system (PEGASIS), respectively.

XingGuo et. al. [25] have stated that at the time of choosing the cluster heads, LEACH protocol, didn’t take the residual energy of nodes into account, this may result in the node with rather low energy to be chosen as a cluster head. Thus, it will cause the cluster created by this low-energy node to stop functioning at an early stage, leading to wastage of entire network’s resource. To overcome this situation, they introduced an energy factor when choosing a cluster head, which can prevent a node with very low-energy from becoming a cluster head. On conducting, simulation specific to LEACH protocol and improved algorithm in terms of network lifetime, network stability, collecting data packages and energy consumption, results show that proposed improved algorithm has better performance compared with LEACH.

Wang et. al. [26] have stated that Energy efficiency in Wireless Sensor Networks (WSNs) has always been a issue of concern. Sleep Scheduling (SS) mechanism is an efficient method to manage energy of each node and is capable to prolong the lifetime of the entire network. They proposed a Software-defined Network (SDN) based Sleep Scheduling algorithm SDN-ECCKN to manage the energy of the network. In the proposed algorithm, every computation is completed in the controller rather than in sensors and there is no broadcasting between each two nodes. Results show advantages in energy management, such as network lifetime, the number of live nodes and the number of solo nodes in the network.

Jiaet. al. [27] have proposed dynamic cluster head selection method (DCHSM) for wireless sensor networks in order to solve the problem of unreasonable cluster head selection that may lead to the over lapping coverage and unbalanced energy consumption in while communicating with in the cluster. DCHSM has been proposed by analyzing the sensor network energy consumption based on the redundant nodes and energy heterogeneity. The experimental analysis is undertaken on four aspects i.e. coverage, life cycle, number of active nodes and average residual energy. The proposed method overcomes disproportionate energy consumption, improves information redundancy in transmission process, reduces energy consumption and extends life time of the network. Experimental results show that this method balances the network node energy in two phases compared with the existing algorithms. The network lifetime is increased by 50%, higher than that of low energy adaptive clustering hierarchy (LEACH), and increased by 30%, higher than that of distribute energy-efficient clustering algorithm (DEEC); The survival time of the network is also longer than that of energy – balanced deterministic clustering algorithm and adaptive energy optimized clustering algorithm, achieving the effectiveness of network energy consumption along with longest network lifetime.

Handy et al. [28] have focused on reducing the power consumption of wireless micro-sensor networks by modifying the existing LEACH protocol. They have extended LEACH'S stochastic cluster-head selection algorithm by a deterministic component. This has resulted in an increase in network lifetime by about 30% depending on the network configuration. The paper also presents a new approach to define lifetime of micro-sensor networks using three new metrics FND (First Node Dies), HNA (Half of the Nodes Alive), and LND (Last Node Dies).

Zhu et al. [29] have presented an analytical model to estimate and evaluate the node and network lifetime in randomly deployed multi-hop sensor networks. The procedure proposed attempts to extend the lifetime of the communication critical nodes and as a result the overall network's operation lifetime. The proposed model takes care of the energy consumed in processing, communication and sensing but it does not consider energy consumption of transient energy, sensor logging and actuation.

Inwhee Joe [30] stated that due to the remote nature and size constraints of sensor nodes, they rely on limited battery energy which cannot be replenished in many applications. Thus, low power consumption technology is a major issue in wireless sensor networks in order to prolong system lifetime. They have proposed to maximize energy efficiency in wireless sensor networks using optimal packet length in terms of power management and channel coding. The use of power management cannot improve energy efficiency, but it saves lot of energy because the transceiver is turned off while it is not used. They have evaluated optimal packet length without power management in a way that energy efficiency can be maximized. They have also shown that BCH code for channel coding improves energy efficiency significantly compared to convolutional code.

Jiang et al. [31] stated that due to the widespread adoption of sensor-nets for commercial and scientific usage, it is important that sensor-networks have long and predictable life times. A balance is sought between network lifetime and network performance, but recent history shows that unexpected and dynamic environmental conditions often scamper expected energy budgets. For example, many nodes in the Great Duck Island deployment were speculated to have died prematurely because unexpected overhearing of traffic caused radios to become operational for longer periods than it was originally predicted. This pattern was also repeated in the Redwoods deployment, but on account of apparently different reason: some nodes seemingly died prematurely because they became disconnected from the wireless network and exhausted their batteries trying to reconnect. They have suggested that such problems can be prevented by treating energy as a fundamental design primitive and implementing energy management architecture.

Chauhan et al. [32] stated that Wireless sensor networks (WSNs) are mainly used for systematic collection of useful information and for the transmission of the collected data to the sink/ base station for further analysis and processing. Despite the innumerable applications of WSNs, the sensor nodes of these networks have limited energy, limited computing power and limited bandwidth, in which energy is major constraint. Clustering has been widely used in WSNs to limit the energy consumption in nodes; this also decreases the communication load, and thereby prolongs the network lifetime by minimizing the redundant information using the data aggregation model on the cluster heads. An information similarity based clustering algorithm has been proposed, where transmission of the data to the sink is done using the least spanning tree algorithm. This approach firstly uses improved LEACH algorithm for election of cluster heads and then cluster formation under the elected cluster heads is done depending upon the non-cluster head node's maximum information similarity with the cluster head nodes. By utilizing the sleep scheduling and least spanning tree algorithm, this approach effectively reduces the redundant data transmission and whole energy consumed in the network.

Kuila et al. [33] stated that clustering is an efficient technique to improve scalability and life time of a wireless sensor network. They proposed an Energy Efficient Load-Balanced Clustering (EELBC) algorithm that addresses energy efficiency as well as load balancing. EELBC is a min-heap based clustering algorithm. Some of the high energy nodes designated as gateways are treated as cluster heads (CHs). A min-heap is built using cluster heads on the number of sensor nodes allotted to the Cluster heads. The algorithm runs in O (n log m) time for *n* sensor nodes and *m* Cluster heads. The experimental results show the efficiency of the proposed algorithm in terms of load balancing, energy efficiency, execution time and also the number of sensor nodes that die during the network period.

Raghatate et al. [34] focus on reducing the consumption of energy and thus improving wireless sensor network lifetime. Clustering sensor node is an effective topology for the energy constrained networks. They have developed energy saving algorithm in which clusters are formed considering a subset of high energy nodes as a cluster-head and another subset of powerful nodes are placed in sleep mode. When Cluster heads exhaust their energy, another subset of nodes becomes active and acts as a cluster head. Simulation results show that it can extend the network lifetime than LEACH protocol, and accomplishes better performance than existing clustering algorithms such as LEACH. The protocol follows the first order radio model. Energy is dissipated while receiving and transmitting data. Considering propagation in line of sight, energy consumption for short distances is d^2 and d^4 due to multipath fading propagation for the long distance. Transmission energy and receiving energy are calculated as shown in equation (5) and (6) below:

$$E_{Tx}(l,d) = \begin{cases} lE_{elect} + lE_{fs}d^2, & d < d_0 \\ lE_{elect} + lE_{mp}d^4, & d > d_0 \end{cases} \quad (5)$$

$$E_{Rx}(L) = E_{elect}(L) \quad (6)$$

Here d is the distance between the receiver and transmitter and L signifies the number of bits to be transmitted or received. Value of d_0 is calculated as per equation (7) below:

$$d_0 = \sqrt{E_{fs}/E_{mp}} \qquad (7)$$

In this approach, two types of sensor nodes, i.e., High Energy nodes (powerful nodes) and normal nodes are considered. It is assumed that there are 'N' number of sensor nodes deployed in an area, where the initial energy of the normal nodes is assumed to be E_0, and m is the percentage of high-power nodes, which have 'a' time more energy than the normal ones.

Thus $(m * N)$ high power nodes are equipped with initial energy of $(E_0 *(1+\alpha))$, and $((1-m) *N)$ normal nodes are equipped with initial energy of E_0. The total initial energy of the network is given by equation (8) below:

$$E_{total} = N \cdot (1 - m) \cdot E_0 + N \cdot m \cdot E_0 \cdot (1 + \alpha) = N \cdot E_0 \cdot (1 + \alpha \cdot m) \qquad (8)$$

Therefore, using heterogeneous network the total energy of the system is increased by a factor of $(1+\alpha \cdot m)$.

The drawback of this approach is that with the death of cluster head the entire network becomes dead, though some nodes are still alive, therefore all sensor nodes are not utilized. Due to this the network does not work till the death of last node.

Wang et al. [35]in their work stated that techniques with low power consumption should be used to develop and design wireless sensor network protocols and data fusion algorithms to improve and maximize the battery life. Network protocols minimize energy consumption through localized communication and control. The proposed scheme exploits trade-offs between computation and communication. In addition, various data fusion algorithms such as beam-forming, aggregate data from multiple sources to reduce data redundancy and enhance signal-to-noise ratios. This further reduces the required communication overhead. The authors developed a sensor network system which functions on a localized clustering protocol and beam-forming data fusion to enable energy-efficient collaboration. From the implementation of two beam-forming algorithms, i.e. the Maximum Power and Least Mean Squares (LMS) beam-forming algorithms, it was concluded that LMS algorithm requires less than one-fifth the energy required by the Maximum Power beam-forming algorithm with only a 3 dB loss in performance.

Ahmad et al. [36] stated that energy consumption and energy modelling are important issues to consider in design and implementation of Wireless Sensor Networks (WSNs), which help the designers to optimize energy consumption in WSN nodes. The first step to reduce energy consumption in WSNs is knowledge of sources of energy consumption. Therefore, for evaluation of communication protocols an accurate energy model is required. They have developed an analytical model at the level of sensor nodes for evaluating energy consumption. Focus has been laid on optimisation of transmission power and modulation size, to minimize the energy consumed by a transceiver for delivering one bit of data without error. They have concluded that for a given modulation scheme, the average energy consumed per bit by transmission over AWGN channel as a function of the transmission power has a unique minimum value. They have provided closed-form for optimising the transmission power and have computed optimal transmission power as a function of the distance for different modulation schemes. Moreover, they have also investigated energy savings gained from optimizing the constellation size.

Gao et al. [37] stated that clustering technique is used in number of applications; it is a significant tool that classifies identical groups of objects based on attribute values. The ant colony clustering algorithm is a swarm-intelligent method used to handle clustering issues. It is inspired by the behaviour of ant colonies that cluster their corpses and sort their larvae. To improve computational efficiency and accuracy of existing ant colony clustering algorithm, a new abstraction ant colony clustering algorithm using data combination mechanism is proposed. The abstraction ant colony clustering algorithm is used to cluster benchmark problems. Its performance is compared with the ant colony clustering algorithm and other methods used in existing literature. In context of similar computational difficulties and complexities, the results show that the abstraction ant colony clustering algorithm produces results that are not only more accurate but also more efficiently determined than the ant colony clustering algorithm and other methods.

Thus, the abstraction ant colony clustering algorithm can be used for efficient multivariate data clustering.

Yun-Zhong et al. [38] stated that for transmitting images over wireless sensor networks, requires reduction in energy dissipation and increasing the network lifetime. They have applied the existing research carried out in clustering algorithm on heterogeneous sensor networks and have proposed an energy efficient prediction clustering algorithm, which is adaptive to sensor networks with heterogeneous energy profile. The proposed algorithm enables the nodes to select the cluster head considering key factors of energy and communication cost, thus the nodes with higher residual energy have higher probability of becoming cluster heads in respective clusters, than the ones with lower residual energy. This technique also ensures uniform dissipation of network energy. In order to reduce energy consumption and prolong network lifetime, an energy consumption prediction model is established for regular data acquisition nodes, when broadcasting in clustering phase. Simulation results show that compared with current clustering algorithms; this algorithm can achieve longer sensor network lifetime, higher energy efficiency, and superior network monitoring quality in wireless sensor networks with application in image clustering.

Munadi et al. [39] stated that energy consumption in wireless sensor networks (WSN) is a fundamental issue in implementing various applications. Each node in a wireless sensor network is only supplied by a limited energy reserve, a battery. In most of applications, the nodes are spread randomly in the field and communication links are transferred using the contention-based MAC protocol. The amount of energy consumption required for S-MAC protocol and T-MAC protocol has been analysed. It has been shown by simulation results that T-MAC protocol has ability to save 25% more energy than S-MAC protocol. Ability of T-MAC protocol has been found even better when compared with 802.11 MAC protocol. In case of variable duty cycle, the energy consumption is further affected and it has been found that T-MAC protocol can save 10% more energy from consumption than S-MAC protocol. The proposed scheme performs much better in comparison to 802.11 MAC protocol. Based on various duty cycle values, the energy consumption of T-MAC protocol is 10% more efficient than for S-MAC protocol. The 802.11 MAC protocol consumes energy more than other two protocols and its lifetime is shorter than lifetime of both S-MAC and T-MAC protocols.

Menget. al. [40] have proposed an energy-efficient data aggregation transfer protocol based on clustering and data prediction “DACP”. In the initialization phase sensor network nodes send messages to sink node, the sink node then divides entire network into several clusters and elects cluster head node for each cluster. In the prediction phase sensor member nodes receive predicted data and compare it with sensed data to decide whether send it or not. In the data aggregation phase cluster head nodes aggregate sensed data received from cluster member nodes and decide to send it to sink node or not according to receiving predicted data. It is effective in reducing data transmission and improves the efficiency of data aggregation by data prediction. The accuracy of data prediction technique plays significant role in the energy consumption.

Kavithaet. al. [41] have proposed energy efficient fault-tolerant multipath routing technique which utilizes multiple paths between source and sink. This protocol efficiently utilizes the energy availability and available bandwidth of nodes to identify multiple routes to destination. To achieve reliability and fault tolerance, reliable paths are selected based on the average reliability rank (ARR) which is further based on each node's reliability rank (RR). The reliability rank of the node represents the probability of a node to correctly deliver data to the destination. In case the existing route encounters some unexpected link or route failure, the algorithm selects the path with the next highest ARR, from the list of selected paths. Simulation results show that the proposed protocol minimizes the energy and latency and maximizes the delivery ratio.

Jeonget. al. [42] have stated that in wireless sensor networks, the data aggregation periods of each cluster vary depending upon the different sensing environment and considering entire network as uniform lead to energy consumption in areas which are not of much significance or interest. Similarly in areas requiring focus, same data aggregation algorithm may be inefficient because, measurement intervals are fixed regardless of current environment. They have suggested that data aggregation periodic time can be distinguished according to characteristics of the cluster. They have proposed a new cluster-based routing protocol MPDA (Multi-Periodic Data Aggregation). They have distinguished the data aggregation period by considering the interested area that is needed to monitor frequently. Thus, MPDA has multiple data aggregation periods according to characteristics of each cluster. It is possible to save the energy and increase the accuracy of measurement. MPDA has been evaluated in respect of LEACH and has been found to perform better in terms of a few errors and energy consumption.

Jinet. al. [43] have stated that many researches on object tracking in wireless sensor networks are under practice, however most of them cannot effectively deal with trade-off between missing rate and energy efficiency. They have proposed a dynamic clustering mechanism for object tracking in wireless sensor networks. The clusters are being formed dynamically as per the movement route, the proposed method can not only decrease the missing-rate but can also decrease the energy consumption by reducing the number of nodes that participate in tracking and minimizing the communication cost, thus can enhance the lifetime of the whole sensor networks. The simulation result shows that this method achieves lower energy consumption and lower missing-rate.

Samarahet. al [44] have stated that Object Tracking Sensor Networks (OTSNs) is one of the most interesting applications of Wireless Sensor Networks. OSTNs are used to track certain objects in a monitored area and to report their location to the application's users. They have proposed Prediction based Tracking technique using Sequential Patterns (PTSP), with objective to reduce energy dissipation by OTSNs, while maintaining acceptable missing rate levels. PTSP is tested against basic tracking techniques to determine the appropriateness of PTSP in various circumstances. PTSP is based on a data mining technique, named Sequential Patterns, to generate a set of patterns that serve as base for predicting the future location of a moving object. The generated patterns are updated regularly to guarantee capturing the recent behaviours of the moving objects. On simulation, PTSP outperformed all the other tracking schemes by keeping a low energy consumption level while maintaining an acceptable level of missing rate.

Sharma et. al. [45] have proposed an improved algorithm for cluster head selection by reducing network overhead on clusters and transmits the data from source to sink through expanding nodes' life-time. The Base Station Controlled and Energy Efficient Centralized Hierarchical Routing Protocol (BSEECH) provides method for transmitting data by dividing nodes into different levels in hierarchical format. It succeeded in reducing the network overhead by increasing number of cluster heads by having one cluster head at each level. The proposed algorithm increases the network lifetime, decreases the number of dead nodes during transmission, and provides the guaranteed transmission of data.

Sementeet. al. [46] have analysed and implemented a WSN to control a instrumented process in limited power source environments. It is based on IEEE 802.15.4 standard, using ZigBee and Modbus protocols. They have presented simplified and robust system architecture, emphasizing the control subsystem of charge and discharge, using solar panels, as well as software optimized for tasks of network controlling and sensing. They have ensured four key requirements: scalability, reliability, timeliness and energy efficiency. the battery lifetime can be improved by three times the original time by using energy harvest system. Moreover, using both resources: energy harvest and rational sampling, the lifetime can be improved in years, almost a perpetual system. They have illustrated battery charger dynamic and static behaviour, particularly the response of battery charger to input voltage from solar panel. Since solar energy variation is slow and sometimes can be randomly captured by solar modules. They have further stated that the proposed physical energy efficiency scheme is based on solar panel battery charger, developed by them, could also be used with other topologies or approaches.

Zhang et. al.[47]have stated that unbalanced energy consumption is an inherent problem in wireless sensor networks characterized by multi-hop routing and many-to-one traffic pattern. This uneven energy dissipation can significantly reduce network lifetime. They have addressed the issue of balancing energy consumption for uniformly deployed data-gathering sensor networks. They have formulated the energy balancing problem as problem of optimal allocation of transmitting data by combining the ideas of corona-based network division and mixed-routing strategy together with data aggregation. They presented the solutions for balancing energy consumption among nodes both within the same coronas and within different coronas. They initially proposed a localized zone-based routing scheme that guarantees balanced energy consumption among nodes within each corona. They have also designed an offline centralized algorithm with time complexity O(n) (n is the number of coronas) to solve the transmitting data distribution problem aimed at balancing energy consumption among nodes in different coronas. The approach for computing the optimal number of coronas in terms of maximizing network lifetime is also presented. Based on this model, an energy-balanced data gathering (EBDG) protocol and its extension to large scale data-gathering sensor networks has been developed. Simulation results show that EBDG can improve system lifetime by an order of magnitude compared with a multi-hop transmission scheme, a direct transmission scheme, and a cluster-head rotation scheme.

Piedraet. al. [48] in their work have presented a survey on recent WSNs based on several fields related to environmental research e.g. eco-informatics, precision agriculture and wildlife observation. They have focused on the identification of limitations and open problems therein. They have inferred that sensor networks can fulfil the ecological requirements of constructing complex and data-quality data-sets. WSNs are capable to monitor a vast scale field, in-situ, and to send the measurements back to the laboratory for a posteriori analysis. WSNs provide number of advantages to eco-informatics such as the possibility of constructing quality data-sets that coupled to machine learning based prediction systems; can be used for ecological and process modelling. WSNs have permeated the disciplines that greatly rely on control and decision-making processes like medical health care, agriculture, ecology and industrial automation. In ecology, an infrastructure consisting of networks of interconnected sensors can provide in-situ high-precision monitoring of natural phenomena at large-scale.

They have reviewed several applications that have been proposed in the field of disaster prevention, wildlife observation, forest monitoring and water ecosystems. The potential of WSNs in environmental research is critical to facilitate the understanding of the many complex environmental interactions. WSNs can provide timely effective and well-managed information. It has been found that possibilities for retrieving physical, chemical information and even behavioural treats of determined ecological entities or systems, is key and very useful for both environmental researchers and managers.

However, still certain limitations need to be reinforced; for instance, developing new techniques that permit the processing and detection of erroneous data generation as the number of nodes increases.

Mathapatiet. al. [49] have proposed to develop an Adaptive Energy Efficient Forwarding Protocol (AEEFP) with aim of keeping the energy consumption low while achieving high reliability. The data forwarding probability is adaptively determined based on the measured loss conditions. They have estimated the density of a region using the neighbourhood information of nodes located in that region. The neighbourhood information is collected using a topology discovery scheme. The data forwarding probability is adaptively determined based on the measured loss conditions. In this protocol, only for high loss rates, a node uses high transmission power to reach the sink. Whenever the loss rate is low, it adaptively reduces the transmission power. Since energy consumption is minimized, the network lifetime is maximized. Since the source rebroadcast the data, until the packet loss is minimized, high data reliability is achieved. By simulation results we show that the proposed protocol achieves high reliability while ensuring low energy consumption and overhead.

Sasikumaret. al. [50] have proposed a wireless sensor network consisting of spatially distributed independent sensors to monitor physical and environmental conditions and to cooperatively pass the data collected, to a sink through the network. For energy efficiency and network stability, they have proposed distributed clustering. They have implemented k-means clustering algorithm in network simulator. k-means is a prototype-based algorithm that alternates between two major steps, assigning observations to clusters and computing cluster centres until a stopping criterion is fulfilled. In the centralized way of clustering if a packet drops while sending the node information to the central node or while resending back from central node to the individual nodes (i.e., it is more dependent on the routing algorithms), then the node will be left out. Where as in distributed clustering while exchanging the control messages the routing algorithms are not involved since when a node broadcasts its information, all the nodes which are in its receiving range will receive it and again broadcasts it. In this way the message travels the whole network. Simulation results are obtained and compared which show that distributed clustering is efficient than centralized clustering.

Miller et al[51] stated that each node must conserve maximum energy for increasing the life of sensor network. They proposed a protocol in which the energy cost of communication is: the amortized energy cost of communication over multiple packets. Due to limited storage space, they also allow sensors to control the number of buffered packets. To achieve this, a two-radio architecture is used which allows a sensor to "wakeup" a neighbour with a busy tone and send its packets for that destination. However, this process is expensive because all neighbours must be awake and listen to the primary channel to determine who the intended destination is. Therefore, triggered wakeups on the primary channel are proposed to avoid using the more costly wakeup procedure. The model proposed considers energy utilised in processing and communication along with transient energy, but it does not account for energy consumption of sensor sensing, sensor logging and actuation. They have also proposed a protocol for efficiently determining duration of wakeups so that the energy consumption is reduced.

Kim et. al. [52] stated that it is conserve energy of nodes in wireless sensor networks for organising the continuous network than to consider efficiency owing to trait of applications. Former researches have proposed protocols like Flooding, SPIN, DD and LEACH. Though LEACH utilises hierarchical routing and can have sensing double data or managing regionally data transmittance, it is not efficient as it is not appropriate for the sensor nodes having the limiting range. Therefore, there is requirement of a network protocol which realistically supports limiting range of transmittance, supports sensing double data and manages it regionally compared to non-hierarchical routing. They have suggested routing technique based on clustering (RTBC) for preventing double data, which recognizes diachronic trait in surrounding of wireless sensor network. They have also compared RTBC with the established non-hierarchical routing techniques by defining the process of creating the clusters, routing with in the cluster and routing out of cluster. They have undertaken simulation and experimented preventing double data of RTBC and analysing the efficiency of managing data regionally, inducing the realistic routing technique based on clustering. Based on their research they have concluded that realistic routing technique can be used to prevent double data through clustering and managing data regionally.

Manisekaranet. al. [53] have presented a new energy efficient dynamic clustering technique for large-scale sensor networks in which by monitoring the received signal about power from its neighbouring nodes, each node estimates the number of active nodes in real time and computes optimal probability of becoming a cluster head, so that the amount of energy spent in both intra and inter cluster communications can be minimized. Cluster head selection is an important problem in sensor networks. Cluster-based routing has been shown to be more energy efficient and increase the network lifetime through data aggregation. The goal is to select cluster heads that minimize transmission costs and energy usage. Based on the clustered architecture, this work proposes a Multilevel Hierarchical Approach in Dynamic Clustering using Election Algorithm for the efficient Cluster Head selection and Dynamic Energy Efficient Hierarchical routing algorithm for energy efficient routing. When comparing existing work the Multilevel Hierarchical Approach will work efficiently. The new clustering and routing algorithms works efficiently and reduces the energy consumption of sensor nodes.

Kaur et. al. [54] have proposed a distance based deterministic energy efficient (DDEC) clustering protocol which is self-organizing, distributed, dynamic and energy efficient. This new approach is an improvement over DEC [55]. DEC outperforms the probabilistic-based models we have considered, by guaranteeing that a fixed number of cluster-heads are elected per round. At different rounds cluster-heads are elected using the local information of their residual energies within each clusters to choose the appropriate cluster-heads. It selects cluster head on the criteria of residual energy and approximate radius of cluster. This protocol guarantees uniform and well distributed election of fixed number of cluster heads. Simulation implemented in MATLAB reflects better results of proposed protocol comparable to the existing protocols in heterogeneous environment in terms of stability period and network lifetime. They have shown that DDEC has more stable region period than ESEP, DEC and LEACH protocols. DDEC is best for those applications that require 90% -100% monitoring.

Balaet. al. [56] have proposed an idea of deterministic HEED which takes care of cluster head which has not been elected in 1/pi rounds. To ascertain the performance of HEED comparison has been made with Multilevel Heterogeneous-Hybrid Energy Efficient Distributed Protocol (MH-HEED) and the Deterministic-HEED (D-HEED) for Wireless Sensor Network (WSN) considering three different deployment strategies (circular, grid and rectangular). The results envisage that there is increase of about 364.3%, 268.7% and 300% comparing D-HEED over H-HEED, whereas this increase is about 25%, 22.9% and 15.38% over MH-HEED in case of circular, grid and rectangular deployment respectively.

Koucheryavyet. al. [57] have stated that one of the approaches to enhance the lifetime of WSN is to allow only some nodes in a cluster of sensor nodes, called cluster heads, to communicate with the base station. They have adopted a unique approach to the cluster head election problem, specifically concentrating on Homogeneous Wireless Sensor Networks. This cluster-based network organization methodology is based on Voronoi diagram that supports nodes deployed in densely populated network areas as better candidates for becoming cluster head nodes, active sensor nodes and routers.

Sasirekhaet. al. [58] stated that data aggregation is an intelligent technique used in WSN, wherein the data from disparate sources are accumulated at intermediate nodes, thereby reducing the number of packets to be sent to the sink. Literature study shows that various routing algorithms are used to perform data aggregation based on the network topology. In order to provide an improved performance amongst the existing, a routing algorithm called cluster-chain mobile agent routing (CCMAR) has been proposed. It makes full use of the advantages of LEACH and PEGASIS (power-efficient gathering in sensor information systems). CCMAR divides the WSN into a few clusters and runs in two phases. The proposed system is simulated and evaluated for the performance metrics such as energy consumption, transmission delay and network lifetime. The results demonstrate that the proposed CCMAR outperforms LEACH, PEGASIS and other similar routing algorithms; energy efficient cluster-chain based protocols, though fault tolerance and security are the major issues.

ZHANG et.al.[59]have proposed a heterogeneous ring domain communication topology with equal area in each ring in an effort to solve the energy balance problem in original IPv6 routing protocol for low power and lossy networks (RPL). A new clustering algorithm and event-driven cluster head rotation mechanism are also proposed based on this topology. The clustering information announcement message and clustering acknowledgment message were designed according to RFC and original RPL message structure for clustering and routing. An energy efficient heterogeneous ring clustering (E2HRC) routing protocol for wireless sensor networks is then proposed and the corresponding routing algorithms and maintenance methods are established. Experimental results show that in comparison against the original RPL and E2HRC routing protocol more effectively balances wireless sensor network energy consumption, thus decreasing both node energy consumption and the number of control messages.

Hsiang-Hung Liu et. al. [60] stated that rumour routing is a classic random-walk routing protocol that, unfortunately, is not scalable and can result in spiral paths. We consider that the shortest distance between two points is a straight line and that two straight lines in a plane are likely to intersect and develop for WSNs an improved protocol called straight-line routing (SLR), in which we construct a straight path using two-hop information without the assistance of geographic information (local information). SLR thus reduces the energy consumption of sensor nodes in WSNs. SLR builds both the query path and the event path without any need for geographic information, taking advantage of the fact that two nonparallel lines intersect on a plane. Both RR and SLR paths are created on such a basis. Optimal routing in energy-constrained networks is not practically feasible because it requires future knowledge. Keeping the path straight provides a natural way to address the energy cost problem of existing geographic routing protocols. We have demonstrated the advantages of SLR and have used simulation results to show that SLR outperforms RR and achieves higher successful path discovery ratios and lower hop stretch and saves more energy in WSNs.

Yu et. al. [61] stated that the performance of WSN is severely influenced by energy hole problem, which brings a different energy consumption velocity between different nodes and a large portion of energy wasting in these nodes. To solve this problem, a progressive decentralized single-hop (PDSH) method is conceived. PDSH data gathering method works with several phases, in each of which sensors may act in single or multi-hop mode. It works in uniformly deployed sensor networks, and the main idea is to balance the energy consumption ratio between every neighbouring ring. By obtaining a series of laws of the traffic model and the energy model of the network during phases, they proved that PDSH can be adaptive to general sensor network cases and can balance the energy consumption ratio of the network. The initial simulation results show that theoretically this method is quite energy efficient, but the actual performance is little worse. After several more simulations, PDSH is compared with other similar type of data gathering methods and it has been found that, it can improve the system's life span to a considerable extent and balance the energy consumption burden of the network pretty well. It has also been shown through simulations that system's life span varies with the different network divisions in the same network phenomena, and finding the best network division would be an important job before implementing PDSH in a real sensor network and better network division may be found through mathematical deduction, simulations, or real network tests. The well-balanced energy consumption rate results in the extension of the system's life span. The method also adapts in general cases and has been proven to attain most of the original aims of energy conservation.

Halderet. al. [62] stated that a significant approach to conserving energy wireless sensor networks is judicious deployment of sensor nodes within the network area so that the energy flow remains balanced throughout the network and prevents the problem of occurrence of energy holes. They have started with analysis of network lifetime, found node density as the parameter which has significant influence on network lifetime and derived the desired parameter values for balanced energy consumption. They have proposed a probability density function (PDF) to meet the requirement of energy balancing. Further PDF's intrinsic characteristics have been derived and shown its suitability to model the network architecture considered for the work. A node deployment algorithm is also developed based on this PDF. Performance of the deployment scheme is evaluated in terms of coverage-connectivity, energy balance and network lifetime. They derived certain constraints involving important network parameters, which should be satisfied in order to achieve the target. A qualitative analysis has shown the extent to which our proposed PDF has been able to provide desired node density derived from the analysis on network lifetime. Finally, the results of quantitative analysis are compared with three existing deployment schemes based on various distributions. The proposed scheme has achieved the desired results.

Alim Al Islam et. al. [63] have stated that the new generation of increasingly sophisticated wireless sensor network applications, like HP's CeNSE demand high network throughput which easily exceeds the capability of the low-power 802.15.4 radios prevalent in today's sensor nodes. They have investigated an energy-efficient approach to supplementing an 802.15.4-based wireless sensor network with high bandwidth, high power, transmission efficient and longer-range radios such as 802.11. They have exploited a key observation that the high-bandwidth radio achieves low energy consumption per bit of transmitted data due to its inherent transmission efficiency, hybrid network architecture is proposed, that utilizes an optimal density of dual-radio (802.15.4 and 802.11) nodes to augment a sensor network having only 802.15.4 radios. They have presented a cross-layer mathematical model to calculate this optimal density, which strikes a delicate balance between the low energy consumption per transmitted bit of the high-bandwidth radio and low sleep power of the 802.15.4. Experimental results obtained using a wireless sensor network test bed reveal that the proposed architecture improves the average energy per bit by 44% and 67% and end-to-end delay by significant margins compared with a network having only 802.15.4. Moreover, the proposed architecture attempts to evenly distribute energy consumption throughout the network. This phenomenon eventually results in up to 68% and 121% increase in the time elapsed before the death of the first node and half of the nodes having only 802.15.4

in comparison to the architecture with no transmission efficient radio. These results confirm that the strategic deployment of transmission-efficient radios can support high-data-rate sensor network applications while achieving high energy efficiency.

Qing et al [64] proposed Distributed Energy-Efficient Clustering (DEEC)protocol, it classifies nodes as normal nodes, advanced nodes, and super nodes. The energy intensity of super nodes is the highest, when compared to normal and advanced nodes, so super nodes act as cluster heads. Information collected by the normal and advanced nodes is passed on to the super nodes (acting as CHs) in each cluster. Super nodes convey the information received to the BS from different clusters. The DEEC has a longer lifetime and is more effective at messaging than current clustering protocols in heterogeneous environments. Cluster heads are elected by a probability, based on the ratio between the residual energy of each node and average energy of the network. The stages of being cluster heads for nodes differ according to their initial and residual energy. Nodes with high initial and residual energy have more likelihood to be cluster heads than the nodes with lower energy. DEEC adapts the rotating stage of each node to its energy.

Yagoutaet. al. [65] have stated that the optimal deployment of the sink in the controlled field can also conserve network energy by reducing distances between the emitting nodes and the sink. However, deploy a sink in the middle of the controlled field is almost impossible for WSN applications such as battlefield control, or the control of seismic, volcanic and toxic zones. Various researches in this direction have proved that in such scenarios a mobile sink can provide similar level of energy conservation as can be achieved with a sink centrally located in the field. But while considering the sink mobility quality of service is an important metrics to be considered, which has great significance in real time applications. They have studied the impact of sink mobility on energy consumption and QoS metrics in WSN with hierarchical routing protocols. The simulation results have shown that sink mobility improves energy consumption, throughput, packet latency and reliability in comparison to a sink which is located outside the field and may even give result better than those for a centrally located sink.

Nevertheless, with high node densities and high packet rate, latency and reliability abruptly degrade.

Kulkarni et. al. [66] stated that developers of WSNs face challenges that arise from communication link failures, limited energy, memory and computational constraints. Many issues in WSNs are formulated as multidimensional optimization problems, and are approached through various techniques already being practiced by the nature. Most analytical methods suffer from slow speed and lack of convergence towards a final solution. This calls for fast optimization algorithms that produce quality solutions utilizing fewer resources. Particle swarm optimization (PSO) is one such technique inspired by social behavior of bird flocking or fish schooling. It is a simple, effective, and computationally efficient optimization algorithm with insignificant computational burden. It has been applied to address WSN issues such as optimal deployment, node localization, clustering, and data aggregation. However, iterative nature of PSO can prohibit its use for high-speed real-time applications, especially if optimization needs to be carried out frequently. PSO requires large amounts of memory, which may limit its implementation to resource-rich base stations. Literature has abundant successful WSN applications that exploit advantages of PSO. PSO moderately suits data aggregation needs frequent distributed optimization and fast solutions. PSO highly suits static deployment, localization, and clustering. The authors have taken up various issues being faced in WSN and have discussed the suitability of PSOs for WSN applications.

Nataf et al. [67] stated that battery is a major hardware component of wireless sensor networks. These constrained networks are made possible by the processor size reduction and high-performance battery. Nevertheless, these networks have to be careful of their energy consumption because they are usually deployed for a long time or because sensors are so small that their battery has a limited capacity. Since embedded systems are widespread, various battery models that relate its use with its lifetime have been proposed. These take into account two phenomena occurring in battery cell; the Rate Capacity Effect and the Recovery Effect. The first gives the energy consumed under a constant current load as in the case of transmitting and the second gives the energy recovered during inactivity or low current load. At a constant current load, oxidation at the anode induces reduction at the cathode. The reduction decreases the concentration of positive ions near the cathode and so the available energy. But during inactivity or low current load the positive ions near the anode have time to move toward the cathode, thus increasing the available energy and so the battery lifetime. It may be noted here that the recovery process occurs during idle time which is generally up to 90% of the WSN node life. The work presents energy consumption retrieval process and observes in simulated world how battery reacts to network events and configuration parameters.

Chiparaet. al. [68] have proposed Real-time Power-Aware Routing (RPAR) protocol to resolve the inherent conflict between the need to achieve desired quality of service and energy efficient communication. The proposed protocol achieves application–specified communication delays at low energy cost by dynamically adapting transmission power and routing decisions. RPAR features a power-aware forwarding policy and an efficient neighbourhood manager to discover eligible forwarding choices that are optimal for resource-constrained wireless sensors. Another distinguishing feature of RPAR is that, in contrast to existing protocols that treat real-time performance and energy efficiency in isolation, RPAR integrates real-time routing and dynamic power adaptation algorithms to achieve application-specified communication delays at low energy cost. The proposed protocol also handles realistic properties of WSNs such as limited memory, lossy links, and bandwidth. Simulations based on a realistic radio model of MICA2 motes show that RPAR significantly reduces the deadline miss ratio and energy consumption compared with existing real-time and energy-efficient routing protocols.

Mehmmood et. al. [69] have proposed an innovative game theoretic energy balanced (GTEB) geographical routing protocol for extending lifetime of wireless sensor networks (WSNs). The protocol ensures that forwarding nodes run out of energy approximately at the same time. Network density has been considered to divide the transmission region around a sender node into set of forwarding regions. The amount of traffic to be forwarded to these regions is determined on the basis of their available energy through Evolutionary game theory (EGT) and Classical game theory (CGT) is used to select one forwarding node in the forwarding region to forward a packet. They have observed that game theory is an efficient tool for balancing energy consumption and combination of two different types of games are crucial to achieve a network wide energy balance. They have found evolutionary games to be useful in modelling the phenomenon where every node tries to spread a population of data packets to achieve energy balance in its neighbourhood without a defined global energy profile and classical games have been found to be useful in avoiding redundant transmission among a finite number of nodes in a contention domain. Exhaustive simulations of the proposed protocol have shown that this approach prolongs the network life time and provides a better delivery ration in comparison to similar general purpose and energy balanced routing protocols for WSNs.

Collottaet. al. [70] stated that the rapid growth in adoption of wireless sensor networks (WSNs) is on account of advantages offered in comparison to wired systems like effectiveness, ease of installation, flexibility, scalability and self-organization. Due to the limited energy of the sensor nodes, efficient communication among the nodes is desirable to prolong the network lifetime. The two commonly available options i.e. alternation of active and sleep states and regulation of transmission power, have been independently regulated to affect the energy consumption of the nodes. Two fuzzy logic controllers have been used dynamically to adjust the sleep time and transmission power of nodes to optimize energy consumption. The first fuzzy logic controller evaluates the throughput to workload ratio and remaining battery energy in order to adjust the sleep time of devices, while the second controller adjusts transmission power according to battery energy and link quality.

Zhang et. al. [71] have proposed an energy-balanced routing method based on forward-aware factor (FAF-EBRM) to select the next-hop node according to awareness of link weight and forward energy density. Additionally, a spontaneous reconstruction mechanism for local topology is designed. FAF-EBRM has been compared with LEACH and EEUC, and experimental results indicate that FAF-EBRM outperforms LEACH and EEUC, which balances the energy consumption, extends the function lifetime, and guarantees high quality of service of WSN. They have shown that distribution of node degree, strength, and edge weight follow power law and represent “tail,” so the topology has robustness and fault tolerance, reduced the probability of successive node breakdown, and enhances the synchronization of WSN of IA.

Chen et. al [72] have proposed a max-min approach with an objective to maximize the minimum residual energy across the network. They have proposed a general formula for the lifetime of wireless sensor networks which holds irrespective of the underlying network model comprising of factors like network architecture and protocols, data collection initiation, lifetime definition, channel fading characteristics, and energy consumption model. The formula identifies two key parameters at physical layer that affect the network lifetime: the channel state and the residual energy of sensors. Based on this formula, a medium access control protocol has been proposed that exploits both the channel state information and the residual energy information of individual sensors. The work provides not only gauge for performance evaluation of sensor networks but also a guideline for the design of network protocols and reveals that a lifetime-maximizing protocol should exploit both channel state information (CSI) and residual energy information (REI) of individual sensors. A greedy approach to lifetime maximization has also been proposed, which achieves considerable improvement in lifetime performance

Yang et al[73] have designed a low-power wireless data acquisition and transmission system based on ZigBee. The results show that system has advantages with lower data error rate. It is able to meet needs of remote monitoring of parameters in industrial environment. From low-power design point of view, low-power data acquisition and transmission system based on ZigBee has been researched. Experimental results show that system is stable and reliable in 70 meters area, data error rate is less than 1%, which can meet remote monitoring of parameters in the industrial environment.

Zhou et. al.[74] have proposed a new method to prolong the network lifetime based on the improved particle swarm optimization algorithm, which is an optimization method designed to select target nodes. The protocol takes into account both energy efficiency and transmission distance, and relay nodes are used to alleviate the excessive power consumption of the cluster heads. The proposed protocol results in better distributed sensors and a well-balanced clustering system enhancing the network's lifetime. The proposed protocol is compared with comparative protocols by varying a number of parameters, e.g., the number of nodes, the network area size, and the position of the base station. Simulation results show that the proposed protocol performs well against other comparative protocols in various scenarios.

Chaudhari et.al.[75] have proposed a hybrid energy harvesting low energy adaptive clustering hierarchy algorithm (HEH-LEACH). As per the algorithm the hybrid-powered motes have been made the cluster heads to enable simultaneous harvesting of energy from renewable sources like wind and solar. The algorithm utilizes the environmental condition and meteorological data for solar as well as wind energy. The nodes can utilizes any of the three power sources as per availability with priority to solar and then to wind and lastly from batteries. The algorithm reports considerable improvement in network lifetime.

2.8 REVIEW OF SIMULATION TOOLS

As part of this research work, proposed protocol has been validated by carrying out simulation on MATLAB. Before starting with MATLAB, as a tool for carrying out simulations few other available simulation tools [76] available for Wireless Sensor Networks were also surveyed. A brief overview of these tools is covered in this section.

2.8.1 Network Simulator 3 (ns-3)

Network Simulator 3[77] popularly known as ns-3 is a discrete event network simulator built using C++ and Python with scripting capability. It is one of the most popular non-specific network simulators, and supports a wide range of protocols in all layers. It contains various inbuilt libraries and modules within a directory. It supports graphical user interface and Python bindings. It is used for studying and analysing network performance or monitoring protocol operations in various controllable and scalable environments. It is easy to write coding in C++ and python and ns-3 code can be combined with other code. Its working process is like an active open source project.

Various models are developed by ns-3 simulation. The simulator features an integrated attribute-based system to manage default and per-instance values for simulation parameters. It focuses on wireless/IP simulations which involve models for Wi-Fi, WiMAX, or LTE for layers 1 and 2 and a variety of static or dynamic routing protocols. It supports a real-time scheduler that facilitates a number of "simulation-in-the-loop" use cases for interacting with real systems. It is targeted primarily for research and educational use. It is the paradigm of reusability and provides complete support of communication protocol models, among non-commercial packages. It is free software, licensed under the GNU GPLv2 license and publicly available for research and development use. There is no Graphical Tool which is available in NS-3, but still graphical results can be interpreted using NetAnim open source software

2.8.2 TOSSIM

TOSSIM is the simulator for TINY OS, which is an open source, BSD-licensed operating system designed for low-power wireless devices, such as those used in sensor networks, ubiquitous computing, personal area networks, smart buildings, and smart meters. It simulates entire TinyOS applications. It works by replacing components with simulation implementations. The level at which components are replaced is very flexible: for example, there is a simulation implementation of millisecond timers that replaces HilTimerMilliC, while there is also an implementation for atmega128 platforms which is general and can be used for any platform, but lacks the fidelity of capturing an actual chip's behaviour, as the latter does. Similarly, TOSSIM can replace a packet-level communication component for packet-level simulation, or replace a low-level radio chip component for a more precise simulation of the code execution.

TOSSIM is a discrete event simulator[78]. When it runs, it pulls events of the event queue (sorted by time) and executes them. Depending on the level of simulation, simulation events can represent hardware interrupts or high-level system events (such as packet reception). Additionally, tasks are simulation events, so that posting a task causes it to run a short time (e.g., a few microseconds) in the future. [79]It compiles directly from TinyOS NesC code, scaling to thousands of simulated nodes. TOSSIM gives programmer an omniscient view of network and greater debugging capabilities. Server-side applications can connect to a TOSSIM proxy just as if it were a real sensor network, easing the transition between the simulation environment and actual deployments.

TOSSIM is scalable and extensible. It replaces Hardware with Software components and captures complete system behavior and interactions between the components. The same code can be used for both simulation and test-bed deployment. It is an Open Source Project and is available for free of cost. But TOSSIM currently does not support gathering power measurements.

2.8.3 QualNet

QualNet is proprietary state-of-the-art simulator for large and heterogeneous networks. As network simulation software, it acts as a planning, testing, and training tool which mimics the behaviour of a physical communications network. QualNet[77] has the capacity to scale nodes, which enables sophisticated analysis. It has robust set of wired and wireless network protocols and device models; it is useful for simulating diverse types of networks. It has a parallel processing architecture and is optimized for speed and scalability. The simulation speed multiplies with the addition of processors. It has robust GUI which covers all aspects of the simulation. QualNet network simulation tool can run on multicore and multi-processor systems to model large networks with high fidelity. It has been used to simulate high-fidelity models of wireless networks with as many as 50,000 mobile nodes. It uses highly detailed standards-based implementation of protocol models. It also includes advanced models for the wireless environment to enable more accurate modelling of real-world networks. It enables the users to design new protocol models, Optimize new and existing models and analyze the performance of networks and perform what-if analysis to optimize them. QualNet and its library of models run on a vast array of platforms, including Windows and Linux operating systems on 64-bit distributed and cluster parallel architectures. Being proprietary software, it is commercial and expensive.

2.8.4 MATLAB

MATLAB (matrix laboratory) is a multi-paradigm mathematical computing environment and proprietary programming language developed by MathWorks Inc. It allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, C#, Java, Fortran and Python. It is intended primarily for numerical computing, but optional toolboxes use MuPAD symbolic engine, allowing access to symbolic computing abilities and Simulink, adds graphical multi-domain simulation with model-based design for dynamic and embedded systems. It provides an interactive environment with hundreds of reliable and accurate built-in mathematical functions. It is easy to learn and use programming capability and user-developed functions. It has several optional toolboxes written for special applications such as signal processing, control systems design, system identification, statistics, neural networks, fuzzy logic, symbolic computations and Simulink.

Table 2.1: Overview of Simulation Tools

Simulation Environment	Programming Language	WSN support
QualNet	C and Parsec	Basic mobility and radio propagation models; 802.11; additionally battery and energy model; up-to-date, but commercial
TOSSIM	nesC	All TinyOS-based WSN protocols can be simulated with TOSSIM without modifications → good approach especially if implemented with TinyOS-based nodes
NS-3	C++; configuration Python	Large no. of protocols available contributed by NS-3 users → complex configuration; unclear situation due to large number of different user contributed implementations
MATLAB	C , Java	Detailed simulation of the end nodes and their architecture, Physical layer parameters, different modulation and encoding techniques, communication channel modelling (SNR, effect of different Noise schemes, Interference, distance etc..), various methods to monitor and record results, making use of rich library of MATLAB/Simulink.

2.9 REVIEW OF TESTBEDS

In the recent past numerous researches have been conducted and variety of physical test beds have been setup by the researchers to verify their work. [80] Describes in detail a vast selection of WSN test beds developed over the past few years. The paper describes general architecture and highlights unique features of each test bed to choose the best test bed as per specific requirement. The test beds have been classified based on their designs. General Test beds are deployed indoors without any outside interference. Such test beds are deployed mainly by academic institutes. These test beds usually consist of a network of sensor nodes, channel for test bed management connectivity, a database for logging data and a management software with interactive user interface. The software is designed to handle scheduling of sensor nodes for experiments, controlling network topology, programming the nodes, debugging faulty networks, for analysis and visualisation of data.

On the other hand Server based Test beds have a centralised server based management. MoteLab[81] was one of the very first fully developed WSN test beds using MicaZ motes. It is an open source tool that is available on the Internet to any registered user. All Motelab code is available for institutions to build their own test beds. It consists of a MySQL database server, a PHP web server, a Java based data logger and a job daemon that assigns experiments to networked motes. The motes are connected through Ethernet interface to gain access to the back-channel. ORBIT [82] is a radio grid network test bed developed by Rutgers University, designed to serve as evaluation tool for wide range of wireless network protocols. It has multiple back-end services that can control the test bed through an Ethernet back-channel interface. The test bed supports mobile nodes and, is robust against failures. It can be used to test multiple radio technologies.

Another category of test beds comprise of the once that use a single PC as the central point of the test bed which takes care of all the data logging and the management functions. These arrangements use serial/USB back-channels to interface with the motes. These are flexible and can be easily adapted to different scenarios. But they have limitations regarding scalability and no simultaneous or remote user access. One such example is LabVIEW Test bed [83]. It uses off the shelf components to create a user friendly test bed along with management tool developed in LabVIEW environment. This interface program is installed on a central PC. Once motes are programmed individually through a RS-232 interface, the LabVIEW application can record and visualise all test bed data in real time. The test bed comprises of two sets of motes, the first is consists of 15 MicaZ motes in a multi-hop architecture and the second with 8 Cricket motes in a single hop configuration connected to the base station.

To harness the best of both the words, there are hybrid test beds in which a central management server is used but the test bed is dependent on separate gateway devices that perform control and data management functions and supply connectivity to motes. This approach is more scalable as new gateways can be added to extend the network capability. IBM WSN Test bed [84] is one such test bed developed at IBM's Zurich laboratory. The test bed evaluates various short range radio communication technologies. It can either be configured in a flat or meshed architecture. The sensor units are designed using FPGA and implement multiple sensors so that these can be interfaced with various radio nodes depending upon the experimental requirements. The wireless network thus created is connected with the enterprise network through a Power PC based gateway node. The data is derived from the network using a Java middle ware program and can be used for further analysis.

Another set of test-beds address the limitation of confinement to single or fixed environment. Such multiple site test beds are deployed at multiple locations and are controlled from a central location. SensLAB[85] is one such very large scale open wireless sensor network test bed spread across 4 different sites in France. The objective of the test bed is evaluation of scalable wireless sensor network protocols and applications. SensLAB’s main and most important goal is to offer an accurate open access multi-users scientific tool to support the design, development, tuning, and experimentation of real large-scale sensor network applications. The SensLAB test-bed is composed of 1024 nodes and it is distributed among 4 sites. Two sites offer access to mobile nodes. Every sensor node is also able to be configured as a sink node and can exchange data with any other sink node of the whole SensLAB test-bed (locally or remotely) or any computer on the Internet.

Few test beds like SenseNeT[86] do not rely on any additional hardware like wired infrastructure or gateway nodes by using the existing wireless channel for node management and control purposes as well. This makes test-bed more scalable and reduces costs. A software component is installed on the motes, which is used to interact with the central servers through existing wireless channel. Remote users can access test bed through a web interface while an application and database server manages the test bed, reprograms nodes and records data. A base station node is used to interact between the management hardware and the network of MicaZ motes. The test bed has self-organising and self-healing properties that ensures depleted nodes can be replaced easily.

More work is being done and innovative enhancements are being added to the test bed architecture with an aim to improve upon resource allocation, scalability, control, accuracy, reliability, availability and improving user experience.

2.10 SUMMARY

From the review of routing protocols for WSNs, it can be concluded that the flat protocols may be an ideal solution for a small network with fixed nodes. However, in a large network they become infeasible because of link and processing overhead. The hierarchical protocols try to solve this problem and to produce scalable and efficient solutions. They divide the network into clusters, to efficiently maintain the energy consumption of sensor nodes and perform data aggregation and data fusion in order to reduce the number of transmitted messages to the sink. The clusters are organised based on energy reserve of sensors and sensor's proximity to the cluster head. Thus, hierarchical protocols are suitable for sensor networks with heavy load and wide coverage area. Location based protocols use location information in order to calculate distance among nodes, and may be useful for highly dynamic networks as they do not need a state in routers nor in packet header and does not cause flood in the search.

It is also evident that, low energy adaptive clustering hierarchy (LEACH) protocol has remained in the attention of research community ever since its inception [8].

Numerous diverse modifications have been proposed by researchers over all these years. The variants of the LEACH protocol have been proposed in both single hop and multi hop scenarios. Some of the key takeaways are:

a) Most successors of LEACH are an improvement over the basic LEACH protocol.
b) These can be broadly classified into two categories based on data transmission from cluster head to base station as single hop or multi-hop communication.
c) Many of the newly designed protocols have focussed on improving the energy efficiency apart from performance factors.
d) Most of these protocols are distributed in nature and require location information.
e) Single hop clustering protocols have an edge over multi hop clustering routing protocols due to the additional overheads of path set up and identification of relay nodes/ cluster heads.
f) Only few researchers have considered energy consumption during cluster formation and cluster head selection, although focus has been given on contribution to energy consumption by other factors like node location, node density, distance from sink, optimal number of clusters etc.
g) Concern for security has been addressed in most protocols at the cost of energy efficiency. To obtain a secure energy efficient WSN requires optimising trade-off between energy efficiency and network security.
h) Focus has been on deterministic clustering instead of probabilistic approach to clustering due to more reliability. LEACH related protocols offer a promising improvement over conventional LEACH; however, there is still much scope for developing convenient and efficient LEACH variants. Some of the key research areas are QoS based LEACH routing for multimedia and real time applications, another areas for focus are energy harvesting in WSNs, clustering in heterogeneous networks on account of varying communication and processing capabilities of constituent nodes.

CHAPTER III

ENERGY CONSUMPTION PERSPECTIVE

3.1 INTRODUCTION

Wireless sensor networks (WSNs) are known to be highly energy-constrained and each network's lifetime has strong dependence on individual node's battery capacity. Energy efficiency is of great concern in sensor networks, since maintenance and hardware cost is dominated by battery replacement. Building a wireless sensor network requires the constituting nodes to be developed and made available for maximum time. The sensor nodes perform numerous principal tasks – computation, storage, communication and sensing/actuation. Depending upon the application, the nodes might have to be small, inexpensive and energy efficient. They have to be equipped with right sensors, required memory and computational resources along with adequate communication facilities. For devising energy efficient routing algorithms, it is mandatory to understand the phenomenon of energy consumption in sensor nodes.

This chapter discusses various factors affecting the energy efficiency of wireless sensor networks and covers in detail the energy consumption perspectives.

3.2 FACTORS AFFECTING ENERGY EFFICIENCY OF WSN

(i) Lifetime of WSN: Network lifetime has been a critical concern in WSN research. While numerous energy-efficient protocols have been proposed to prolong the network lifetime, variety of definitions of network lifetime have also been used for the different scenarios and protocols. The lifetime of a sensor network is most commonly defined as the time to the first sensor node failure, which may seem over-pessimistic in many envisaged deployment scenarios. In case of dense deployments, time upto which 60-70% nodes in the network survive can also be considered network lifetime.

(ii) Topology and Design Issues: Wireless Sensor Networks (WSN) are highly distributed self-organized systems. WSN have been deployed in various fields.

Because of some hardware problems, especially with respect to energy supply and miniaturization, WSN have certain short comings such as routing challenges and design issues, topology issues and Quality of Service support issues. Design issues emphasize on designing the Wireless Sensor Networks in such a way that it should provide a fault tolerant communication with low latency. Topology issues include arrangement/spread of nodes, geographic routing and coverage related issues. Quality of Service aims at providing better networking services over current technologies.

(iii) **MIMO based and Multi-hop Sensor Networks:** Total energy consumption includes energy consumed in transmission and electronic circuitry. Multi-Input-Multi-Output (MIMO) systems have good spectral efficiency but more circuit that consumes energy as compared to individual single-antenna nodes that cooperate to form multiple-antenna transmitters or receivers. It has been shown that, by transmitting and/or receiving information jointly, even after considering the local energy cost necessary for joint information transmission and reception, large amount of energy saving is possible for transmission distances, larger than a given threshold.

(iv) **Dense Wireless Sensor Networks:** Decentralized detection in a network of wireless sensor nodes involves the collection of redundant information about a phenomenon of interest (PoI) from geographically dispersed nodes. The energy overheads involved in transmission and processing of redundant information can be avoided by data aggregation techniques viz. min, max, mean etc.

(v) **Congestion and Contention in WSN:** Wireless Sensor Networks (WSNs) are characterized by the collaborative information transmission from multiple sensor nodes observing a physical phenomenon. Due to the limited capacity of shared wireless medium and memory restrictions of the sensor nodes, channel contention and network congestion can be experienced during the operation of the network. In fact, the level of local contention and the network congestion are closely coupled due to the multi-hop nature of sensor networks. Therefore, the unique characteristics of WSN call for a comprehensive analysis of the network congestion and contention under different network conditions.

(vi) **Optimization of WSN for Environmental Measurements:** Adaptive behaviour of autonomously working WSNs tries to maximize cost efficiency of deployments. This includes maximizing the lifetime through power consumption optimization and recharging energy reservoirs with the use of energy harvesting techniques by deploying solar cells and other such means. The efficient resource usage is guided by information about energy balance in sensor network.

(vii) **Cluster based WSN for periodic Monitoring Applications:** Clustering is one of the most popular approaches used in wireless sensor networks to conserve energy and increase node as well as network lifetime. LEACH is among the most popular clustering protocols proposed for wireless sensor networks. Network lifetime and energy consumption analysis for cluster-based wireless sensor networks based upon LEACH protocol for periodic monitoring applications induce unbalanced energy consumption among sensor nodes and hence affect the network lifetime when compared with the results obtained from the analytical model of this protocol. This highlights the need for an adaptive clustering protocol that can increase the network lifetime by further balancing the energy consumption among sensor nodes.

3.3 ENERGY CONSUMPTION IN SENSOR NODE

A sensor node is a small wireless device that is capable of sensing the data and transmitting it wirelessly to one or many neighbouring nodes. The main components of a typical sensor node also known as mote are: microcontroller (with memory) a radio transceiver, external memory, power source and required sensors. Wireless sensor networks comprise of thousands of such nodes.

Figure 3.1 below shows the key components of a typical sensor node. It has processor with memory which is doing all the processing or calculations and the data captured is stored in the memory which is then transmitted to the base station through the network as per instructions via communication interface.

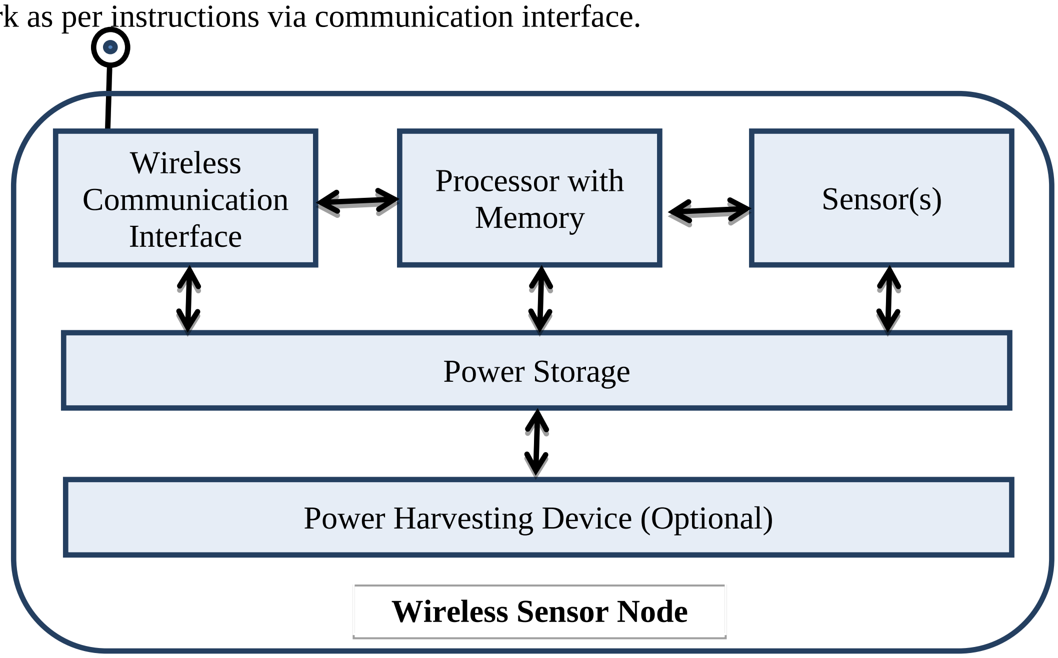


Figure 3.1: Main constituents of a typical Sensor Node

A sensor with in the node is a device that produces measurable response to a change in physical or chemical parameters. More specifically, a sensor is "a device that responds to a stimulus, such as heat, light, or pressure, and generates a signal that can be measured". Sensors are either passive or active devices. Passive sensors in element form include seismic, acoustic, strain, humidity, and temperature-measuring devices. Passive sensors in array form include optical [visible, infrared 1 micron (mm), infrared 10 mm], and biochemical measuring devices. Passive sensors tend to be low-energy devices. Active sensors like radar and sonar; are high-energy systems.

For functioning of node, energy is required which is available through the power source attached. Depending upon usage, power is consumed from power source. Moreover, the power sources in respective nodes are not replaceable. So it is needed to manage the load and reduce the battery power usage which in turn increases the network lifetime. The issue of power consumption is required to be addressed as a design time constraint. In most instances, communication circuitry and antennas are the primary elements that draw most of the energy. Each of the components has to operate balancing the trade-off between as small energy consumption as possible on one hand and the need to accomplish their tasks on the other hand. Both communication device and the controller should be turned off as long as possible. To wake up again, the controller can be reactivated after some time using a pre-programmed timer, alternatively the sensors could be programmed to raise an interrupt if a given event occurs, for example, room temperature being measured exceeds a set threshold value or an incoming transmission is detected by the transceiver. Such pre-processing can be highly specific as per requirement of the application, but should remain simple enough for continued operation resulting in improved energy efficiency.

Out of the various functions performed by nodes, some are useful and some are wasteful. The power consumed by useful functions is called useful power consumption viz. transmitting or receiving the data, processing the query request, forwarding the query and data to neighbours. On the other hand the power consumed by wasteful functions like idle listening to the channel and waiting for the possible traffic, retransmitting because of collisions, overhearing and receiving packets not belonging to it, generating and handling control packets, over-emitting sensor receiving packets when it is not ready is called wasteful power consumption.

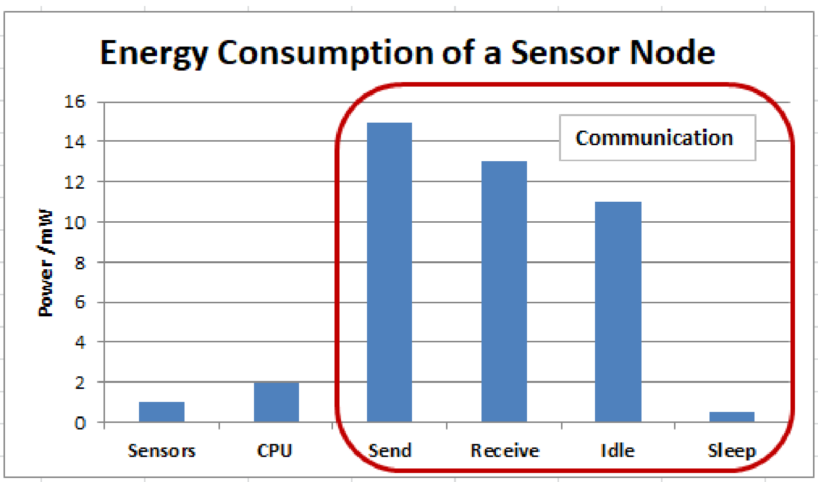


Figure 3.2: Energy Consumption of a Sensor Node

As shown in Figure 3.2 above, the communication cost dominates the energy budget of any sensor node. Sensor nodes deploy RF circuitry for transmitting and receiving signals. The power consumption of CMOS circuits is proportional to the product of the transistor area, clock rate, and the square of the voltage swing. RF circuits need far higher clock rates, bigger transistors, and larger voltage swings than the baseband digital circuits. Thus, by reducing the number of bits to be transmitted by doing processing locally, power consumption of a sensor network can be radically reduced.

In most applications, for majority of the time there is nothing of interest to report, but still sensors need to be constantly vigilant for events. The solution is to dedicate some specialized low-power circuits to be looking for events using simple processing (e.g. energy detection) which has a high false alarm probability but the desired missed detection probability. Then more sophisticated processing is triggered, perhaps using general purpose processors. Only after receiving alert from this general purpose processor, the sensor node will be enabled to communicate with its neighbours. If the detection certainty is high enough, it may inhibit its neighbours from communicating, and send the decision back to the remote user. Alternatively, it may excite its neighbours to become involved in cooperative processing to achieve a higher level of certainty before engaging in long-range communications. By means of this processing hierarchy, both the signal processing and communications energy costs can be minimized, while meeting false alarm and detection probability targets.

3.4 POWER CONSUMPTION AND OPERATING MODES

Power saving is a very critical issue in energy-constrained wireless sensor networks. As per the literature survey, many schemes can be found, which have significant contributions in energy conservation. To improve energy efficiency and to increase the network lifetime, Sleep mode is introduced in the network. This is done by reducing the time where the sensor is idle. The entire operation of a sensor node can be divided into four modes as shown in the Figure 3.3 below.

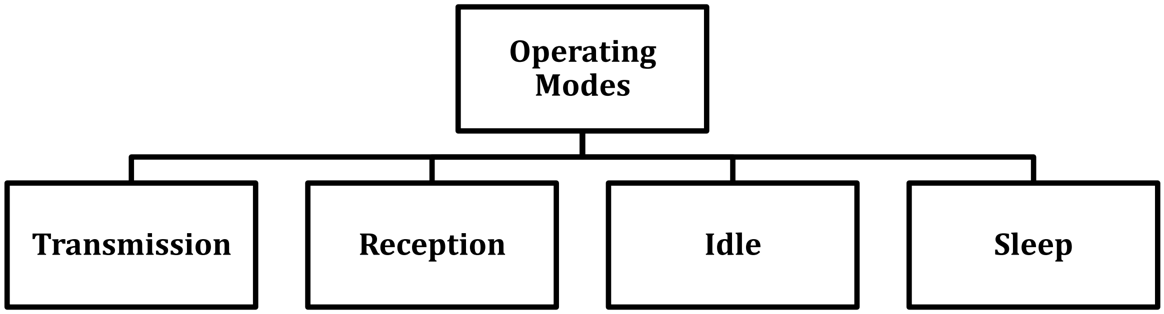


Figure 3.3: Operating modes of a Sensor Node

Transmission Mode: Transmission mode means transferring of data between two nodes. In the transmission mode the energy is consumed in transmitting the data to the neighbouring nodes. In a sensor network each node is connected to all the nodes by any of the path. Thus data can be transmitted to the neighbouring nodes in the network as per destination address assigned by the transmitting node.

Reception Mode: Reception mode means receiving of data between two nodes. In the reception mode the energy is consumed in receiving the data from various neighbouring nodes. In this the data is received by the node if its address matches the destination address assigned by the transmitting node.

Idle Mode: In the idle mode the node remains in idle state. In this state the channel is ready to receive but is not doing so. In this mode some of the hardware functions are switched off and thus the energy consumption is little bit less.

Sleep Mode: In sleep mode the node is not active or the significant parts of transceiver are switched off, thus consuming lesser power. Sleep time is set optimal so as to avoid the delay of information. Sensor networks use a fixed low-power radio mode for putting the radio to sleep. The reduction of the battery usage is caused by the sleep mode operation while at the same time it maximizes the network lifetime by introducing the sleep control.

3.5 ASSESSING ENERGY CONSUMPTION IN SENSOR NODE

Operation states of different components of sensor nodes have different power consumption. As already mentioned, batteries having small capacities, and recharging by energy scavenging is complicated therefore the volatile energy supply for a sensor node is a premium commodity. Hence, energy consumption of sensor node must be controlled tightly. The main consumers of energy are the controller, the radio transceiver, memory to some extent and any other component depending upon application. One important contribution to reduce power consumption comes from chip-level and lower technologies.

Designing low-power chips is the best starting point for an energy-efficient sensor node. But this is only one side of the picture, as any advantages gained by such designs can easily become worthless when the components are improperly operated. The crucial observation for proper operation is that most of the time a wireless sensor node has nothing to do. Hence, it is best to turn it off. Naturally, it should be able to wake up again, on the basis of external stimuli or on the basis of time. Though, completely turning off a node is not possible, but rather, its operational state can be adapted to the tasks at hand. Introducing and using multiple states of operation with reduced energy consumption in return for reduced functionality is the core technique for energy-efficient wireless sensor node. These modes can be introduced for all components of a sensor node, in particular, for controller, radio front end, memory, and sensors. Different models usually support different numbers of such sleep states with different characteristics.

3.5.1 Microcontroller

For a microcontroller, typical states are “active”, “idle”, and “sleep”; a radio modem could turn transmitter, receiver, or both on or off; sensors and memory could also be turned on or off. The usual terminology is to speak of a “deeper” sleep state if less power is consumed. While such a graded sleep state model is straightforward enough, it is complicated by the fact that transitions between states take both time and energy. The usual assumption is that the deeper the sleep state, the more time and energy it takes to wake up again to fully operational state (or to another, less deep sleep state). Hence, many a times, it may be worthwhile to remain in an idle state instead of going to deeper sleep states even from an energy consumption point of view. Figure 3.4 below illustrates notion based on a commonly used model [87], [88]. At time t_1, the decision whether or not the microcontroller is to be put into sleep mode should be taken to reduce power consumption from P_{active} to P_{sleep}. If it remains active and the next event occurs at time t_{event}, then a total energy of $E_{active} = P_{active} (t_{event} - t_1)$ has been spent uselessly idling. Putting the component into sleep mode, on the other hand, requires a time τ_{down} until sleep mode has been reached; as a simplification, assume that the average power $\tau_{down}(P_{active} + P_{sleep})/2 + (t_{event} - t1 - \tau_{down})P_{sleep}$ energy is required in sleep mode as opposed to consumption during this phase is $(P_{active} + P_{sleep})/2$. Then, P_{sleep} is consumed until t_{event}. In total, $(t_{event}-t_1)P_{active}$ when remaining active. The energy saving (1) is thus:

$$E_{saved} = (t_{event} - t1)\, P_{active} - (\tau_{down}\, (P_{active} + P_{sleep})/2 + (t_{event} - t1 - \tau_{down})\, P_{sleep}) \quad (1)$$

Once the event to be processed occurs, however, an additional overhead (2) of:

$$E_{overhead} = \tau_{up}(P_{active} + P_{sleep})/2 \quad (2)$$

is incurred to come back to operational state before the event can be processed, again making a simplifying assumption about average power consumption during makeup. This energy is indeed an overhead since no useful activity can be undertaken during this time. Clearly, switching to a sleep mode is only beneficial if $E_{overhead} < E_{saved}$ or, equivalently, if the time to the next event is sufficiently large as shown in equation (3) below:

$$(t_{event} - t_1) > \frac{1}{2}(\tau_{down} + \frac{P_{active}+P_{sleep}}{P_{active}- P_{sleep}}\tau_{up}) \quad (3)$$

Careful scheduling of such transitions has been considered from several perspectives [87], lot of medium access control research in wireless sensor networks can be regarded as the problem of when to turn off the receiver of a node.

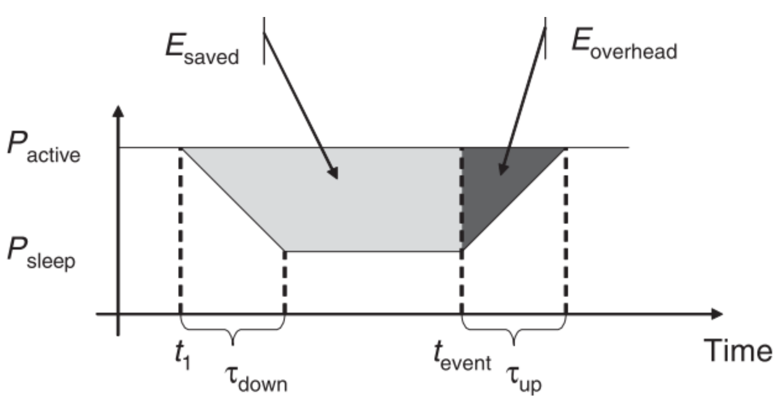


Figure 3.4: Energy savings and overheads for sleep modes

3.5.1.1 Dynamic Voltage Scaling

A more sophisticated possibility than discrete operational states is to use a continuous notion of functionality/power adaptation by adapting the speed with which a controller operates. The idea is to choose the best possible speed with which to compute a task that has to be completed by a given deadline. One solution is to switch the controller in full operation mode, compute the task at highest speed, and go back to a sleep mode as quickly as possible. The alternative approach is to compute the task only at the speed that is required to finish it before the deadline. The rationale is the fact that a controller running at lower speed, that is, lower clock rates, consumes less power than at full speed. This is due to the fact that the supply voltage can be reduced at lower clock rates while still guaranteeing correct operation. This technique is called Dynamic Voltage Scaling (DVS) [89], This technique is actually beneficial for CMOS chips: As the actual power consumption P has quadratic dependence on the supply voltage V_{DD} [90], reducing the voltage is a very efficient way to reduce power consumption. Power consumption also depends on the frequency f, as depicted in equation (4) below:

$$\text{Hence } P \propto f . V_{DD}^2 \tag{4}$$

Consequently, dynamic voltage scaling also reduces energy consumption.

3.5.2 Memory from an Energy Perspective

The most relevant kinds of memory are on-chip memory of a microcontroller and FLASH memory – off-chip RAM is rarely if ever used. In fact, the power needed to drive on-chip memory is usually included in the power consumption numbers given for the controllers. Hence, the most relevant part is FLASH memory – in fact, the construction and usage of FLASH memory can heavily influence node lifetime. The relevant metrics are the read and write times and energy consumption. All this information is readily available from manufacturers' data sheets and do vary depending on several factors. Read times and read energy consumption tend to be quite similar between different types of FLASH memory. Writing is somewhat more complicated, as it depends on the granularity with which data can be accessed (individual bytes or only complete pages of various sizes). One means for comparability is to look at the numbers for overwriting the whole chip. Considerable differences in erase and write energy consumption exist, up to ratios of 900:1 between different types of memory.

3.5.3 Radio Transceivers

A radio transceiver has essentially two tasks: transmitting and receiving data between a pair of nodes. Similar to microcontrollers, radio transceivers can operate in different modes; the simplest ones are being turned on or turned off. To accommodate the necessary low total energy consumption, the transceivers should be turned off most of the time and only be activated when necessary – they work at a low duty cycle. But this incurs additional complexity, time and power overhead that has to be taken into account.

3.5.3.1 Modelling Energy Consumption during Transmission

In principle, energy consumed by a transmitter is due to two sources [91]: one part is due to RF signal generation, which mostly depends on chosen modulation and target distance and hence on the transmission power P_{tx}, that is, the power radiated by the antenna. A second part is due to electronic components necessary for frequency synthesis, frequency conversion, filters, and so on. These costs are basically constant. One of the most crucial decisions when transmitting a packet is thus choice of P_{tx}. desired transmission power P_{tx} is known and is a function of system aspects like energy per bit over noise E_b/N_0, bandwidth efficiency η_{BW}, distance *d* and path loss coefficient γ.

The transmitted power is generated by the amplifier of a transmitter. Its own power consumption P_{amp} depends on its architecture, but for most of them, their consumed power depends on the power they are to generate. In the most simplistic models, these two values are proportional to each other, but this is an oversimplification. A more realistic model assumes that a certain constant power level is always required irrespective of radiated power, plus a proportional offset, indicated in equation (5) below:

$$P_{amp} = \alpha_{amp} + \beta_{amp} P_{tx} \qquad (5)$$

where α_{amp} and β_{amp} are constants depending on process technology and amplifier architecture. In addition to amplifier, other circuitry has to be powered up during transmission as well, like, baseband processors. This power is referred to as P_{txElec}.

The energy to transmit a packet n-bit long (including all headers) then depends on how long it takes to send the packet, determined by nominal bit rate R and coding rate R_{code}, and on total consumed power during transmission. If, in addition, transceiver has to be turned on before transmission, start-up costs also are incurred. These effects can be summarised in the equation (6) as:

$$E_{tx}(n, R_{code}, P_{amp}) \ = \ T_{start}P_{start} + \frac{n}{RR_{code}}(P_{txElec} + P_{amp}) \tag{6}$$

The above equation has been derived independent of modulation chosen for transmission and assumes to have a perfect antenna without any losses.

3.5.3.2 Modelling Energy Consumption during Reception

Similar to the transmitter, the receiver can be either turned off or turned on. While being turned on, it can either actively receive a packet or can be idle, observing the channel and ready to receive. Evidently, the power consumption while it is turned off is negligible. Even the difference between idling and actually receiving is very small and can, for most purposes, be assumed to be zero. To elucidate, the energy E_{rcvd} required to receive a packet has a start-up component $T_{start}P_{start}$ similar to the transmission case when the receiver had been turned off (start-up times are considered equal for transmission and receiving here); it also has a component that is proportional to the single-node architecture packet time $\frac{n}{RR_{code}}$. During this time of actual reception, receiver circuitry has to be powered up, requiring a (more or less constant) power of P_{rxElec} – for example, to drive the LNA in the RF front end. The last component is the decoding overhead, which is incurred for every bit – this decoding overhead can be substantial and is relatively complicated to model, as it depends on a number of hardware and system parameters; therefore, the energy required to receive a packet can be expressed as equation (7):

$$E_{rcvd} = T_{start}P_{start} + \frac{n}{RR_{code}}P_{rxElec} + nE_{decBit} \tag{7}$$

Providing concrete numbers for exemplary radio transceivers is more difficult than it is for microcontrollers: Range of commercially available transceivers is vast, with many different characteristics. Transceivers that appear to have excellent energy characteristics might suffer from other shortcomings viz. poor frequency stability under temperature variations, poor blocking performance, high susceptibility to interference on neighbouring frequency channels, or undesirable error characteristics; they could also lack features, those other transceivers have, like ability to tune to multiple frequencies.

3.5.3.3 Dynamic Scaling of Radio Power Consumption

Applying controller-based Dynamic Voltage Scaling (DVS) principles to radio transceivers as well is tempting, but nontrivial. Scaling down supply voltage or frequency to obtain lower power consumption in exchange for higher latency is only applicable to some electronic parts of a transceiver, but this would mean that remaining circuitry – amplifier, for instance, which cannot be scaled down as its consumed power mostly depends on communication distance – still has to be run at high power over an extended period of time [87]. However, frequency/voltage versus performance trade-off exploited in DVS is not the only possible trade-off to exploit. Any such “parameter versus performance” trade-off that has a convex characteristic should be amenable to an analogous optimization technique. For radio communication, in particular, possible parameters include choice of modulation and/or code, giving rise to Dynamic Modulation Scaling (DMS), Dynamic Code Scaling (DCS) and Dynamic Modulation Code Scaling (DMCS) optimization techniques. The idea is to dynamically adapt modulation, coding, etc. to maximize metrics like throughput, energy efficiency. It rests on hardware’s ability to actually perform such modulation adaptations, but this is a commonly found property of modern transceivers. In addition, delay constraints and time-varying radio channel properties have to be taken into account. The details of these approaches are somewhat involved, and partially, complicated optimization problems have to be approximately solved. The required computational effort should not be underestimated and a combined analysis should be undertaken on how best to split up energy consumption. Nonetheless, these approaches are quite beneficial in energy efficiency terms.

3.5.4 Power Consumption of Sensors and Actuators

Providing any guidelines about power consumption of the actual sensors and actuators is next to impossible because of the wide diversity of these devices. For some of them – for example, passive light or temperature sensors – the power consumption can perhaps be ignored in comparison to other devices on a wireless node (although Hill et al. [92] report a power consumption of 0.6to1 mA for a temperature sensor). For active devices like sonar, power consumption can be quite considerable and must even be considered in the dimensioning of power sources on the sensor node, not to overstress batteries, for example. To derive any meaningful numbers, requires a look at the intended application scenarios and the intended sensors to be used. Some hints on power consumption of sensor/controller interfaces, namely, AD converters, can be found in reference [93], [94] In addition, the sampling rate evidently is quite important. Not only does more frequent sampling require more energy for the sensors as such but also the data has to process and, possibly, communicated somewhere.

3.6 RELATIONSHIP BETWEEN COMPUTATION AND COMMUNICATION

Looking at energy consumption numbers for both microcontrollers and radio transceivers, an evident question to ask is which is the best way to invest precious energy resources of a sensor node: Is it better to send data or to compute? What is the relation in energy consumption between sending data and computing? Again, details about this relationship heavily depend on particular hardware in use, but a few rule-of-thumb figures can be given here. Typically, computing a single instruction on a microcontroller requires about 1 nJ. Also, 1 nJ suffices to take a single sample in a radio transceiver; Bluetooth transceivers could be expected to require roughly 100 nJ to transmit a single bit (disregarding issues like start-up cost and packet lengths)[94]. In a slightly different perspective, communicating 1 kB of data over 100 m consumes roughly same amount of energy as computing three million instructions[3].

3.7 SUMMARY

It gives clear understanding that communication is comparatively more expensive operation than computation; still energy required for computation cannot be simply ignored. Depending on computational task, it is usually still smaller (but noticeable) than energy for communication. This basic observation motivates numerous design decisions for networking architecture of wireless sensor networks. The core idea is to invest into computation within network whenever possible to save on communication costs.

CHAPTER IV

THE IEEE 802.15.4 STANDARD

4.1 INTRODUCTION

For commercial success one needs a standards-based wireless technology that has performance characteristics that closely meet the requirements for reliability, security, low power and low cost. For such wireless applications a targeted standard has been developed by the IEEE. The IEEE 802.15 Task Group 4 was chartered to investigate a low data-rate solution with multi month to multiyear battery life and very low complexity. The standard is intended to operate in an unlicensed international frequency band. Potential applications for this standard are home automation, wireless sensors, interactive toys, smart badges, and remote controls. The scope of the task group has been to define the physical layer (PHY) and the media access control (MAC). This standards-based interoperable wireless technology is optimized to address the specific needs of low-data-rate wireless control and sensor-based networks.

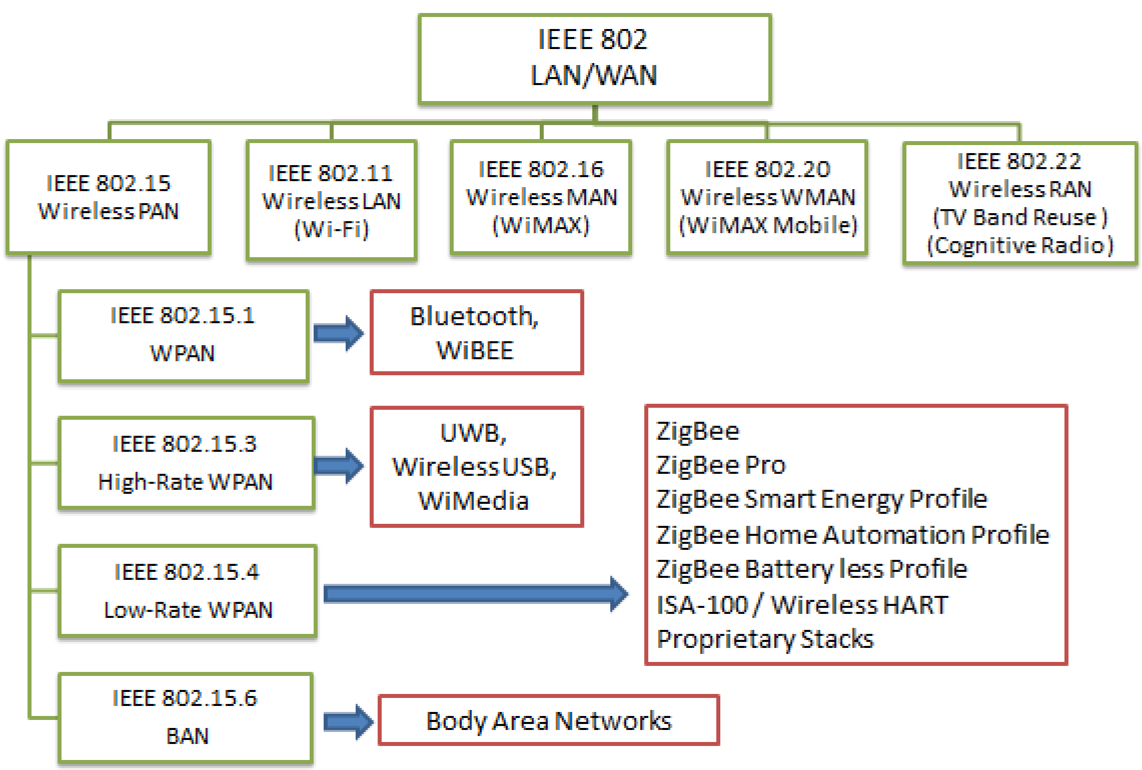


Figure4.1: IEEE 802 Family

The mission for this standard was to empower developers who had little ability or interest in the radio technology or communication protocols to effectively use and benefit from radios based upon the standard [95]. Figure 4.1 depicts the family tree of IEEE 802 for better understanding of requirement specific features of different protocols.

4.2 IEEE 802.15.4

IEEE 802.15.4 [95]standard represented a significant break from the “bigger and faster” standards that the IEEE 802 organization continues to develop instead of higher data rates and more functionality, this standard addresses the simple, low-data volume universe of control and sensor networks. It was ratified in the year 2003, as a standard for Low Rate Wireless Personal Area Networks. Figure 4.2 below shows the IEEE 802.15.4 protocol stack.

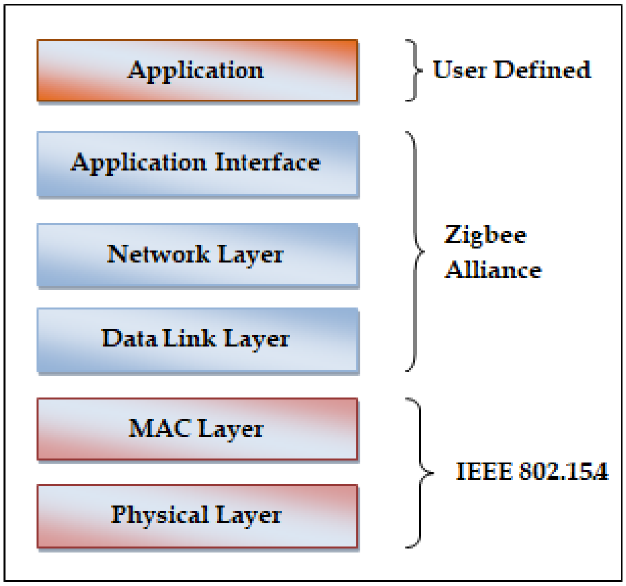


Figure 4.2: IEEE 802.15.4 protocol stack

IEEE STD 802.15.4 specifies the RF, PHY and MAC layers, and there are a variety of custom and industry-standards based networking protocols that can sit atop this IEEE stack. Outside of the standard, various networking techniques like ZigBee alliance have got developed. These networking protocols allow the rapid creation of mesh networks that are also self-healing. With energy-saving features designed into the basic IEEE standard, and other possibilities applied by the applications developer, IEEE 802.15.4 radios have the potential to be the cost-effective communications backbone for simple sensory mesh networks that can effectively harvest data with relatively low latency, high accuracy, and the ability to survive for a very long time on small primary batteries or energy-scavenging mechanisms like solar, vibrational or thermal power.

It addresses the simple, low-data volume universe of control and sensor networks. The standard has paved the way for manufacturing of inexpensive silicon radios to drive down the cost per node of these networks. It defines an RF and PHYsical layer with Phase-Shift-Key (PSK) transceiver capable of over-the-air speeds up to 250 kbps with radio channels in specific unlicensed 800, 900 and 2400 MHz bands. IEEE 802.15.4 radios have potential to form cost-effective communications backbone for simple sensory mesh networks. These networks can harness data with relatively low latency, high accuracy and ability to survive for a very long time on small primary batteries. The standard specifies the RF link parameters, including modulation type, coding, spreading, symbol/bit rate and channelization:

The standard employs a number of features that are critical to a reliable, robust wireless link. It brings with it the ability to uniquely identify every radio in a network as well as the method and format of communications between these radios, but does not specify beyond a peer-to-peer communications link a network topology, routing schemes or network growth and repair mechanisms. It is intended for low-duty-cycle communications, which, when combined with the relatively high data rate, means that the time required to transfer a small block of data from one device to another is measured in milliseconds, and allows the device, if battery-powered, to spend most of its time sleeping in an ultra-low-power state.

Messages from one node to another can take advantage of receipt acknowledgement to improve transfer reliability. All receivers have some form of channel energy detection to detect potential users of the channel, and there is a Link Quality Indication (LQI) that provides the radios a metric on the signal strength/performance of that link. Finally, 802.15.4 employs direct-sequence spread spectrum to provide coding gain and added resiliency against multipath. Four bits are packed into a single symbol, then the symbol is coded with a 16-chip series per symbol are used for the sub-GHz frequencies, while 32 chips per symbol are used for the 2400MHz band. The spreading code used allows a standard FSK receiver to successfully demodulate the transmitted signal, although at significantly reduced link margin.

However, in particularly cost-sensitive applications, it may be advantageous to sacrifice link margin for cost.

4.2.1 RF Link

The IEEE standard specifies the RF link parameters, including modulation type, coding, spreading, symbol/bit rate, and channelization. Currently, the standard identifies 27 channels spread across three different frequency bands, as described in Table 4.1 below.

Table 4.1: IEEE 802.15.4 Frequency Bands, Channelization and RF Parameters[95]

	Frequency Band (MHz)		
	868.3	902-928	2400-2483.5
No. of Channels	1	10	16
Bandwidth (kHz)	600	2000	5000
Data Rate (kbps)	20	40	250
Symbol Rate (ksps)	20	40	62.5
Unlicensed Geographic Usage	Europe	Americas (approx.)	Worldwide
Frequency Stability	40 ppm		

Due to expected use in short range i.e. 10 – 50 meters, the specified nominal transmitter power output is 0.5 mW (-3dBm) and specified nominal receiver sensitivity: 1% PER at 85 dBm receive power level for 2400 MHz band and 92 dBm receive power level for sub - GHz band. It utilizes PSK (Phase Shift Keying) modulation mode and employs direct – sequence spread spectrum to provide coding gain and added resiliency against multipath.

4.2.2 Physical Layer (PHY)

The 802.15.4 PHY contains specific primitives that manage the radio channel, and control packet data flow. Manages all symbol and bit level timings and is responsible for transmit- receive switching times, intra packet timings and acknowledgement delays. The PHY uses Carrier Sense Multiple Access (CSMA) with Collision Avoidance (CA) to access the radio channel. This means that a radio with data to transmit will first listen to the channel and if the channel is clear, then transmit its packet. However, if the channel is busy, either due to another 802.15.4 station transmitting, or due to interference from a non-802.15.4 station (microwave oven, Wi-Fi access point, etc.), the radio will hold off from the channel for a random period of time before again checking the channel for occupancy. In a system where all stations can hear one another, CSMA-CA can provide nearly a 36% channel usage, but in practical environments where all stations cannot hear one another, the channel usage efficiency is as low as the traditional ALOHA mechanism, about 18%.

The PHY defines four different frames that have unique functions: Data, Acknowledgement (for acknowledging error free receipt of data packet), Beacon (for network establishment by Coordinator) and MAC (Command for sending low level commands from one node to another). The Acknowledgement frame is used by a receiving station to "acknowledge" the transmitting station that a data packet is received without error. The Beacon frame issued by stations that may be implementing significant power saving modes, or by Coordinator and Router devices that are attempting to establish networks. The MAC command frame provides some unique abilities to send low-level commands from one node to another. All IEEE 802.15.4 devices have a unique, 64-bit address. This long address similar to the well-known MAC address used in a 802.11 wireless card or 802.3 Ethernet NIC card. However, in complex networks moving small blocks of information, header size is reduced by allowing devices that join an existing network to "trade in" their 64-bit address for a 16-bit local address. This makes in-network communications more efficient and substantially shortens the packet length. The PAN Coordinator is tasked with handing out the short address when a device joins its network.

4.2.3 Medium Access Control (MAC) Layer

The 802.15.4 MAC contains over two dozen primitives that allow data transfer, both inbound and outbound, as well as management by higher-level entities of the RF and PHY. The MAC sub layer provides access to the upper layers through two Service Access Points (SAP). Data is managed through the MAC-SAP, while control and monitor functions are accessed through the MAC Layer Management Entity interface, called the MLME-SAP.

The MAC layer is responsible for generating network beacons that allow devices to find an existing network, or in the case of TDMA networks, that provide a timing indication for client devices to access the channel during both contention-based and contention-free periods. Most networks that employ a number of mains-powered (or other source of permanent power) routers probably will use the network beacon for network discovery alone. This beacon may be set in increments from approximately 15.83ms to over 4 minutes. The other purpose for the beacon is to signal timing in the operation of TDMA-based networks. Especially in entirely battery-operated networks, it was envisioned that all devices would normally be in a quiescent state, and when an internal timer expired a device would wake up to hear the beacon of its neighbor; the beacon begins an interval called the super-frame interval, which provides not only (Guaranteed Time Slots) GTS intervals for prearranged traffic but also contention based interval where any device can "vie" for its neighbor's attention. Like the beacon intervals described by the equation above, the super-frame interval is selectable by the network coordinator.

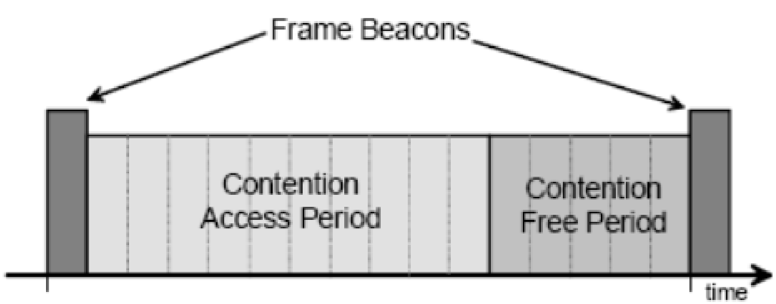


Figure 4.3: Super-frame Structure with GTS Intervals

Figure 4.3 shows a generalized representation of the super-frame interval in-between the network beacons. In the particular case shown in the figure, the super-frame interval is equal to the beacon interval. In all cases, there are a total of 16 equal slot times available; their duration is dependent on the length of the super-frame interval. A device may be allocated one or more GTS intervals in order to transfer network traffic – during that time no other device may use the channel. When a GTS is used, the network does not use the CSMA-CA channel access scheme, hence the phrase "guaranteed time slot". The contention free period always follows the contention access period, where devices not having a prior reservation for a slot time may use the CSMA-CA algorithm to access the channel and pass their traffic. Once the contention free period is completed, the device transmitting the frame beacon may become quiescent, saving energy until the beginning of the next beacon interval.

The MAC layer manages the ability for a device to find a network, to associate to that network and to disassociate as necessary. Upon power up, an upper layer entity commands the transceiver to begin a scan on each channel available in a quest for an existing network. If the device is based upon a FFD, the FFD may attempt to establish its own network, if none can be found. However, assuming the device finds an existing network (discovered by listening on each available channel for an 802.15.4 beacon), the device will attempt to associate to that network. If the network allows the device to associate, then a message is passed up through the MLME-SAP to the network layer above, and that network layer manages the exchange of the device's 64-bit IEEE address with a suitable short address according to the PAN Coordinator's requirements. If a device is required to disassociate itself from a live network, the device will receive a Disassociate command from the PAN Coordinator, with the command initiated above the MAC layer.

The IEEE 802.15.4 specification provides guidance on possible network types; however, in terms of specification it codifies only tools that are necessary for formation of a network, but of unspecified topology or usage. In one of the suggested topology type, all messages from any client device must pass through the hub (PAN Coordinator). In second type, the peer-to-peer, allows each device to communicate directly with peer devices and at its simplest defines direct communications between two devices. However, this method also may be used to create a mesh network if a higher layer entity chooses to do so.

There are several organized efforts to employ the 802.15.4 radio in larger, organized networks. These groups include the ZigBee Alliance, the IETF, and the IEEE itself. In addition, the functionality and cost-effectiveness of the silicon radios provides those with pre-existing proprietary networking techniques to layer that functionality on top of the IEEE radio, allowing them to reduce cost without redeveloping a network function.

An open and growing industry group ranging from product/system OEMs to applications developers to semiconductor companies, the Alliance has worked hard to provide a technology that takes best advantage of the robust IEEE STD 802.15.4 short-range wireless protocol, adding flexible mesh networking, strong security tools, well-defined application profiles, and a complete interoperability, compliance and certification program to ensure that end products destined for residential, commercial and industrial spaces work well and network information smoothly.

4.3 ZIGBEE

The basic features of the PHY and MAC layers provided by the IEEE 802.15.4 provide the capability to developers to take advantage of the cost effective, small radio solutions. ZigBee is the standards-based technology designed to address the unique needs of natively mesh based, Cost-effective, long-battery-lived radios which cannot use high transmit power to ensure successful transfer of data. ZigBee delivers low-latency communication. ZigBee chips are typically integrated with radios and with microcontrollers.

ZigBee operates in the industrial, scientific and medical (ISM) radio bands: 2.4 GHz in most jurisdictions worldwide; though some devices also use 784 MHz in China, 868 MHz in Europe and 915 MHz in the USA and Australia, however even those regions and countries still use 2.4 GHz for most commercial ZigBee devices for home use. Data rates vary from 20 kb/s (868 MHz band) to 250 kb/s (2.4 GHz band).

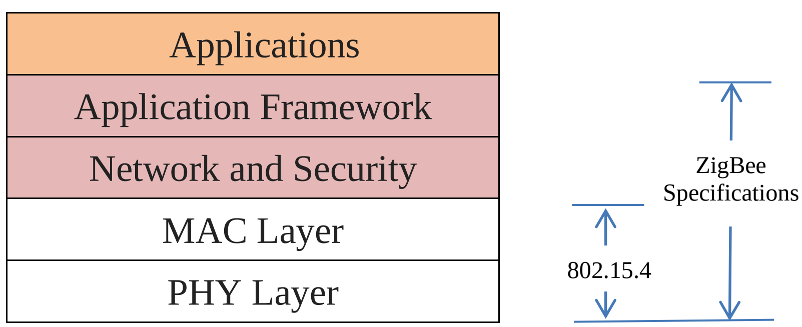


Figure 4.4: The ZigBee Protocol

ZigBee specification includes four additional key components: network layer, application layer, ZigBee Device Objects (ZDOs) and manufacturer-defined application objects. ZDOs are responsible for some tasks, including keeping track of device roles, managing requests to join a network, as well as device discovery and security.

The ZigBee network layer natively supports both star and tree networks, and generic mesh networking. Every network must have one coordinator device. Within star networks, the coordinator must be the central node. Both trees and meshes allow the use of ZigBee routers to extend communication at the network level. Another defining feature of ZigBee is facilities for carrying out secure communications, protecting establishment and transport of cryptographic keys, ciphering frames, and controlling device. It builds on the basic security framework defined in IEEE 802.15.4.Devices in a LR-WPAN can be classified as full function devices (FFDs) and reduce function devices (RFDs). One device is designated as the PAN coordinator which is the responsible for maintaining the network and managing other devices. The ZigBee protocol defines three types of devices:

- ZigBee Coordinator: responsible for initializing, maintaining and controlling the network. There is one and only one per network
- ZigBee Router: connected to the coordinator or other routers. It can have zero or more children nodes. Participate in multi hop routing
- ZigBee End Devices: does not participate in routing

It also defines two types of network topologies: star topology and peer-to-peer topology as shown in Figure 4.5 below. The star pattern is structured, where the coordinator of the network will necessarily be the central node. Peer-to-Peer networks can form arbitrary patterns of connection, and their extension is limited by the distance between each pair of nodes.In the star topology there is no presence of ZigBee Router. There is only a ZigBee Coordinator and zero or more ZigBee End Devices. In the case of the tree, or cluster tree, topology the ZigBee Coordinator and also the ZigBee Router can announce beacons. The ZigBee Router can define dynamics duty cycle per cluster allowing devices to go to sleep not depending on the ZigBee Coordinator but on a closer ZigBee Router. The device would choose a slot and transmit its beacon to avoid collision.

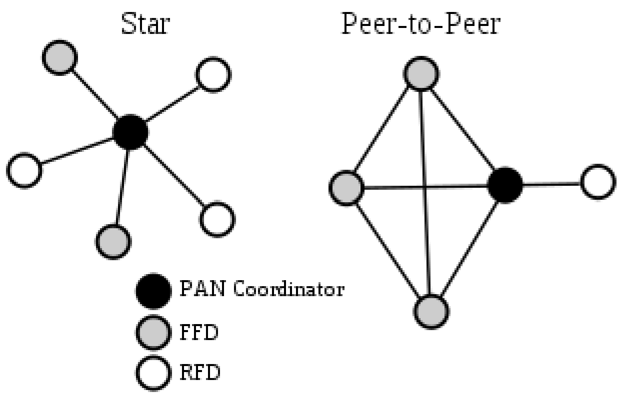


Figure 4.5: ZigBee Network Topologies

4.4 SUMMARY

The IEEE 802.15.4 standard provides the much needed framework for enabling reliable, robust and standards based communication for Low Rate Wireless Personal Area Networks (LR-WPANs). The standard has provided much need thrust from industry to bring down costs and power consumption while improving the performance and adding on more functionality. The standard defines the fundamental lower network layers: PHY and MAC which provide the interface to upper layer network, equipping application developers to take advantage of these cost- effective small radio solutions for inexpensive delivery of data from a large, amorphous sensor network.

CHAPTER V

HIBERNATED CLUSTERING - WIRELESS SENSOR NETWORKS (HC-WSN)

5.1 INTRODUCTION

As discussed during earlier chapters, the energy efficiency in wireless sensor networks is one of the key concerns in improving the network life time. Considering that, WSNs have the basic role of sensing the parameters under consideration and transmitting collected data to the base station, the network routing has significant impact on the energy consumption in the network. To overcome the pitfalls of flat networks, hierarchical networks have been proposed; where in special nodes are identified with in the network to perform the data aggregation and transmission, apart from other nodes which continue with the sensing function. This approach improves the energy efficiency as well as scalability in the network. Over the period of time number of hierarchy based routing protocols have been proposed with significant improvement in energy efficiency of the wireless sensor networks. But still these protocols have one or the other issues.

This chapter covers the improvements needed in some of the existing cluster based approaches and proposed new protocol Hibernated Clustering – Wireless Sensor Networks (HC-WSN). The chapter also covers the simulation of the proposed protocol and is concluded with analysis of the output and comparison with existing protocols.

5.2 CLUSTER BASED ROUTING IN WSN

The cluster based routing protocols[96] in WSNs work on the principle of dividing the sensor nodes into small groups called clusters. Each of these clusters has a special node called cluster head, which communicates with the base station or any other designated node outside the group, on the behalf of all the member nodes. In hierarchical clustering, the cluster heads of respective clusters further group together to form clusters to enable multi-hopping. The cluster heads perform the function of not only aggregating and assimilating data from member nodes but also transmitting the processed data to the sink node or the base station. The activity of data collection, processing and transmitting to the destination consumes lot of energy of the cluster head node; therefore the stability of the cluster head nodes has great impact on the overall network continuity and lifetime. Due to this great significance associated with the role of cluster heads, cluster formation and cluster head selection play a critical role.

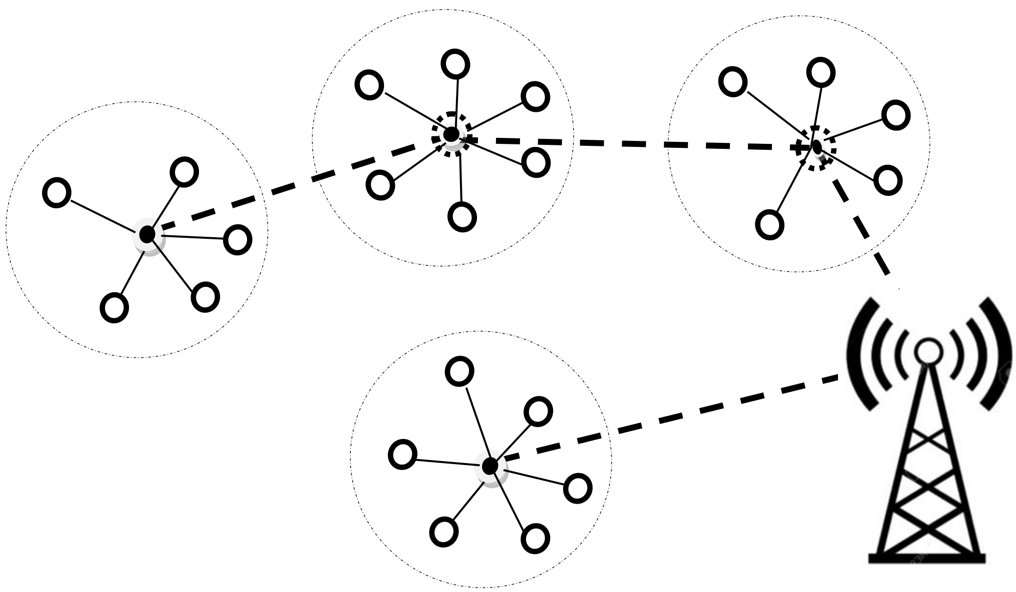


Figure 5.1: Hierarchical Cluster based routing in WSNs

Cluster based routing protocols balance energy consumption[97] among the nodes in the network, increase scalability of the network and reduce the amount of data that is actually transmitted to the base station by utilising various data aggregation and fusion techniques. Consequently, the remaining nodes with in a cluster perform only the limited function of sensing along with transmission of sensed data to the local cluster head. They do not have to maintain complex routing information, thereby reducing the quantum of network communication and energy consumed therein.

Figure 5.1 above depicts the hierarchical cluster-based routing in wireless sensor networks, where in the sensor nodes are organised into clusters and further each cluster has been assigned a hierarchy for transmission data to be aggregated at different levels and consolidated for onward transmission to the next higher level and ultimately to the base station or sink. Here it may be noted that organising a network into different forms of clustering depends upon the nature of application and the parameters to be monitored with regard to the form of data required to be monitored at the base station. For example depending upon the span of the network the temperature being monitored at various locations in an area may be required to be monitored as average value or exact value, which will determine the routing protocol and data aggregation algorithms to be applied.

The cluster based routing protocols[96] have been classified as grid clustered, chain clustered and block clustered. The details are summarised in Table 5.1 below:

Table 5.1: Classification of Clustering Routing Schemes

Block Clustered	**Chain Clustered**	**Grid Clustered**
Nodes are organised into blocks/ grouped on the basis of minimum communication energy.	Nodes are gathered in the form of chain. A node communicates with the closest neighbour and becomes leader to communication to the sink.	The data space is quantized into finite number of cells in the form of grid, on which the clustering operations are performed.
Examples:		
LEACH, HEED, Unequal Clustering Size (UCS) [98], Energy Efficient Clustering Scheme (EECS), TEEN	Power-Efficient Gathering in Sensor Information System (PEGASIS), Concentric Clustering Scheme (CCS), Track-Sector Clustering (TSC)	Geographic Adaptive Fidelity (GAF), Position-based Aggregator Node Election scheme (PANEL), Two-Tier Data Dissemination (TTDD), SLGC

Further, considering whether there exists centralized control during the execution of cluster formation, clustering algorithms can also be categorized into centralized or distributed.

5.3 CLUSTERING ASPECTS OF EXISTING PROTOCOLS

Though the clustering strategy being a layered approach is simple to scale and manage, the key concern in cluster based routing protocols is the strategy for formation of clusters and selection of cluster heads. To attend to this several cluster based routing protocols have been proposed. LEACH[2], PEGASIS[16], HEED[14], SSTBC[24], DEEC[64] and Hybrid-LEACH[15] are few strategies out of the numerous algorithms proposed in this area of research. In this section clustering related aspects of these protocols are discussed.

LEACH [2] is the most referred to basic scheme for cluster based routing. The protocol proposes two step based approach i.e. organisation / establishment of clusters (Setup phase) and data transmission to base station (Steady state phase). For the selection of cluster heads, LEACH adopts equal probability rule, selecting cluster heads during a round in a random manner and distributing the energy of the whole network evenly across each node. The execution of LEACH is a periodic process, and each period or round includes the formation of clusters and data transmission. Figure 5.2 below indicates the flow of data from Cluster Heads to the sink.

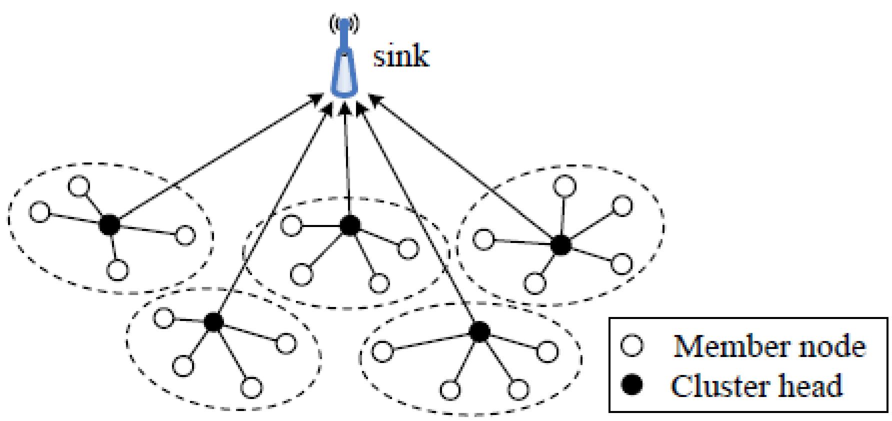


Figure 5.2: LEACH - Single Hop Clustering Scheme

In the Steady state phase (i.e. the stable transmission phase), radios of all kept ON during contention period, a TDMA schedule is built by the cluster head and is broadcasted to all the member nodes in the cluster. This stable transmission phase can be divided into frames; the length of each frame is decided by the number of nodes in the cluster. A data slot is allocated to each node in each frame and data is transferred from member nodes to the Cluster Head, within the assigned TDMA time slot.

At the end of each round, cluster heads and clusters are re-elected; this requires certain amount of energy. In order to conserve energy, the duration of stable data transmission phase should be much longer than the time required for the setup phase. The timeline of setup phase and steady state phase has been depicted in Figure 5.3 below.

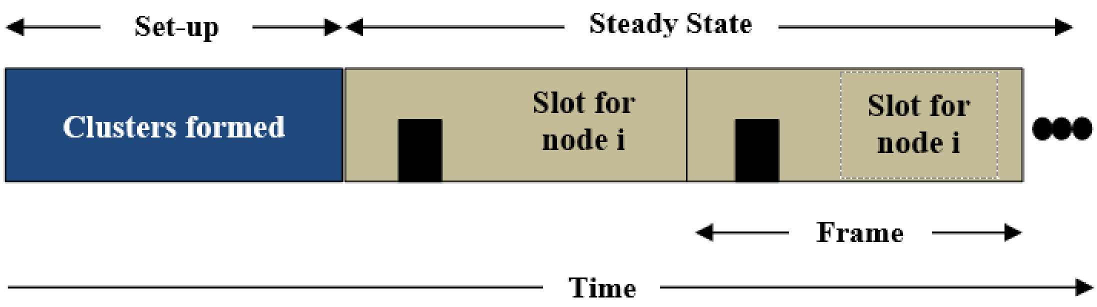


Figure 5.3: LEACH – Timeline of Set-up and Steady State phase

The cluster head, always maintains communication status to receive the data from nodes in its cluster at any time. After receiving data from its member nodes, the cluster head uses various data fusion techniques to eliminate redundancy and optimise data. Finally, the cluster head transmits processed data to the base station. The clusters are formed in LEACH protocol through distributed mechanism where all the participating nodes make autonomous decision for becoming the cluster head at each round. LEACH employs various data fusion techniques and eliminates transmission of redundant data, thus reducing the burden of data transmission on the network. After each round, cluster heads are selected and new clusters are formed. Thus, each node in the network has chance to be cluster head, resulting in the load of the whole network to be distributed evenly among the member nodes. Apart from this there are few weaknesses of LEACH protocol:

i. The selection of cluster heads is probabilistic and does not take the residual energy of individual nodes into account.
ii. LEACH uses single hop clustering routing and cannot be used for larger networks. Cluster heads and clusters generated by LEACH protocol may not be even; resulting in isolated nodes, which cannot join any cluster.

iii. Different amounts of initial energy cannot be considered in LEACH due to the basic assumption of same initial energy.

iv. Nodes with low energy, elected as cluster head could cause energy holes and coverage problems.

- PEGASIS (Power Efficient Gathering in Sensor Information Systems)[16]: This algorithm proposes that only one node, which is closest to the base station will be able to communicate with it. It is an improvement of LEACH. Each node only communicates with its close neighbours and takes turns to be leader for data transmission. Here communication load is evenly distributed among all nodes in the network as all nodes are organized to form a chain and each node communicates with the next node only. The chain is either constructed by the sink using a centralized assignment mode or built by the nodes themselves using a greedy algorithm (for which it is assumed that all nodes have global knowledge of the network). Chain construction starts from the farthest node with closest neighbour becoming the next node on the chain. When a node on the chain dies, it is reconstructed to bypass the dead node. Data is gathered in each round with each node receiving data from one neighbour, fuses it with its own, and transmits it to the next neighbouring node on the chain. Moving from node to node, fused data eventually reaches the sink. The Figure 5.4 below indicates flow of data through greedy chain based approach to the sink.

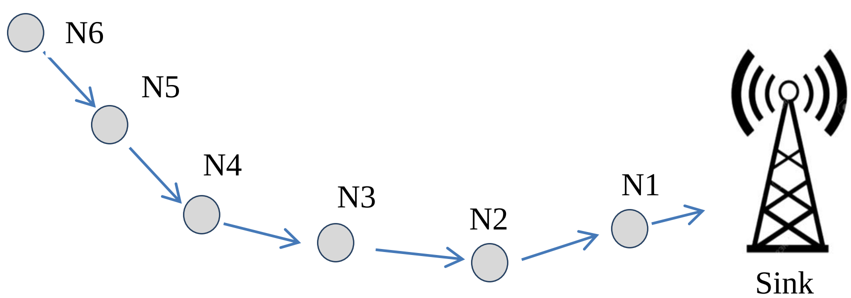


Figure 5.4: Communication scheme in PEGASIS

PEGASIS is able to perform better than LEACH for different network sizes and topologies. It decreases the overhead of dynamic cluster formation and reduces the amount of data transmitted using data fusion. It is able to distribute energy expenditure equally across all nodes.

However, there are some limitations of PEGASIS:

i. It is necessary to have a complete view of the network topology at each node for chain construction.
ii. All nodes must be able to transmit directly to the sink.
iii. The scheme is unsuitable for those networks with time varying topology.
iv. It is difficult for all nodes to maintain a complete database about the location of all other nodes in the network.
v. Some nodes can become bottleneck while communicating with the sink directly.
vi. The scheme lacks scalability.
vii. The energy level of the cluster head is not judged.
viii. The data transmitted to the base station may be excessive.

- HEED (Hybrid Energy-Efficient Distributed clustering) [14]: is a multi-hop clustering algorithm for energy-efficient routing in WSNs. The elected cluster heads have relatively high average residual energy compared to member nodes. HEED aims to achieve even-distributed cluster heads throughout the networks. The cluster heads are periodically elected based on residual energy and intra-cluster communication cost of the candidate nodes. Each node goes through several iterations until it finds the cluster head. If a node cannot find any cluster head, it elects itself to be a cluster head and sends an announcement message to its neighbours. There are two types of status that a sensor node announces to its neighbours: tentative cluster head and permanent cluster head.

  HEED due to its multi-hop inter-cluster routing, performs better than LEACH with respect to the network lifetime; It finds application in large-scale networks. In HEED, the clustering process can be terminated within fixed number of iterations and control overhead can be minimized. The cluster heads are also relatively evenly distributed in the network.

Apart from this there are few limitations:

i. The cluster head selection being probabilistic, even distribution of cluster heads in the network cannot be realised.
ii. For load balancing and longer network lifetime, the scheme proposes even distribution of cluster heads, which in turn require several iterations and broadcasts of large amount of packets, during every round resulting in additional communication overhead.
iii. Some cluster heads, especially near the sink, may die earlier; this will create hotspot in the network.

- Qing et al [64] proposed Distributed Energy-Efficient Clustering (DEEC) protocol, it classifies nodes as normal nodes, advanced nodes, and super nodes. The energy intensity of super nodes is the highest, when compared to normal and advanced nodes, so super nodes act as cluster heads. Information collected by the normal and advanced nodes is passed on to the super nodes (acting as CHs) in each cluster. Super nodes convey the information received to the BS from different clusters. The DEEC has a longer lifetime and is more effective at messaging than current clustering protocols in heterogeneous environments. Cluster heads are elected by a probability, based on the ratio between the residual energy of each node and the average energy of the network. The stages of being cluster heads for nodes differ according to their initial and residual energy. Nodes with high initial and residual energy have more chances to be cluster heads than nodes with low energy. DEEC adapts the rotating stage of each node to its energy.

- H-LEACH: Hybrid-Low Energy Adaptive Clustering Hierarchy for Wireless Sensor Networks [15] elects the channel head for each round, considering residual and maximum energy of nodes for every round. H-LEACH has been compared with LEACH and HEED protocols and it is proved that it is efficient than both the methods. It finds lifetime of nodes in terms of rounds considering the threshold and energy conditions. It uses residual and maximum energy of the nodes to elect the cluster head for each round. The nodes with energy less than the minimum energy required for receiving and transmitting signals are made to die. Total no. of alive nodes are calculated for every round, to have a track on the lifetime of the network.

- It has been found that LEACH and HEED are applicable to homogenous networks until different energy values are considered in HEED. LEACH cannot be implemented for large range networks and it has problem in electing the nodes based on energy considerations. Since probability is also used here, sometimes there is a chance that node is left out for election. HEED can be used as a measure to obtain channel head based on energy parameters apart from threshold condition. All the nodes present in the network get a chance in their life time to become the cluster head, thereby increasing the lifetime of the network.

Based upon the above aspects, the objectives of clustering protocols can be represented as in the Figure 5.5 below.

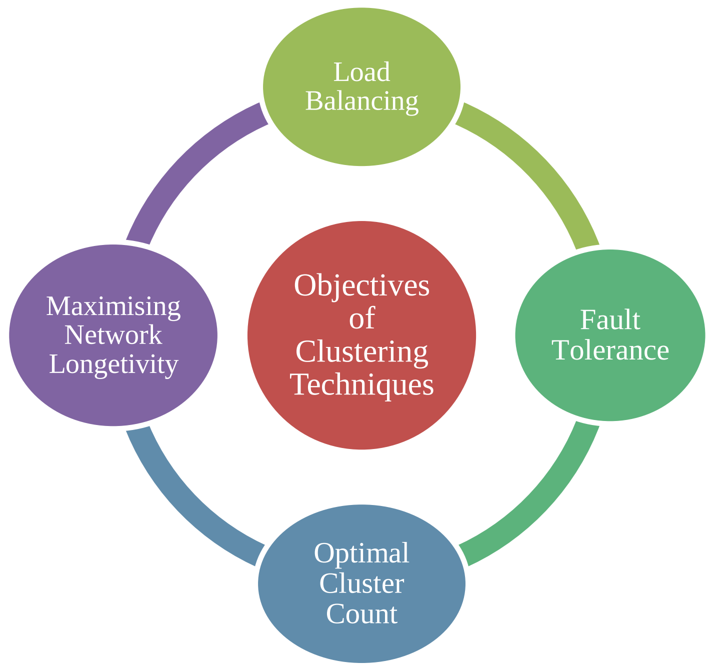


Figure 5.5: Objectives of Clustering Techniques

5.4 FORMULATING THE REQUIREMENT FOR HC-WSN

As elaborated in section 5.3 above, there are limitations of different cluster based hierarchical routing protocols for Wireless Sensor Networks. Accordingly the new protocol has been proposed in order to achieve following milestones to achieve the final objective of improving energy efficiency in a wireless sensor network:

i. Proposing a mechanism capable of handling heterogeneous nodes.
ii. Minimizing transmit distances by creating clusters.
iii. Optimising number of clusters in the network
iv. Minimizing communication overhead in cluster formation.
v. Minimizing number of transmit / receive operations by making the cluster head responsible to communicate with destination.
vi. Enhancing life of lower residual energy nodes through Hibernation (Sleep mode)
vii. Efficient utilization of Energy available with nodes
viii. Optimising the location of the sink to achieve minimum transmission overhead.

5.5 HC-WSN: HIBERNATED CLUSTERING WIRELESS SENSOR NETWORKS

The proposed protocol aims at improving the energy efficiency of the sensor nodes and the wireless sensor network as a whole thus improving the network lifetime. In most of the research literature available, the sensor networks have been assumed to comprise of homogenous nodes and prominent algorithms like LEACH, PEGASIS and HEED have been proposed accordingly. An in-depth analysis advocates that each and every node forming the sensor network is unique in its own way, whether it is the location of deployment, energy levels or the energy depletion rates; each node is different from the other. So while proposing a protocol impacting the network as a whole a generalised and wider perspectives should be considered. Due to this very basic design constraint, the algorithms based on homogeneous clustering have a poor performance in real world scenarios [64].

Also it has been found that most of the research works undertaken for improving energy efficiency of the WSNs [34], have considered nodes as either energy rich or energy optimum, the proposed protocol instead of classifying the nodes in two discrete categories tends to use the varying energy levels of the nodes to decide upon the state of nodes in this cluster based routing protocol.

5.5.1 Salient Features

The proposed protocol "HC-WSN" has been designed for efficient energy consumption with an objective to achieve maximum network lifetime by overcoming shortcomings of the existing cluster based routing protocols. The salient features of the proposed HC-WSN scheme are:

1. It is a hierarchical clustering based routing protocol for energy constrained wireless sensor network nodes.
2. HC-WSN assumes that the radio channel is symmetric i.e. energy required to transmit from A to B is same as energy required for B to A transmission for given SNR.

3. It assumes that all sensors are sensing the environment at fixed rate and thus have data to send to the end user.
4. A linear simple battery depletion model has been assumed, where in the battery is discharged linearly over its service life and the rate of discharge at any time is the current which is drawn from battery.
5. It takes into account the heterogeneity of nodes in a wireless sensor network; therefore, it is not mandatory for the constituent nodes to have same initial energy (E_{0i}– indicates initial energy for i^{th} node in the network).
6. It follows distributed clustering, and nodes are free to form clusters based upon their vicinity (inter node distance *d*) with each other.
7. The member nodes of the cluster select among themselves, a cluster-head which is a sensor node having maximum residual energy, higher than the pre-defined E_{UTH} (Upper Threshold Energy). In case of conflict, the choice of Cluster Head is based on First in First out (FIFO) method.
8. Formation of clusters minimizes the number of transmit / receive operations by making the respective cluster heads responsible to communicate with destination.
9. The member nodes in the cluster are responsible for sensing operation. Hibernation (sleep) is induced in a fraction of member nodes to minimise energy consumption and enhance network life time. At the time of network setup, the nodes are randomly identified for hibernation, though in the later rounds, the residual energy level of nodes becomes the criteria for selection for hibernation. To control the hibernation mode in the network, a hibernation control factor has been built into the algorithm that during a particular round only a certain fixed percentage of nodes (to be assigned initially by the user) can be under hibernation and also that any particular node can be under hibernation for a fixed percentage of rounds. Such nodes hibernated in a particular round have the probability to either stay hibernated or become active during the subsequent round. During the hibernation mode, the sensor node does not transmit or receive, and energy of the node is consumed only on account of sleep mode.

10. Before entering into subsequent round, the residual energy of the member nodes is compared against predefined minimum energy value E_{LTH} (Lower Threshold Energy) required for transmit operation. The nodes not fulfilling the minimal criteria are declared as "Dead". Such nodes do not form part of network and isolating them well in time saves the network from unnecessary communication overheads.
11. To reduce the communication overhead on account of selection of cluster-heads; cluster heads for all the clusters are not selected afresh in each round. The new cluster formation method is initiated based upon the residual energy of the current cluster-head in comparison to the upper threshold energy E_{UTH} defined for cluster heads.
12. The algorithm supports hierarchical multi-hoping through its Cluster of Cluster-heads approach. In an extended wireless sensor network, it is anticipated that most of the cluster heads may not be able to communicate directly with the sink in an energy efficient manner. To overcome this, clusters of underlying cluster heads (as members) are formed depending upon vicinity from the sink or neighbouring cluster heads. Further, to transmit the data from the cluster heads to the sink, the shortest path to the sink either hopped or direct is chosen. The sensed data being transmitted to the base station is fused at subsequent hierarchical levels, depending upon nature of application.
13. To avoid collisions, the transmission of data between the active member nodes and cluster head has been considered on the basis of TDMA schedule.
14. The proposed protocol also attempts to address the issue of ideal positioning of sink as static or mobile on a circular path within or outside the observation field.
15. Depending upon application, suitable data fusion algorithm can be applied at the cluster head level to consolidate the sensing data for onward forwarding to the base station/ sink.
16. HC-WSN takes advantage of the node density to minimise energy consumption. In case of high node density, the number of active nodes with in

the cluster is controlled by inducing sleep. This eliminates the redundant sensing inputs and preserving the battery capacity for longer overall operation of the network.

17. In the present setup, the WSN for simulation has been considered to be alive till at least overall 70% of the nodes are alive.

5.5.2 Evaluation Parameters

In this research work, the proposed protocol has been evolved through continuous improvement in phased manner. The entire process has been divided into four phases, for phase wise induction of new aspects in the proposed protocol for incremental improvement and maximizing energy efficiency. The four main phases have been further divided into steps for micromanagement and ease of control. In the later part of this chapter, the phase wise analysis has been done through MATLAB simulations. To evaluate the proposed protocol, following parameters have been monitored and have been compared with their value in earlier phase to assess the impact. The parameters under focus are:

1) Number of Alive nodes.
2) Average Energy of the network
3) Throughput (Packets received at Base Station)

5.5.3 Experimental Setup

Simulation Tools like “MATLAB” are based on mathematical models and provide enormous flexibility in setting up experimental scenarios. They provide ease in constructing and modification of network settings. They enable the researchers to deploy network topologies without any additional cost. Taking leverage of these features and to ensure accuracy, the simulations have been carried out in following experimental setups:

1. Node density scenario (varying the number of nodes)
2. Time variation scenario (varying number of rounds)
3. Varying position of Base Station

The simulation has been carried out using the following basic parameters:

Table 5.2: Experimental parameter values for simulation

S. No.	Parameter	Value
1.	Distribution Area	100m x100m
2.	No. of Nodes	100
3.	Node Transmission Radius	20 m
4.	Initial Energy of Node	0.5 J
5.	Data Packet Length	4000 bit
6.	Location of Base Station	(50,50)
7.	Amplifier coefficient of sending Node ($d < d_0$)	10pJ/bit/m^2
8.	Amplifier coefficient of sending Node ($d >= d_0$)	0.0013pJ/bit/m^4
9.	Energy consumed in Transmission	50 nJ/bit
10.	Energy consumed in Receiving	50 nJ/bit
11.	Energy consumed in Data Aggregation	5 nJ/bit

5.6 PROCESS FLOW

The flowchart shown as Figure 5.6 gives an idea regarding the process of cluster formation, cluster head selection and data transmission as proposed in the HC-WSN.

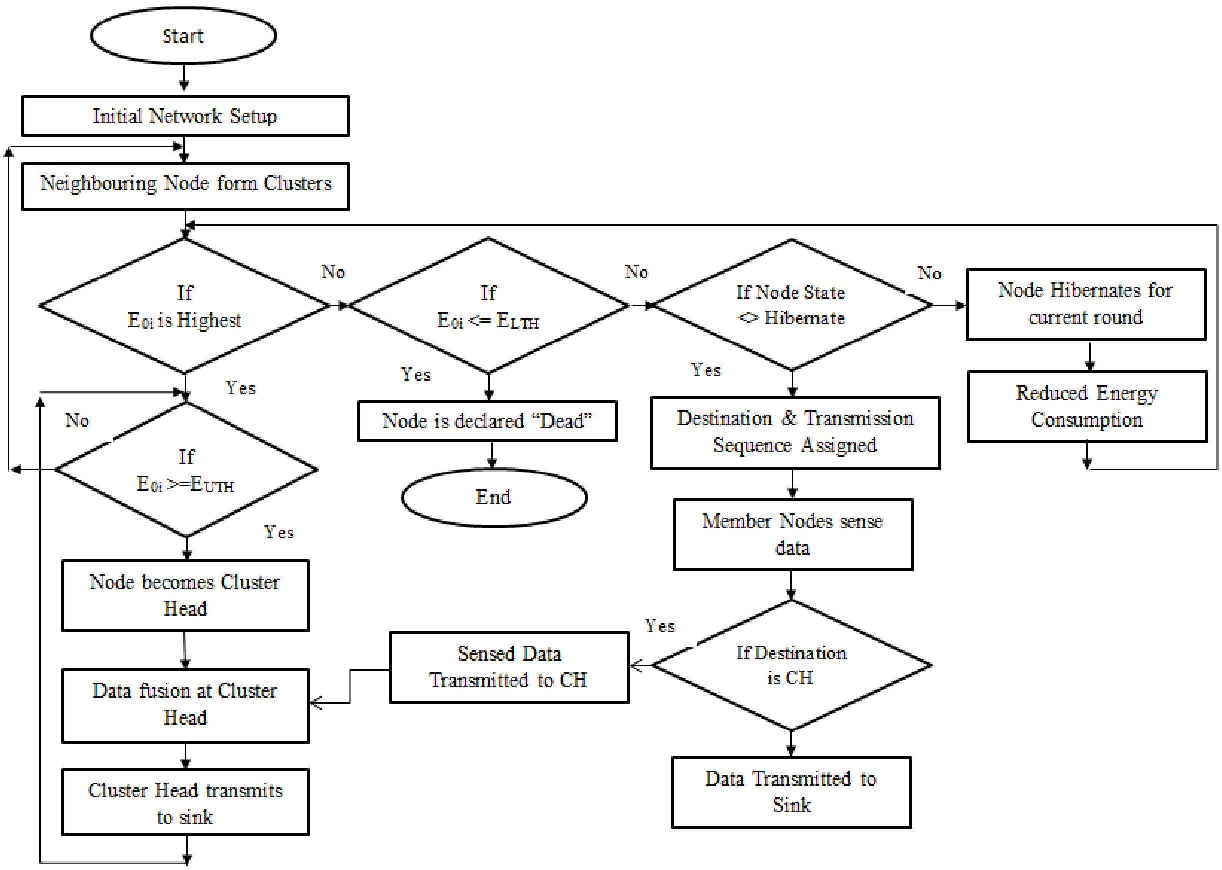


Figure 5.6: HC-WSN Process Flow

5.6.1 Phase –I: Cluster Formation

The Cluster Formation phase has been divided into following key steps (Figure 5.7):

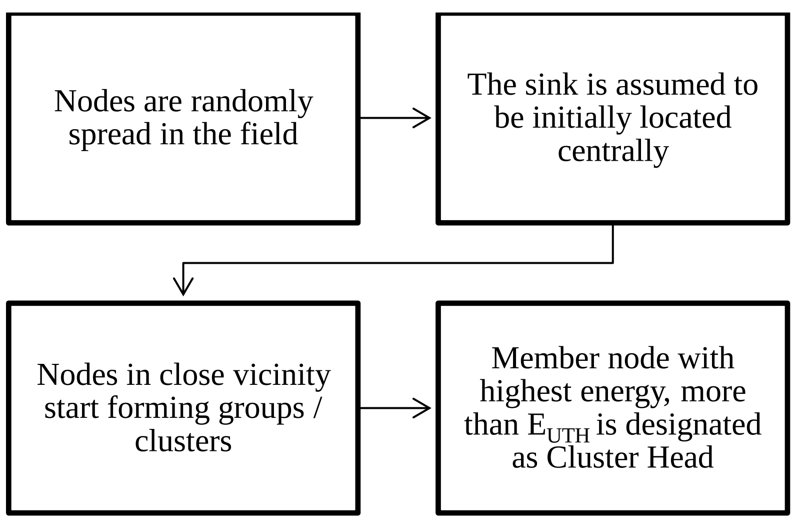


Figure 5.7: Phase-I Cluster Formation

Step-1 Sensor Nodes spread over Field area

At the onset the nodes are spread in the field and initially the sink is assumed to be located centrally. A pictorial representation of this scenario is provided in the Figure 5.7 below. Here the sink is located centrally at (50,50) and sensor nodes are spread randomly in a 100m x 100m area.

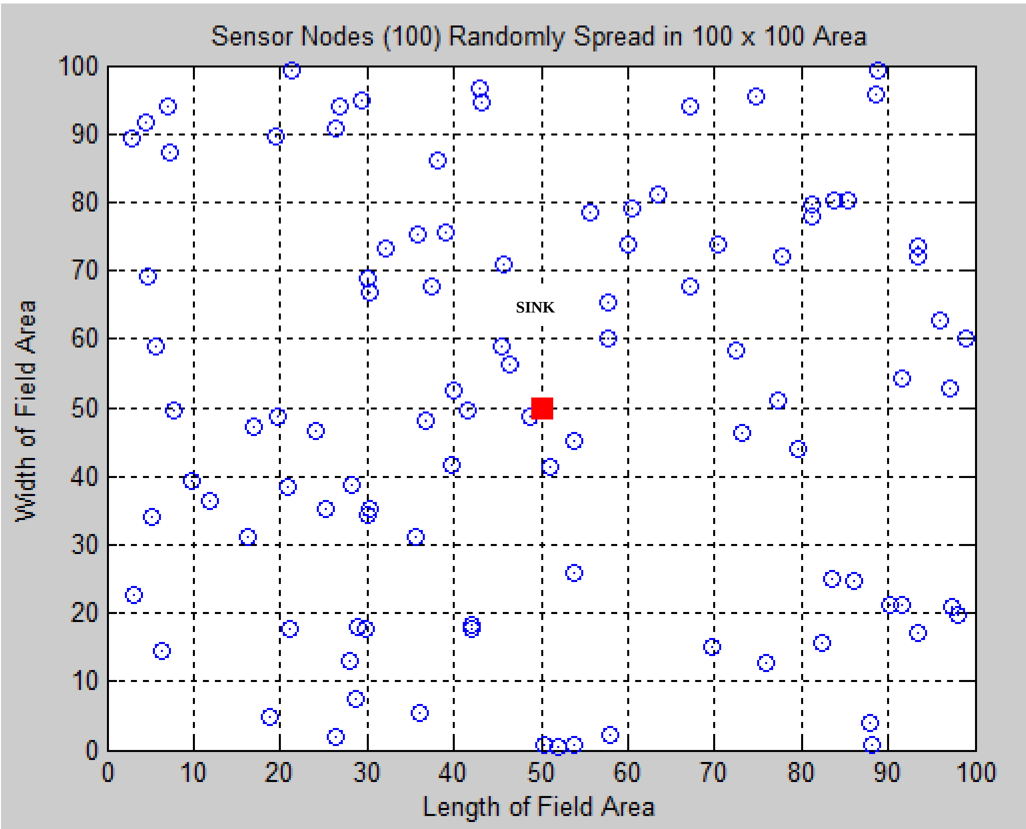


Figure 5.8: Nodes spread over field area

The significance of the Figure 5.8 lies in the fact that in absence of any routing protocol, the sensor nodes will try to transmit the sensed data individually, independently and directly to the sink. If the sink is far away from the nodes, direct communication will require a large amount of transmit power from each node. This will quickly drain out the battery of the nodes and reduce the system lifetime.

Direct communication approach can be adopted, if the reception occurs only at the base station, and if the base station is close to the nodes or if the energy required for receiving the data is large.

Further, to understand the radio hardware energy dissipation better, a simple radio model has been assumed [13]. Here the transmitter consumes energy to run the radio electronics and power amplifier circuit. At the receiver end the energy is consumed to run the radio electronics. Depending on the distance between the transmitter and receiver, the free space (power loss) and the multipath fading (power loss) channel models have been considered.

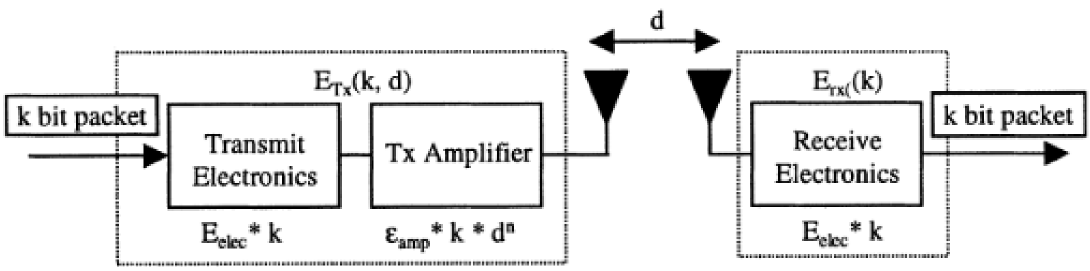


Figure 5.9: Radio energy dissipation model[13]

Thus, to transmit *k* bit message over a distance *d*, radio expends as per equation (1):

$$E_{Tx}(k,d) = E_{Tx} - elec(k) + E_{Tx} - amp(k,d)$$

$$= \begin{cases} kE_{elec} + k\epsilon_{fs}d^2, \ d < d_0 \\ kE_{elec} + k\epsilon_{mp}d^4, \ d \geq d_0 \end{cases} \quad (1)$$

and to receive this message, the radio expends as per equation (2) below:

$$E_{Rx}(k) = \ E_{Rx} - elec(k) = kE_{elec} \quad (2)$$

The electronics energy,E_{elec} depends on factors such as thedigital coding, modulation, filtering, and spreading ofthe signal, whereas the amplifier energy,$\epsilon_{fs}d^2$or$\epsilon_{mp}d^4$, depends on thedistance to the receiver and the acceptable bit-error rate.

As is evident from the above explanation of simple radio model, energy dissipation at the transmitter varies with d^2 in case the distance *d* from the receiver is less than d_o (free space model) but in case, distance (*d*) is more than d_o than it varies with d^4 (multipath fading model). Therefore, instead of establishing direct communication between the nodes and sink, focus has been laid on reducing the transmission distance, which has been achieved through formation of clusters and transmitting the data to the sink or base station through intermediary cluster heads.

Step – 2 Cluster Formation

Now, as the foundation has been laid in Step – 1 above for Cluster formation, the proposed protocol suggests for distributed clustering. The sensor nodes spread in the field area group themselves on the basis of inter-nodal distances. Assuming the sensor node has transmission range of 20 m, the sensor nodes with in this range group together to form the clusters in the simulation environment. Figure 5.10 below shows the random spread of nodes (coloured dots) and formation of clusters identified by different colours (with members of same cluster having identical colour).

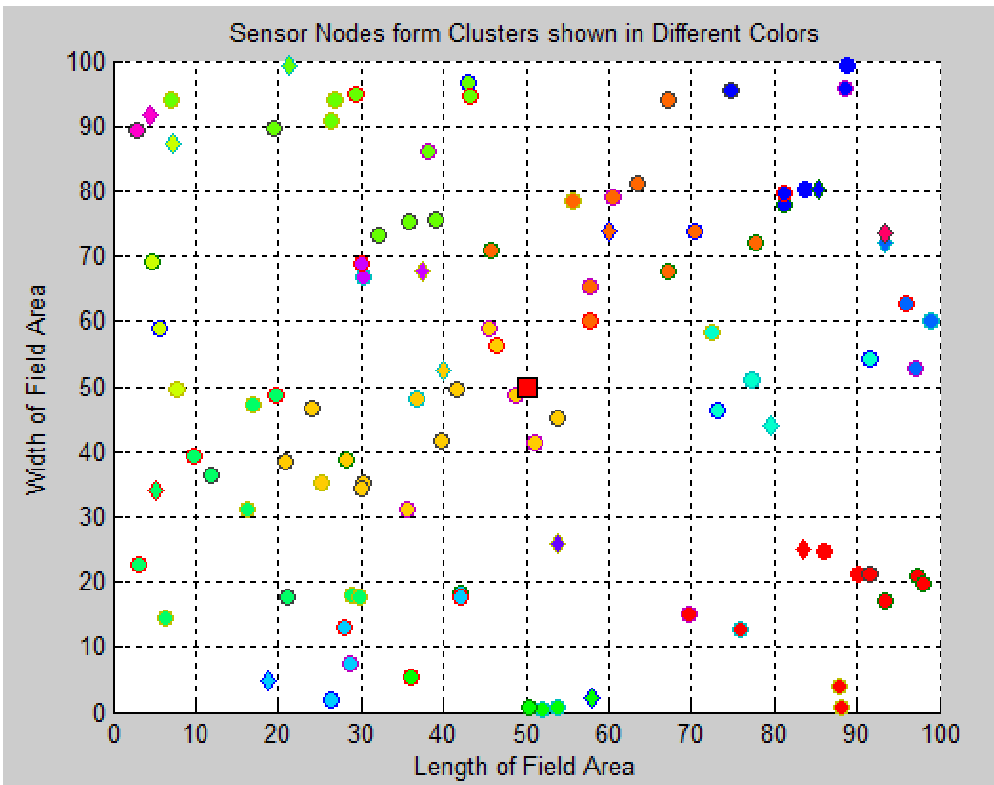


Figure 5.10: Cluster Formation

Apart from reducing transmission overhead, scalability and ease of network management are additional advantages of clustering.

Step–3 Identification of Cluster Head

The clustering based routing algorithms are a boon to the energy constrained wireless sensor networks. Clustering enables uniform distribution of energy consumption in the network by randomly rotating the cluster-heads. LEACH randomly selects the cluster heads on probability basis even far away from the sink. As too many cluster heads are chosen solely on probability basis as a result, some cluster heads drain their energy early thus reducing the lifespan of WSN. Due to these factors, there are certain limitations of LEACH namely:

a) Uneven clusters are formed in the network where some may be very big and some may be very small.
b) Many a times the cluster head selection is unreasonable with energy of cluster heads depleting earlier than that of the member nodes.
c) Residual energy and location of nodes is not considered, this may cause the network to fail early.

In Cluster based routing protocols, the main concern for the researcher is who will form the cluster and how the cluster head will be selected. Over the years, numerous research works have been undertaken to overcome the limitations of LEACH, suggesting different strategies of selecting cluster head and its role rotation using different parameters. In number of clustering based routing schemes the cluster head has been chosen either solely on probabilistic basis or deterministic basis. The cluster head selection strategies may be broadly categorized as deterministic, adaptive and combined metric (hybrid). In deterministic schemes special attributes of the sensor node such as node identification, node degree (number of neighbouring nodes) and in adaptive schemes the resource information like remnant energy, energy dissipated during last round, initial energy of the nodes determine the role of node in different data gathering rounds. On the basis of initiation of cluster head selection, adaptive schemes may be categorized as base station assisted or self-organised (probabilistic). Depending upon parameter considered for cluster head selection, the probabilistic schemes may further be classified as fixed parameter or resource adaptive. In the present research work, while deciding upon the strategy for cluster head selection, factors like residual energy and communication overhead for cluster formation have been considered.

Accordingly following strategy is proposed:

- Cluster Head is chosen from among spatially nearer group of nodes.

- The identified node should have the maximum residual energy in the group.
- The node being considered for role of cluster head should have energy more than predefined fixed value denoted by "E_{UTH}" i.e. *Upper Threshold Energy*.
- In case of two nodes having equal residual energy, the first node encountered is selected as cluster head based on first come first serve basis.
- The value of E_{UTH} is influenced by following factors
    - Average number of nodes in a cluster
    - Data transmission Rate
    - Packet Length
    - Energy required for data transmission
    - Energy required for data reception
    - Average distance between nodes and sink
    - Maximum and Minimum energy of nodes in the observation area
- To reduce the communication overhead in cluster formation and selection of new cluster head, it is not mandatory to select the cluster head on every round. New Cluster Head is chosen only if its energy level (E_0) falls below Upper threshold value (E_{UTH}).
- Based upon the above mentioned factors, the Upper threshold (E_{UTH})value can be defined in terms of equation (3) below:

$$E_{UTH} = (E_{Tx} + E_{Rx}) * g * r * l * d_{HS}^{n} + E_{losses} \quad (3)$$

$$\text{for } E_{Max} \geq E_{UTH} \geq E_{Min}$$

Similarly lower threshold energy(E_{LTH}), considering energy required for transmission has been derived. In the present research work nodes having residual energy less than Lower Threshold Energy(E_{LTH}) as shown in equation (4) below are discarded from the network as "Dead Nodes"

$$E_{LTH} = (E_{Tx}) * l * d_{MH}^{n} * g + E_{losses} \quad (4)$$

where: E_{losses} – on account of energy dissipation from Transmitter Electronics, receiver electronics and transmit amplifier etc.

n is the path loss exponent

d_{HS} - distance between cluster head and the sink

d_{MH}- distance between member node and cluster head

g – number of nodes

r – data transmission rate

E_{Max}– Maximum initial node energy in deployment area.

E_{Min}– Minimum initial node energy in deployment area.

l – Packet length

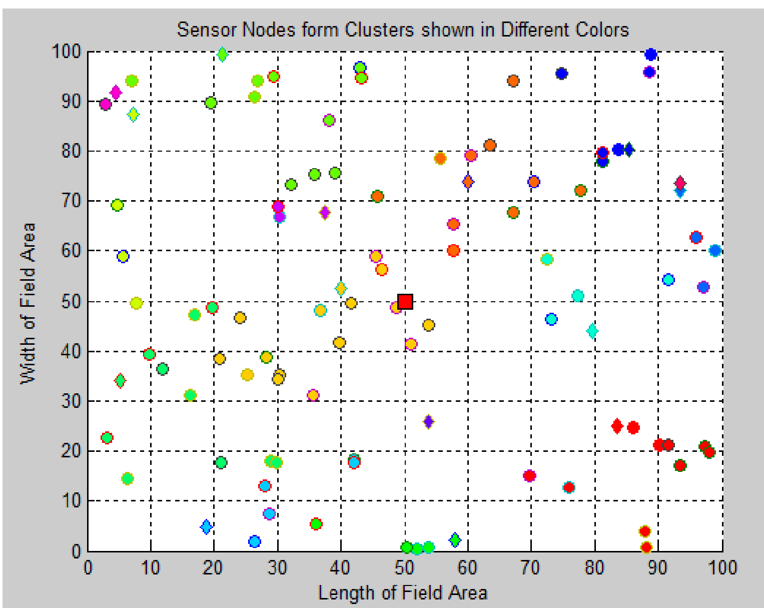


Figure 5.11: Cluster Head Selection

The cluster head selection has been simulated and Figure 5.11 above, it indicates member nodes (round shape) as well as respective cluster heads (kite shaped) belonging to a particular cluster in same colour.

5.6.2 Phase – II: Inducing Hibernation

The term “Hibernation” has been specifically used to correlate with the natural phenomenon gifted by Mother Nature to species surviving in hostile terrain with scarce resources. Similarly WSNs find their applications in hostile environments, where their limited power source which are mostly batteries, cannot be maintained or replaced. In such a scenario, to maximise the life time of the sensor nodes, it is mandatory to judiciously utilise the already scarce battery power. Inspired from the natural phenomenon of hibernation in organisms, where they reduce their activities to conserve the body energy and minimize requirement for food, a sleep or hibernation mode is induced in the sensor nodes.

The proposed mechanism of Hibernation or inducing sleep mode is another approach for energy efficiency where in density of active nodes deployed is reduced. It controls the number of sensors in the operating mode, which are sensing, receiving and transmitting data. Activating a small subset of nodes instead of all not only saves energy, but also reduces the network traffic, thus avoiding collision of packets and decreasing the delay of reporting data to the sink. While adhering to hibernation schedule, two basic requirements of connectivity and coverage should be fulfilled. Connectivity in sensor networks refers to situation when every sensor node in network can communicate with every other node and sink, if required via multiple hops. Coverage is defined as an area that can be reached by the active sensors, which are able to communicate with the sink.

To improve a sensor network’s reliability and extend its longevity, sensor networks are deployed with high densities (up to 20 nodes/m^3[99]). However, if all sensor nodes in such a dense deployment scenario operate simultaneously, excessive energy will be consumed. This will result in increased number of packet collisions due to the large number of packets being transmitted in the network. Also due to high density of nodes, sensing regions of nodes will overlap; this will result in highly correlated and redundant data. Therefore in such scenarios inducing sleep mode prevents transmission of redundant data decreasing both energy consumption and network traffic

Due to distributed nature of WSNs and limited transmission range of sensor nodes, sleep related strategy should be implemented at node level with information about energy status of respective nodes. Inducing sleep is not a new method of energy conservation, but preconditions and mode of implementation distinguish it from similar other strategies. Sleep mode not only reduces transmission and reception activities of sensor nodes, but also to some extent improves energy capacity of battery. Nataf et al. [67] state that various battery models relating to life time take into account two phenomena occurring in battery cell:

The Rate Capacity Effect - gives the energy consumed under a constant current load as in the case of transmitting. At a constant current load, oxidation at the anode induces reduction at the cathode. The reduction decreases the concentration of positive ions near the cathode and so the available energy.

The Recovery Effect- gives the energy recovered during inactivity or low current load. During inactivity or low current load the positive ions near the anode have time to move towards the cathode, thus increasing the available energy and so the battery lifetime.

In case of Wireless Sensor Networks, the recovery process occurs during idle time which is generally up to 90% of the WSN node life. Therefore, Hibernation or inducing sleep mode is one of the most obvious means of power conservation and the transceiver circuitry being idle is turned off, when it is not required. It must not be overlooked that sensor nodes communicate using short data packets, the shorter the packets, the more is the dominance of start-up energy. Therefore, turning off radios during each idling slot may lead to consumption of more energy than in case of an always on radio.

Hence, operation in a power-saving mode[100] is energy-efficient only if the time spent in that mode is greater than a certain threshold. In the present research work, Hibernation mode has been induced to conserve as well as recover the battery energy during the idle time. Hibernation has been induced to lower the active node density in the network at a particular time. HC-WSN proposes to induce hibernation in the member nodes having energy E_{0i} higher than the Lower Threshold and lower than the Upper Threshold.

$$E_{UTH} \geq E_{0i} \geq E_{LTH}$$

Further to maintain optimal number of sensor nodes in Active state for performing the sensing and data transmission functions, a hibernation control factor has been introduced. The hibernation control factor is also responsible for ensuring that a sensor node does not enter a loop of repetitive sleep periods.

5.6.3 Phase –III: Avoiding Collisions

A typical wireless sensor network comprises of hundreds of nodes communicating with their respective cluster heads. The shared wireless channel between sensor nodes and scarce energy scenario makes the medium access control (MAC) a crucial part of the wireless sensor networks. Hence, MAC protocols for WSN should be energy aware and tailored to the physical properties of the sensed phenomenon and the specific network properties so that the access to the channel is coordinated with minimum collisions without affecting the connectivity throughout the network.

Protocols like LEACH [13] deploy TDMA for collision free transmission between member nodes and respective cluster heads. The steady-state phase is divided into frames, for nodes to send data to cluster head during allocated transmission slot at most once per frame. The duration of each slot is constant; hence time to send a frame of data depends on number of nodes in the cluster. The nodes are all time synchronized by the synchronization pulses sent by base station to the nodes. The nodes start the set-up phase at the same time. To reduce energy dissipation, the radio of each non-cluster head node is turned off until its allocated transmission time and it uses power control to set the amount of transmit power based on the received strength of the cluster head advertisement.

TDMA scheduling for collision avoidance is a low-latency approach and bandwidth can be efficiently utilised when all the nodes have data to send to the cluster heads. The cluster head remains awake to receive the data, on receiving data, it performs data aggregation to enhance the common signal. The resultant data are sent from the cluster head to the sink.

Radio is inherently a broadcast medium, so transmission in one cluster interferes with communication in a nearby cluster. To reduce this, each cluster in LEACH communicates using direct-sequence spread spectrum (DSSS)[101]. Each cluster uses a unique spreading code; all the nodes in the cluster transmit their data to the cluster head using this spreading code and the cluster head filters all received energy using this spreading code. This is known as transmitter-based code assignment[102], since all transmitters within the cluster use the same code.

To reduce the possibility of interfering with nearby clusters and reduce its own energy dissipation, each node adjusts its transmit power resulting in fewer overlapping transmissions. For low probability of collisions, little spreading of the data is needed. Data is sent from the cluster head nodes to the sink using a fixed spreading code and CSMA. S-MAC protocol makes serious efforts to avoid collision by having a node back off for the random duration before transmission[39],. It uses traditional mechanism like exchange of RTS / CTS and virtual listening by NAV (Network Allocation Vector) which intimates the node regarding on going transmission and when it will end.

Due to physical properties of events being monitored through WSN applications, the information may be highly correlated according to the spatial distribution[103] of the sensor nodes. Intuitively, data from spatially separated sensors are more useful to the sink than highly correlated data from closely located sensors. Hence, it may not be necessary for every sensor node to transmit its data to the sink. Instead, a smaller number of sensor measurements might be adequate to communicate the event features to the sink within a certain reliability constraint. As a result, the energy consumption of the network can be reduced by exploiting spatial correlation in the WSNs.

HC-WSN being a cluster based algorithm organises nodes into clusters. The clusters have been formed based upon the spatial vicinity of nodes. Further to reduce the active node density, the hibernation (sleep mode) has been induced among the nodes with in the clusters. These nodes remain in hibernation for fixed number of rounds. To avoid collisions with in the cluster, all members having data are allotted slots for undertaking data transmission; accordingly member nodes transmit the data as per their allocated slots. The data at the cluster head level is aggregated and sent to the base station. This approach enhances the throughput of the network due to reduced collisions.

5.6.4 Phase – IV: Choosing Sink Locations

In this research work the sink has been initially chosen to be static and located centrally. But through the literature survey it has been anticipated that in many real time applications of Wireless Sensor Networks, like monitoring volcano eruptions, deployment in hostile environments like warzones, central positioning of the sink or base station is not possible.

Apart from this sink mobility and sink location plays an important role in determining the energy consumption pattern of nodes, thereby influencing the energy efficiency of the network and its lifetime. Nodes communicating with a sink that is centrally placed will last much longer than the scenario in which the sink is located far apart from the deployment area. The mobility and the mobility pattern also have influence on the communication with the network and therefore the energy consumption. For example a sink moving a circular path with in the area of deployment will have better efficiency of transmission than a sink which moving along the boundary of the deployment area.

Similarly the density of nodes also has a distinct relation with the location of the sink. The closer the sink to the dense location more efficient will be the network. Extensive research work has been undertaken in this field. To attend to this issue in HC-WSN, various scenarios to position the sink have been evaluated using MATLAB simulations. The proposed strategies are:

1. Static position of the sink chosen randomly within or outside the test area.
2. Moving the sink on a circular path inside the boundary of field area under consideration.
3. Moving the sink on a circular path outside the boundary of field area under consideration.

5.7 SIMULATION AND RESULTS

The salient features of the proposed protocol and the phased approach adopted have been explained in the earlier sections. This section provides the details of the simulations carried out in MATLAB to evaluate the proposed protocol. The evaluation has been done as three cases covering all the aspects proposed above. The details are:

(i) **CASE- I**: Simulating different phases covered for formulating the proposed protocol. This covers four phases as:

a. All nodes transmitting directly to the Sink

b. Part nodes in Hibernation, active nodes transmitting directly to Sink

c. Formation of Clusters: Member Nodes transmitting to Cluster Heads.

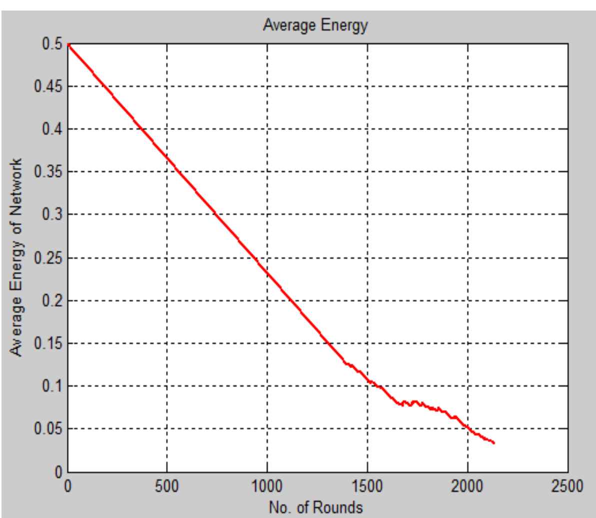
d. Complete proposed protocol: Hibernated Clustering – Wireless Sensor Networks (HC-WSN).

(ii) **CASE- II**: Comparison of the proposed protocol with existing protocols like LEACH[13] and H-LEACH[15].

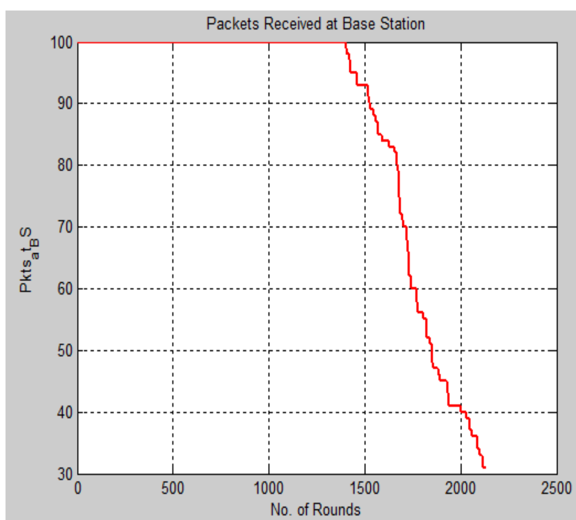
(iii) **CASE- III**: Simulating impact of factors like sink position, sink mobility, duration and node density for improved operation of network.

Case-I: Simulating different phases covered for formulating proposed protocol.

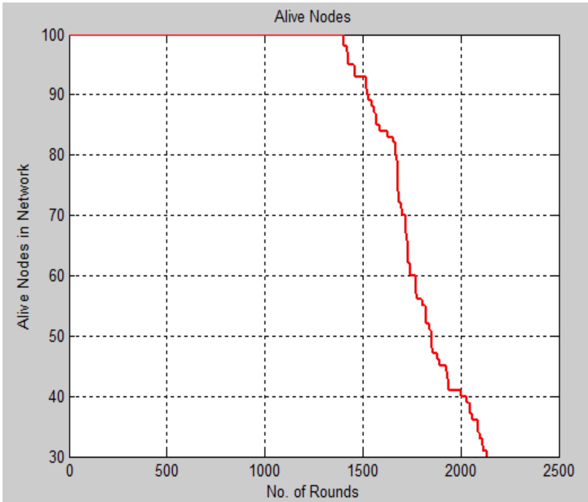
a. All nodes transmitting directly to the Sink



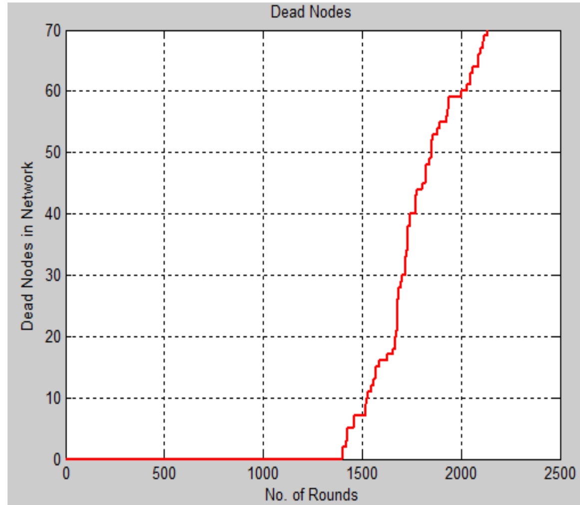
(i) Average Energy of Network



(ii) Throughput



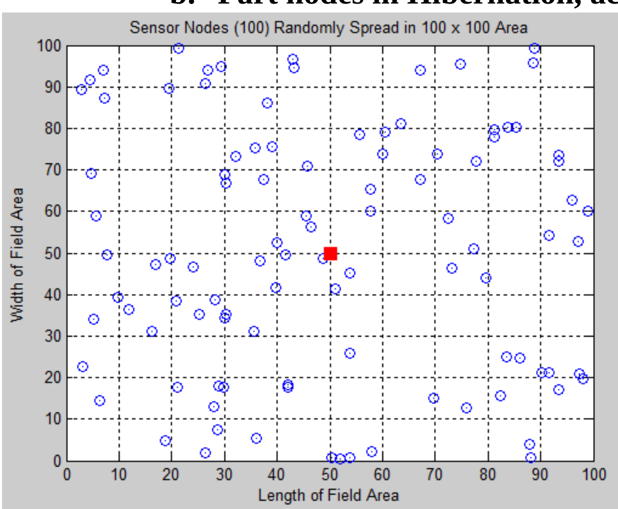
(iii) No. of Alive Nodes



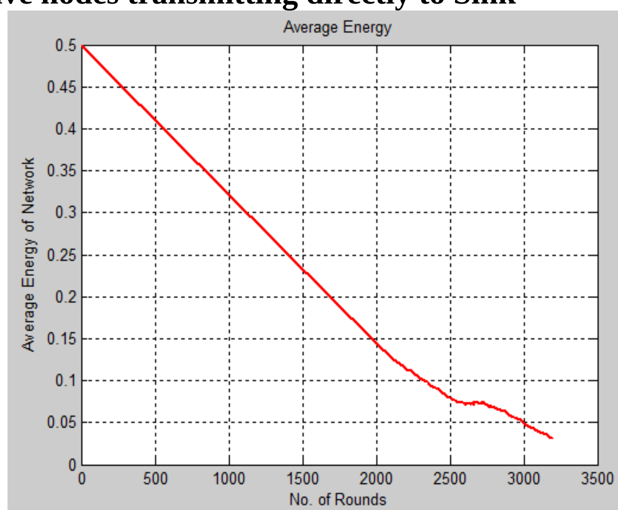
(iv) No. of Dead Nodes

Figure 5.12: Direct Communication from Nodes to Sink

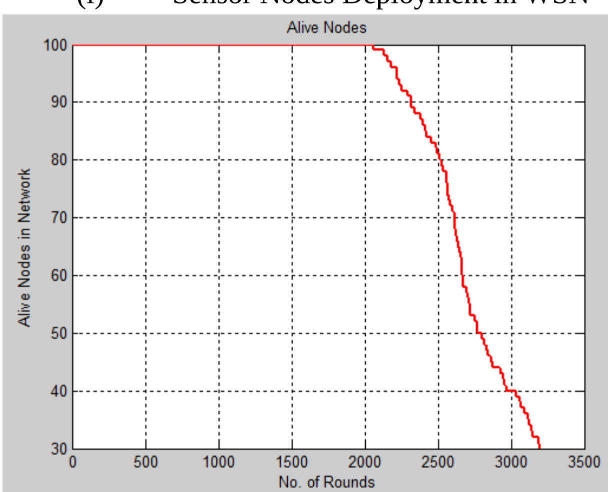
b. Part nodes in Hibernation, active nodes transmitting directly to Sink



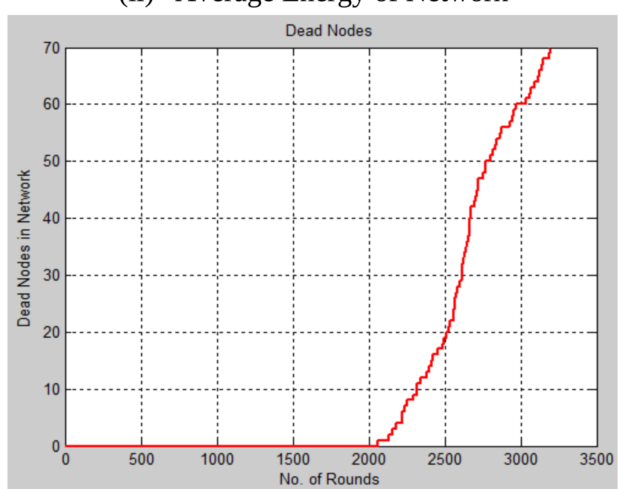
(i) Sensor Nodes Deployment in WSN



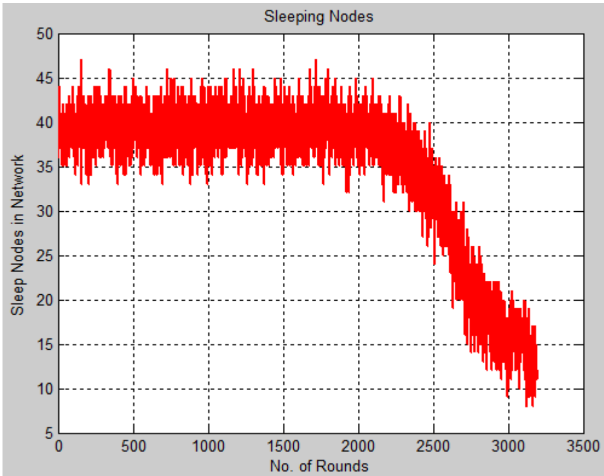
(ii) Average Energy of Network



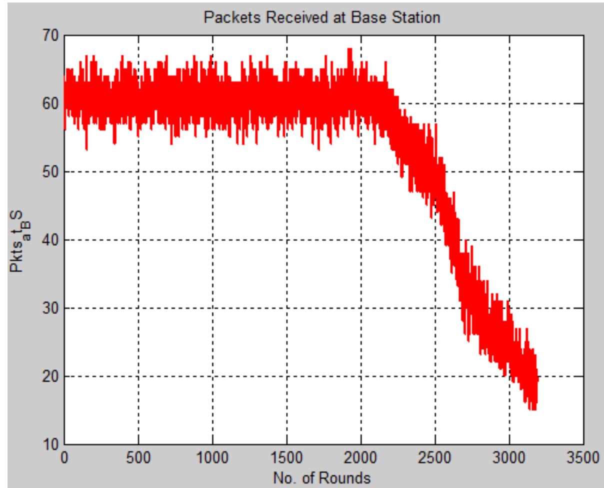
(iii) No. of Alive Nodes



(iv) No. of Dead Nodes



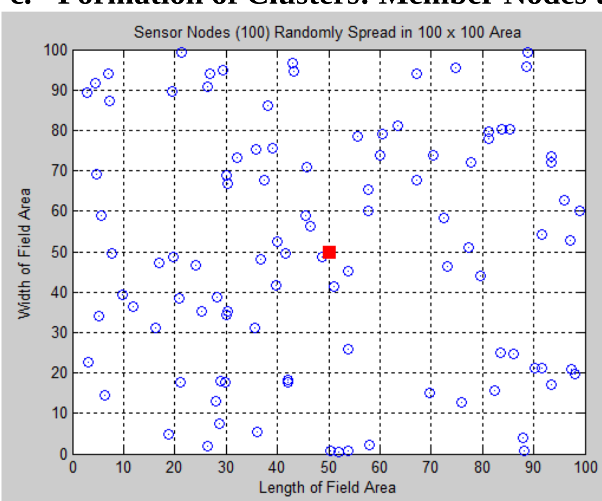
(v) No. of Hibernated Nodes



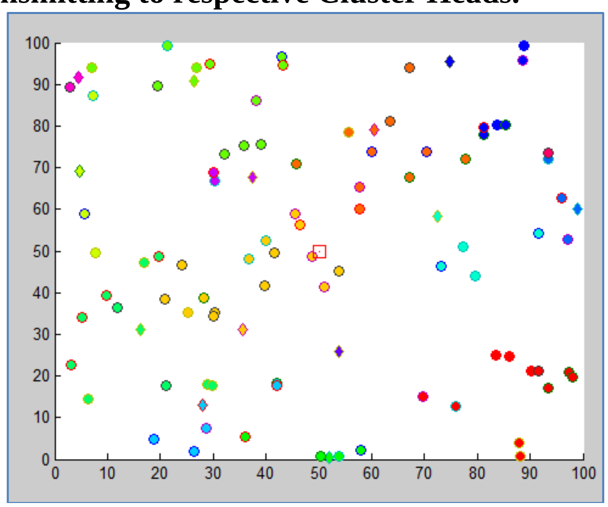
(vi) Throughput

Figure 5.13: Part nodes in Hibernation, active nodes transmitting directly

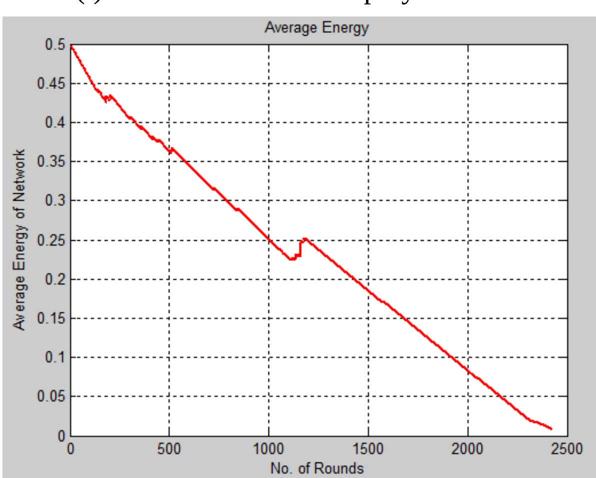
c. Formation of Clusters: Member Nodes transmitting to respective Cluster Heads.



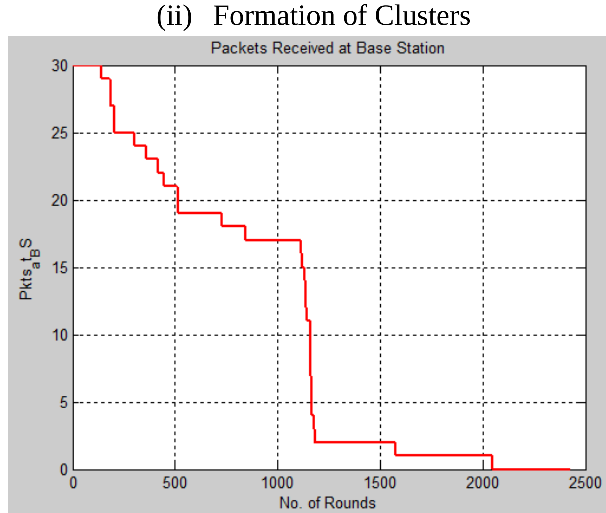
(i) Sensor Node Deployment in WSN



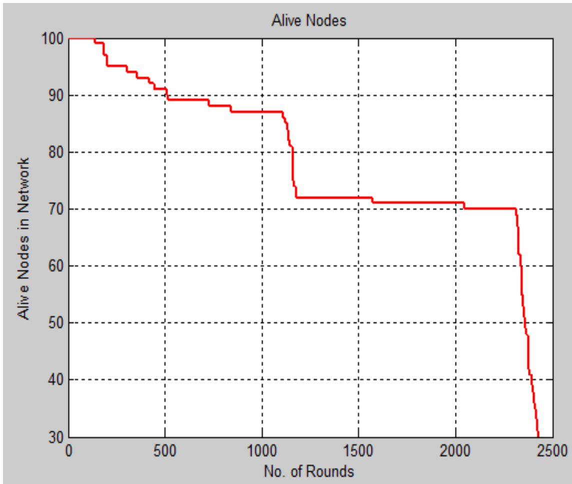
(ii) Formation of Clusters



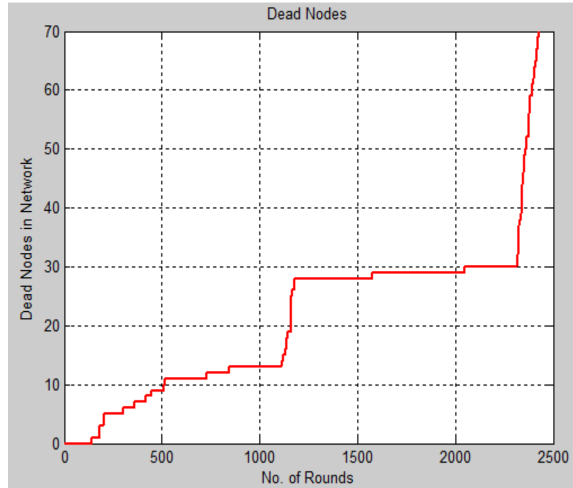
(iii) Average Energy of Network



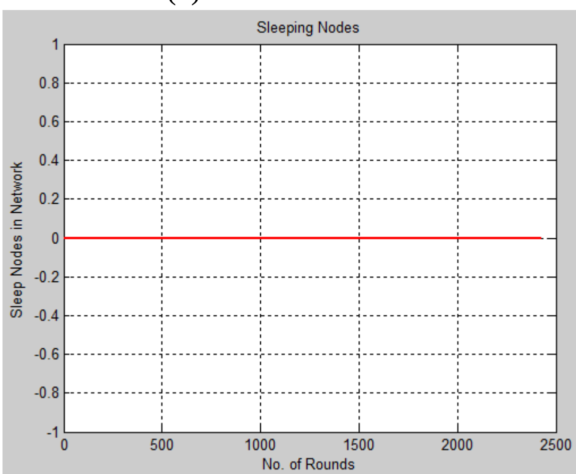
(iv) Throughput



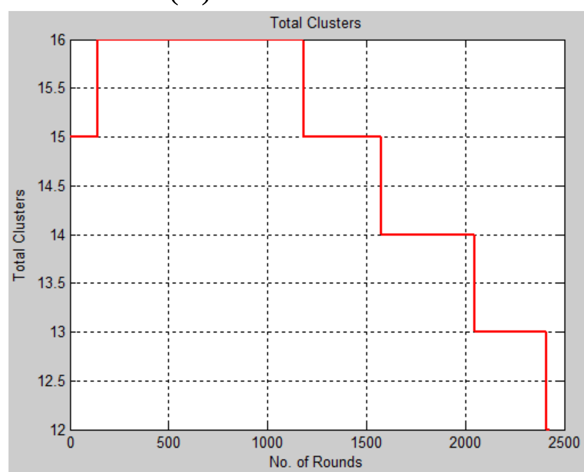
(v) No. of Alive Nodes



(vi) No. of Dead Nodes



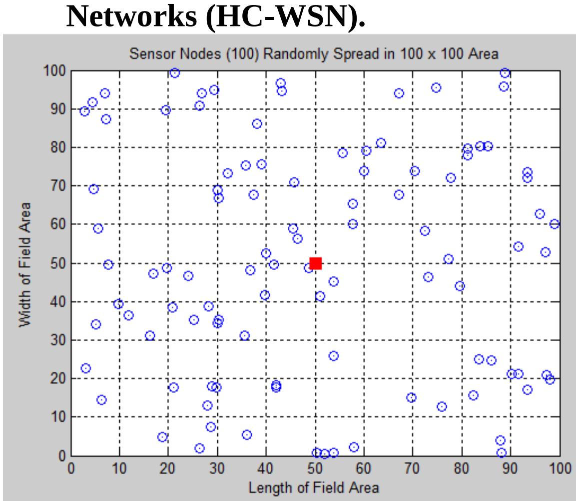
(vii) No. of Hibernated Nodes



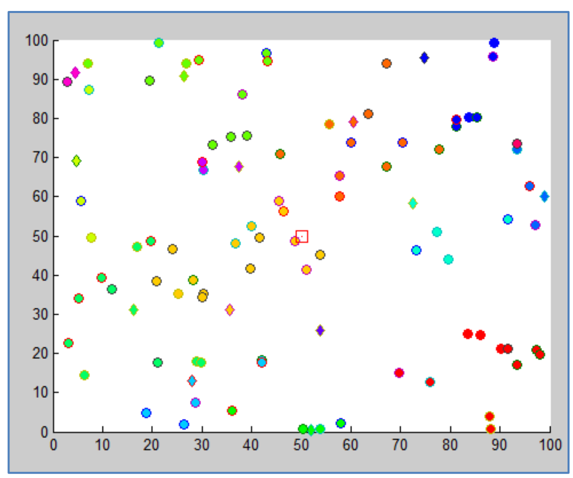
(viii) No. of Clusters

Figure 5.14: Simulation Results: Formation of Clusters

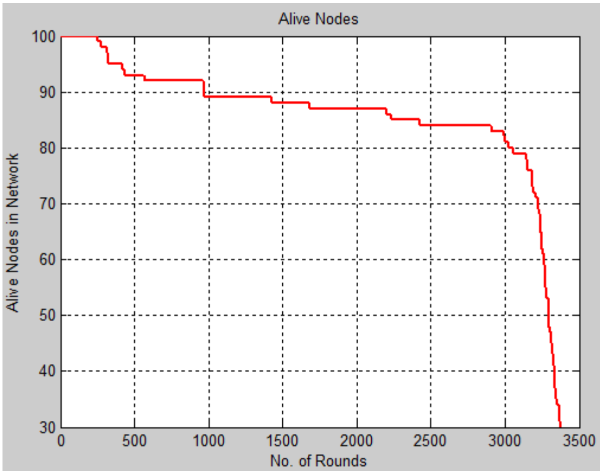
d. Complete proposed protocol: Hibernated Clustering – Wireless Sensor Networks (HC-WSN).



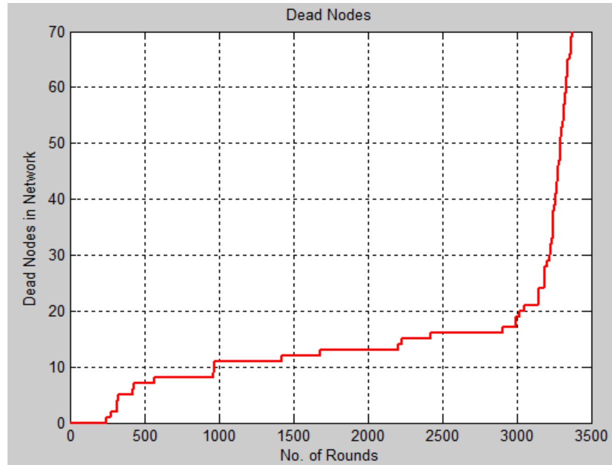
(i) Sensor Node Deployment in WSN



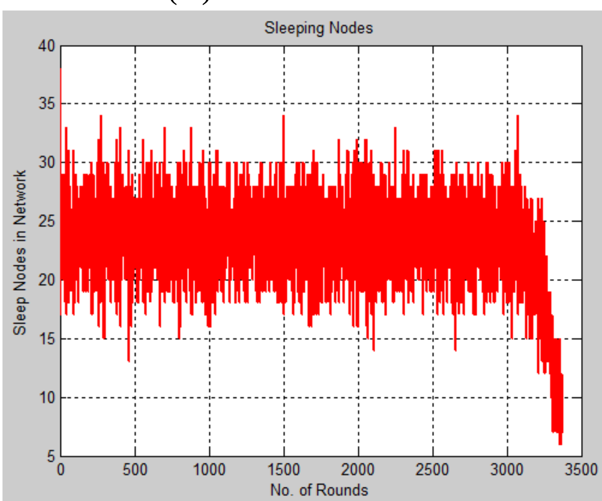
(ii) Formation of Clusters



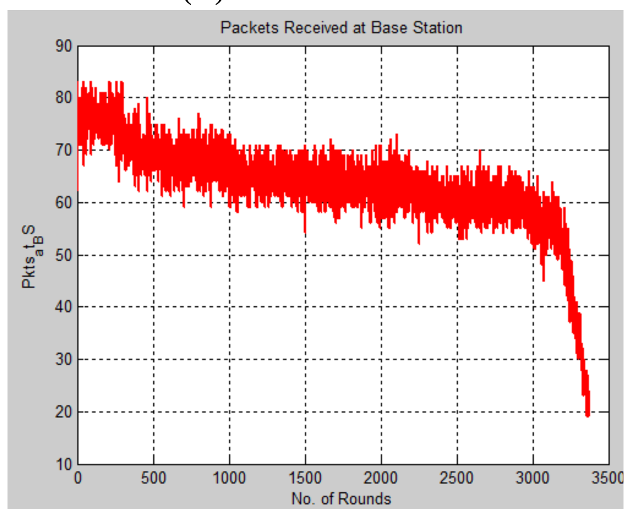
(iii) No. of Alive Nodes



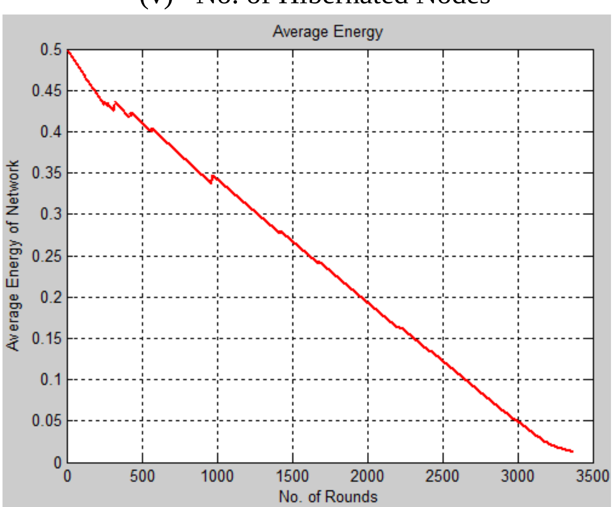
(iv) No. of Dead Nodes



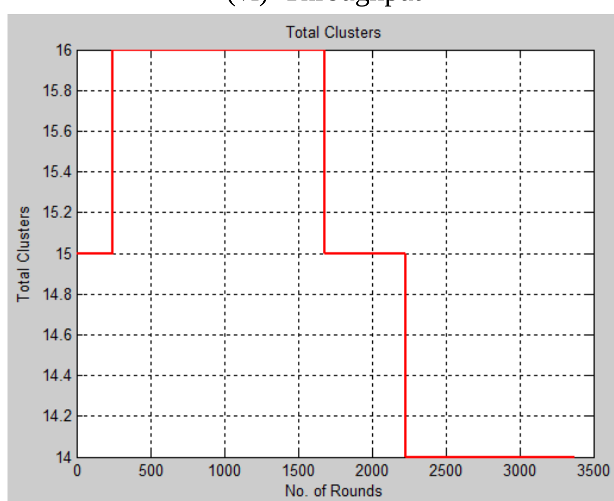
(v) No. of Hibernated Nodes



(vi) Throughput



(vii) Average Energy of Network



(viii) No. of Clusters

Figure 5.15: Simulation Results: Proposed Protocol – HC-WSN

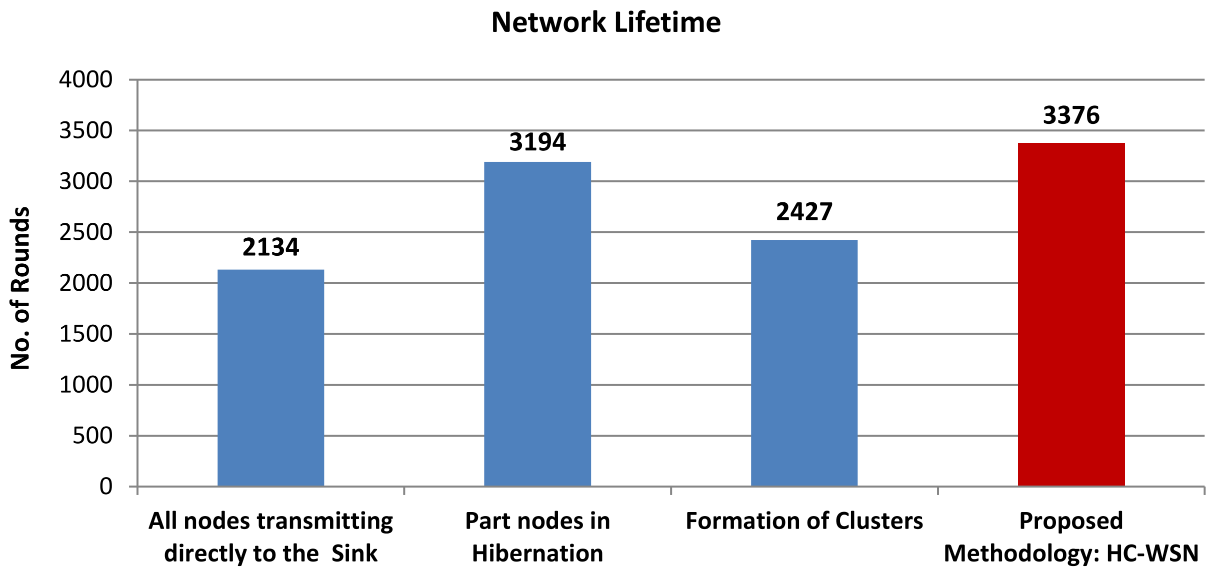


Figure 5.16: Comparison of Network Lifetime in all four phases considered

The simulation results of the above four phases have been compared in terms of Network Lifetime, which in this research work has been assumed to be the number of rounds up to which at least 70% of the nodes in the network are alive. The graph in Figure 5.16 indicates that the network with the proposed protocol has 70% alive nodes till 3376 rounds which is higher than all the other three cases considered. This implies that the proposed protocol has improved the network lifetime over a normal or solely clustered or a solely sleep induced network.

Case - II: **Comparison of proposed protocol (HC-WSN) with existing protocols namely LEACH and Hybrid-LEACH proposed earlier.**

The proposed protocol HC-WSN is compared with existing LEACH and Hybrid-LEACH protocol. Hybrid-LEACH (H-LEACH) is a variant of LEACH, [15], it has been proposed by Razaque et al in 2016. The Hybrid LEACH has been found to be better than LEACH with presence of live nodes for longer duration. The simulation has been set up with 100 nodes randomly spread over the deployment area for 100 rounds as shown in Figure 5.17 below.

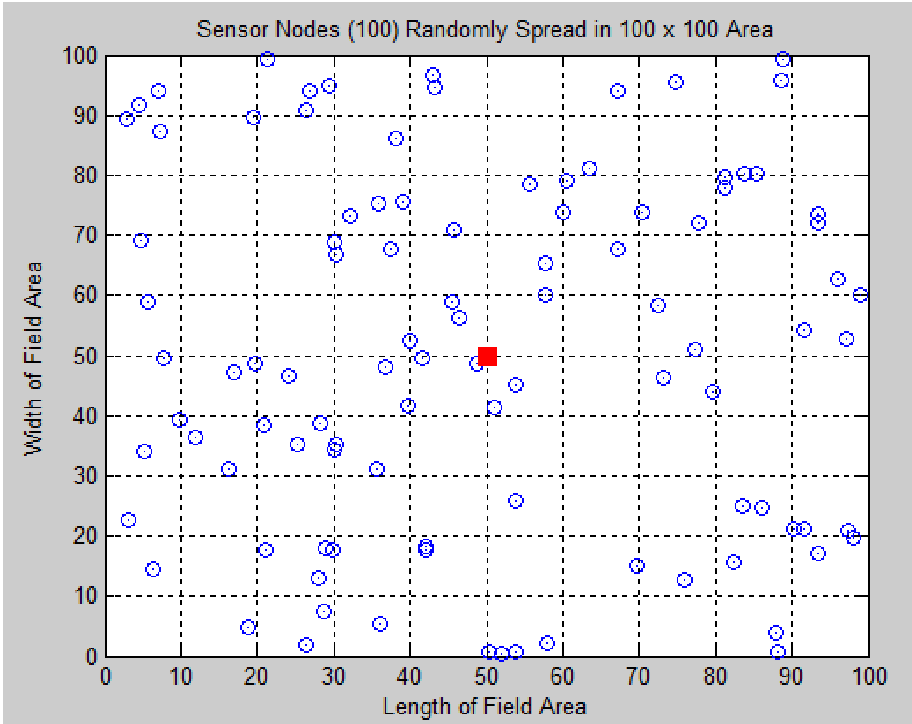


Figure 5.17: Sensor Nodes spread over 100 x 100 area

The comparison has been done in terms of number of alive nodes, average energy of the network and throughput.

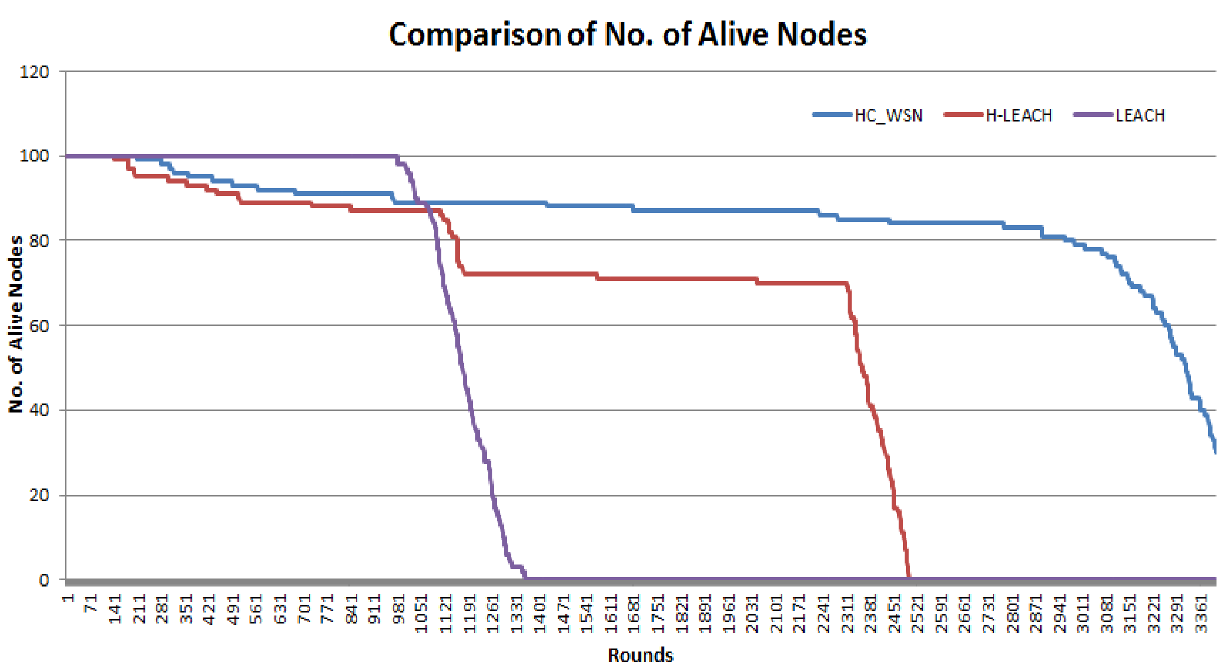


Figure 5.18: Comparison of Alive nodes in HC-WSN, Hybrid LEACH and LEACH

(I) Comparison of Alive Nodes

The output of the HC-WSN has been shown with blue line, output of Hybrid-LEACH has been indicated with the red and LEACH has been indicated with purple line. The graph plotted shown in Figure 5.18 above, indicates that the number of alive nodes, is available for a longer duration i.e. the network survives and operates for higher number of rounds.

(II) Comparison of Average Energy

The graph shown in Figure 5.19 indicates the comparison of average energy of network among HC-WSN, Hybrid-LEACH and LEACH. It is shown from the graph that HC-WSN (depicted in blue colour) preserves better average energy of the network for higher number of rounds than in case of Hybrid LEACH and LEACH.

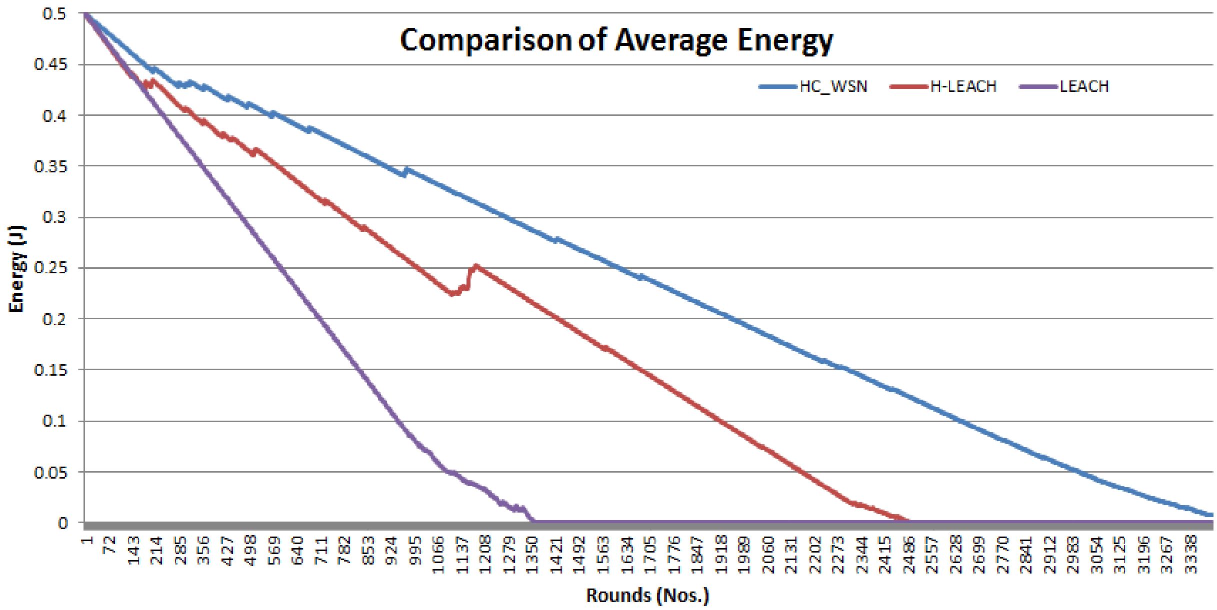


Figure 5.19: Comparison of Average Energy in HC-WSN, Hybrid LEACH and LEACH

(III) Comparison of Throughput

Similarly the throughput of the network has been compared among the three protocols and the results are depicted in Figure 5.20 below. Here more number of packets are transmitted to the base station in case of HC-WSN indicated in blue than Hybrid LEACH and LEACH indicated in red and purple respectively.

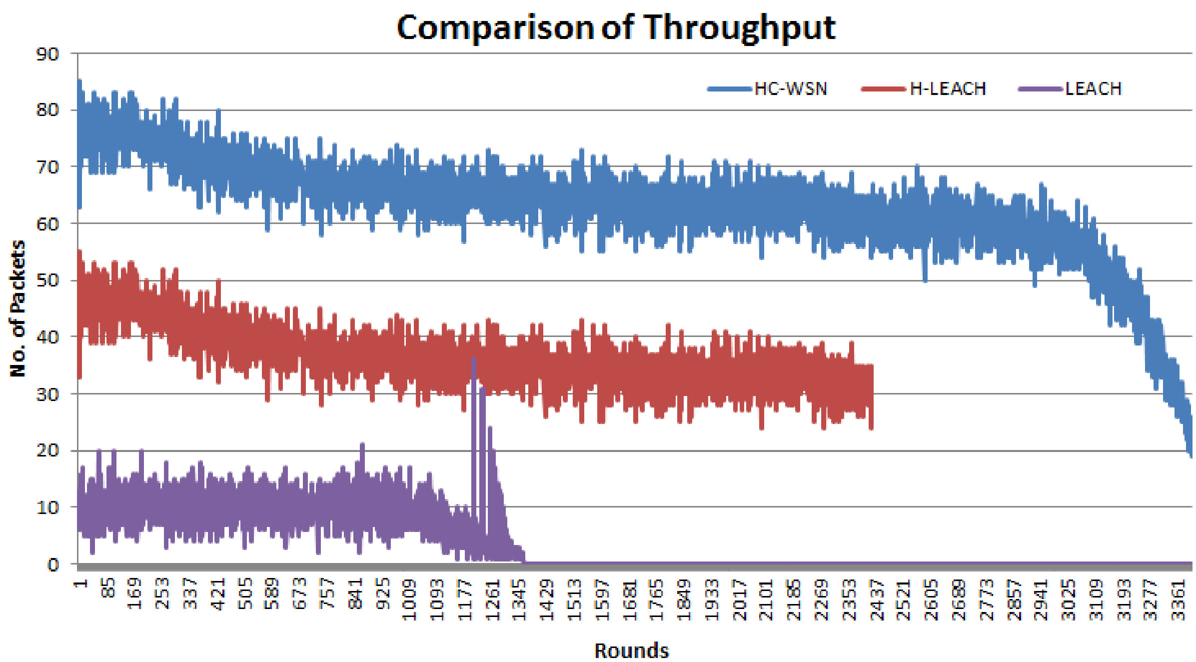


Figure 5.20: Comparison of Throughput in HC-WSN, Hybrid LEACH and LEACH

From the above simulations it can be concluded that, in comparison to Hybrid LEACH and LEACH the proposed protocol HC-WSN has performed better in terms of number of alive nodes, throughput as well as average network energy and thus indicates the enhanced overall network life time.

Case - III: Simulating impact of factors like sink position and sink mobility for improved operation of network. The different approaches undertaken are shown in Figure 5.21 below:

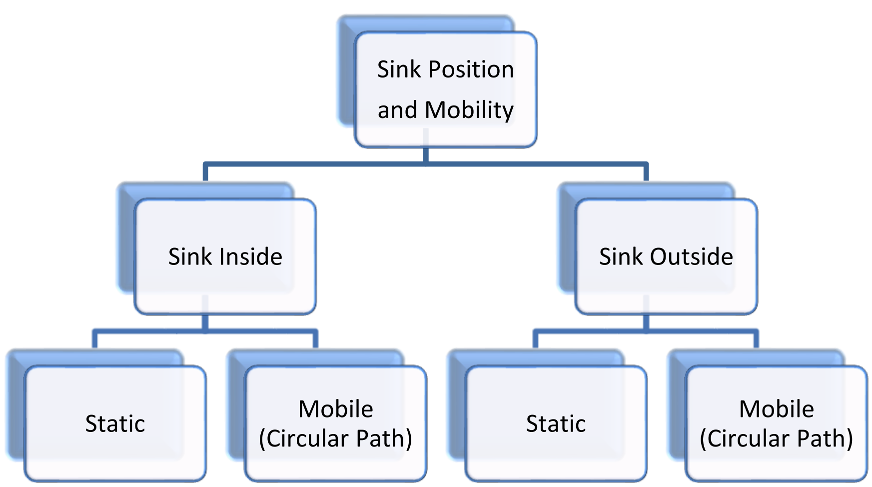


Figure 5.21: Scheme of Approaches taken

Approach – I: Sink statically located outside deployment area

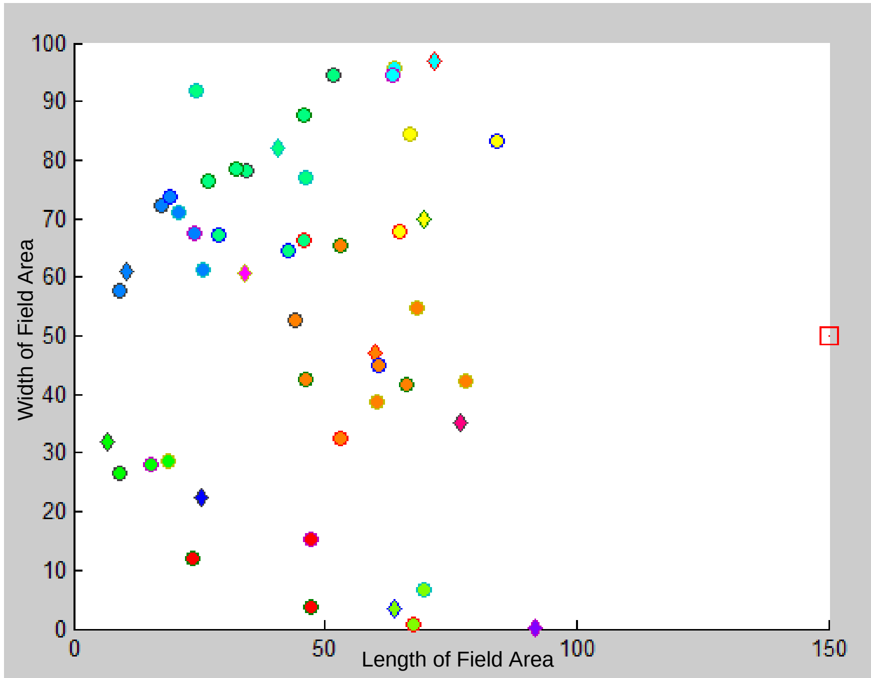


Figure 5.22: Sink statically located outside deployment area
[50 nodes, sink (150,50)]

Approach – II: Sink statically located inside deployment area

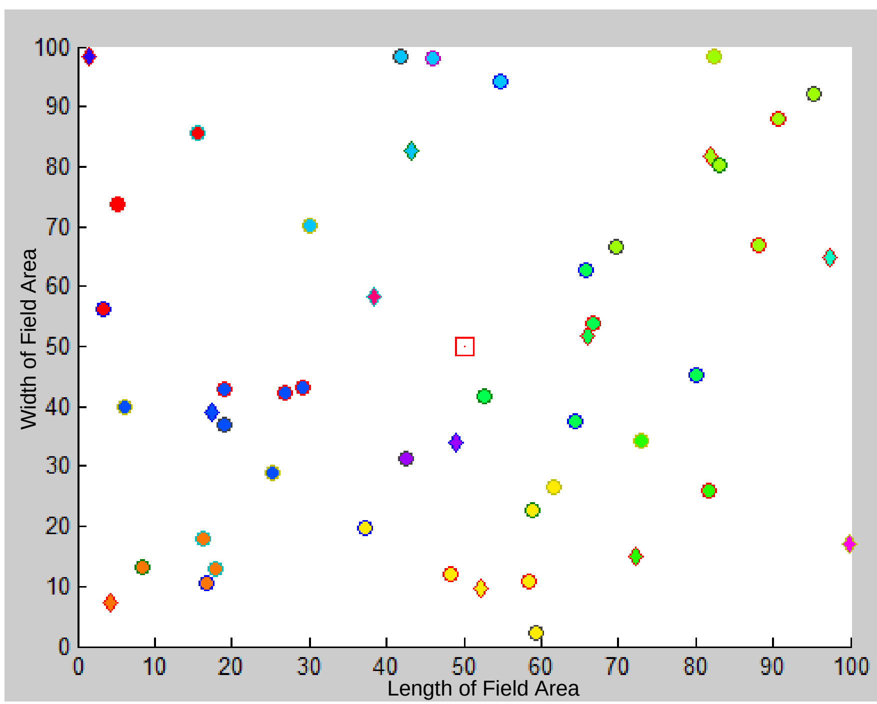


Figure5.23: Sink statically located inside deployment area
[50 nodes, sink (50,50)]

Approach – III: Sink moving in circular path inside deployment area

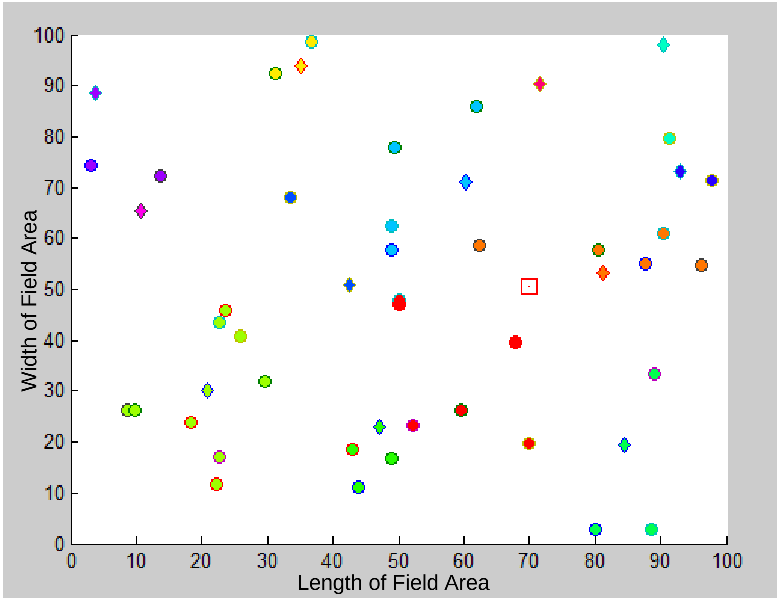


Figure5.24: Sink moving in circular path inside deployment area

Approach –IV: Sink moving in circular path outside deployment area

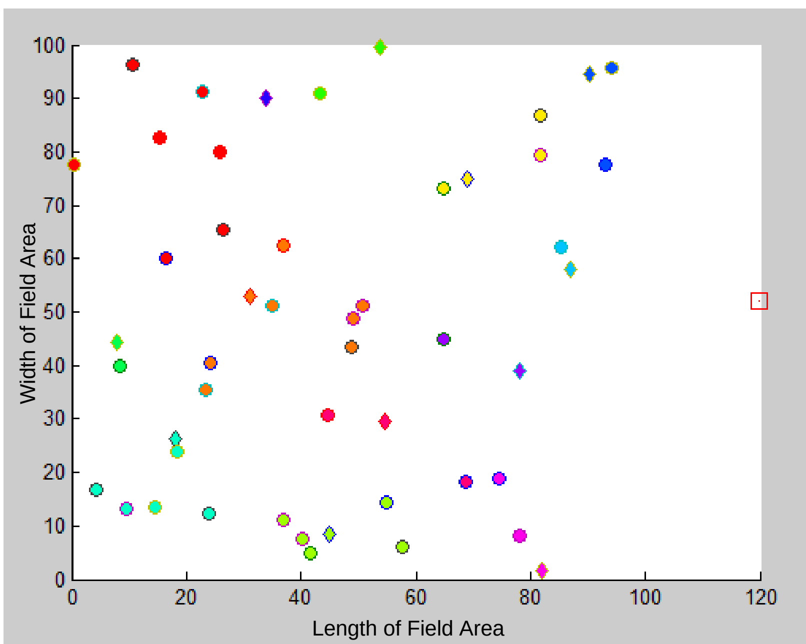


Figure 5.25: Sink moving in circular path outside deployment area

The above four approaches have been simulated for variation in node density i.e. number of nodes [50 nodes and 100 nodes] and duration i.e. number of rounds [100 rounds and 200 rounds]. The evaluation of these approaches has been done in terms of (i)

Comparison of number of alive nodes (ii) Comparison of average energy of nodes and (iii) Comparison of Throughput – Packets received. The outcomes have been represented in the graphs below:

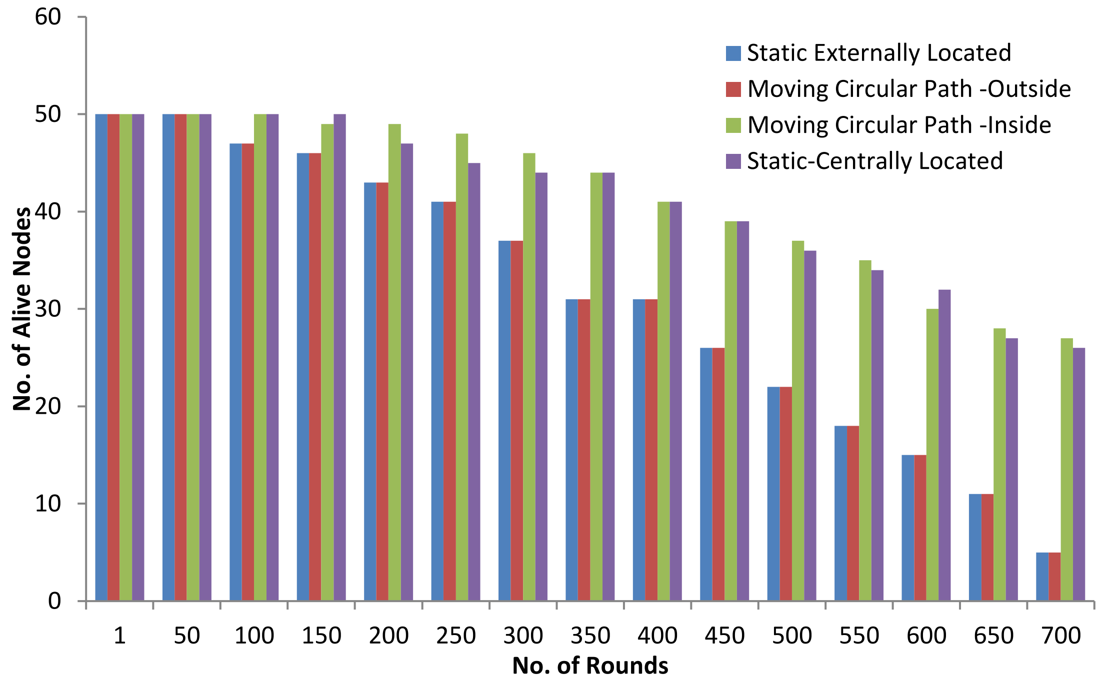


Figure 5.26: Comparison of Number of Alive Nodes [50 Nodes; 700 Rounds]

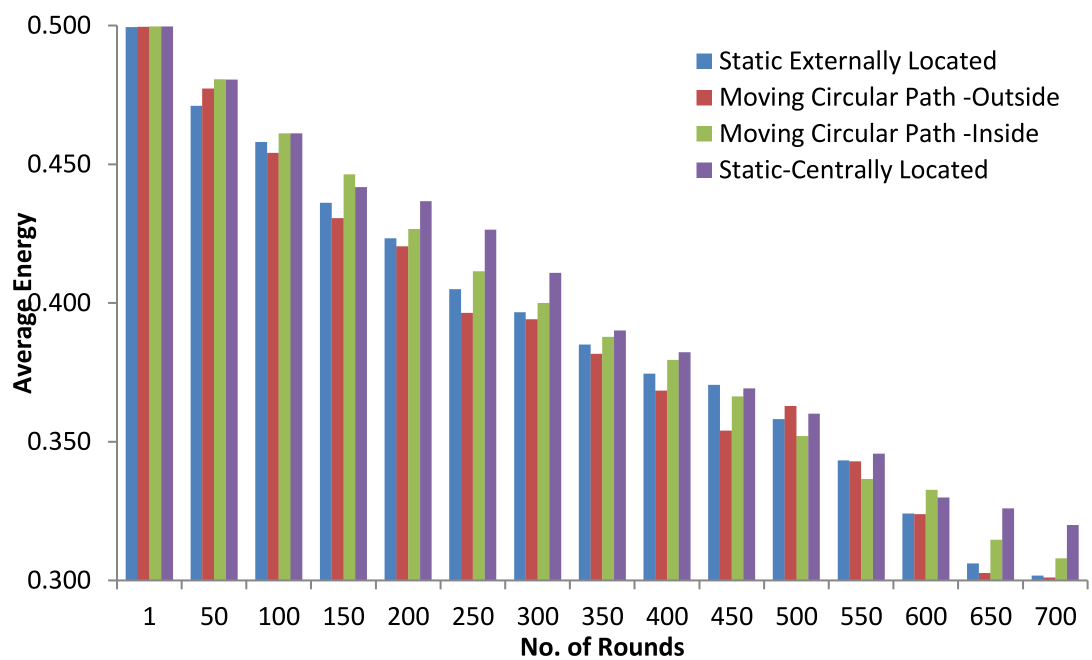


Figure 5.27: Comparison of Average Energy of Nodes [50 Nodes; 700 Rounds]

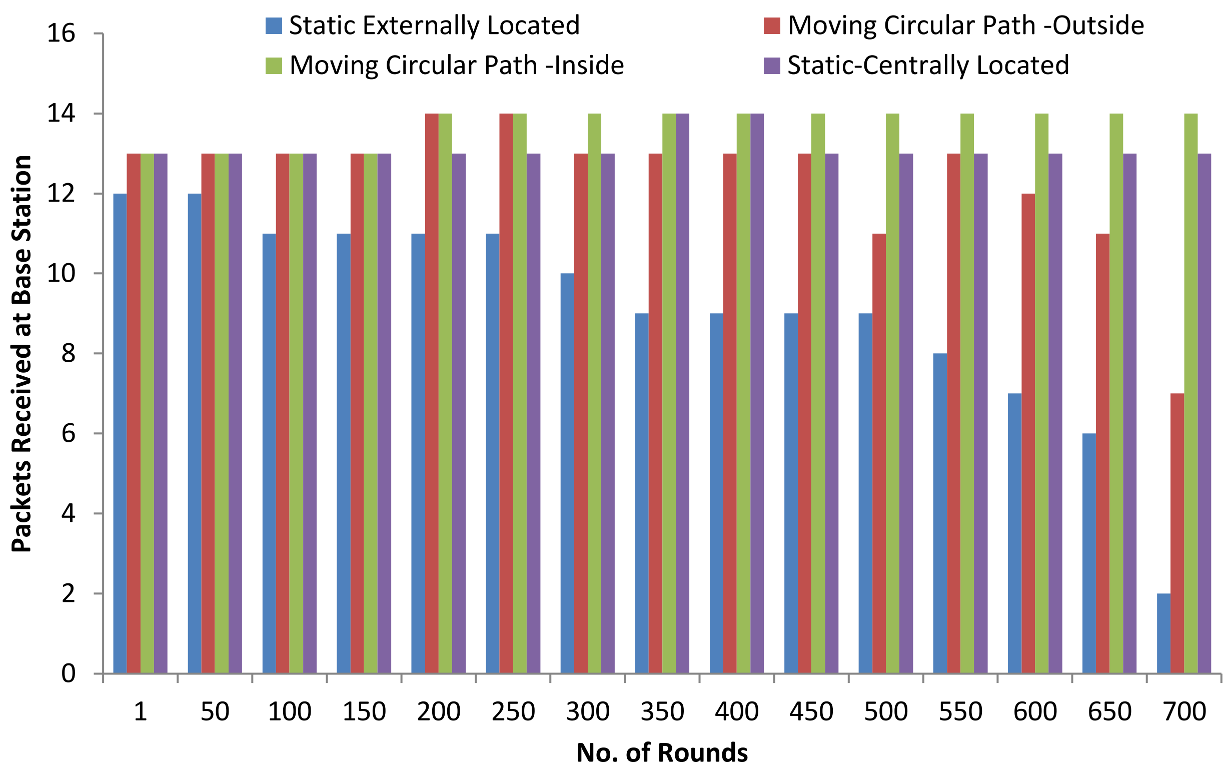


Figure 5.28: Comparison of Throughput [50 Nodes; 700 Rounds]

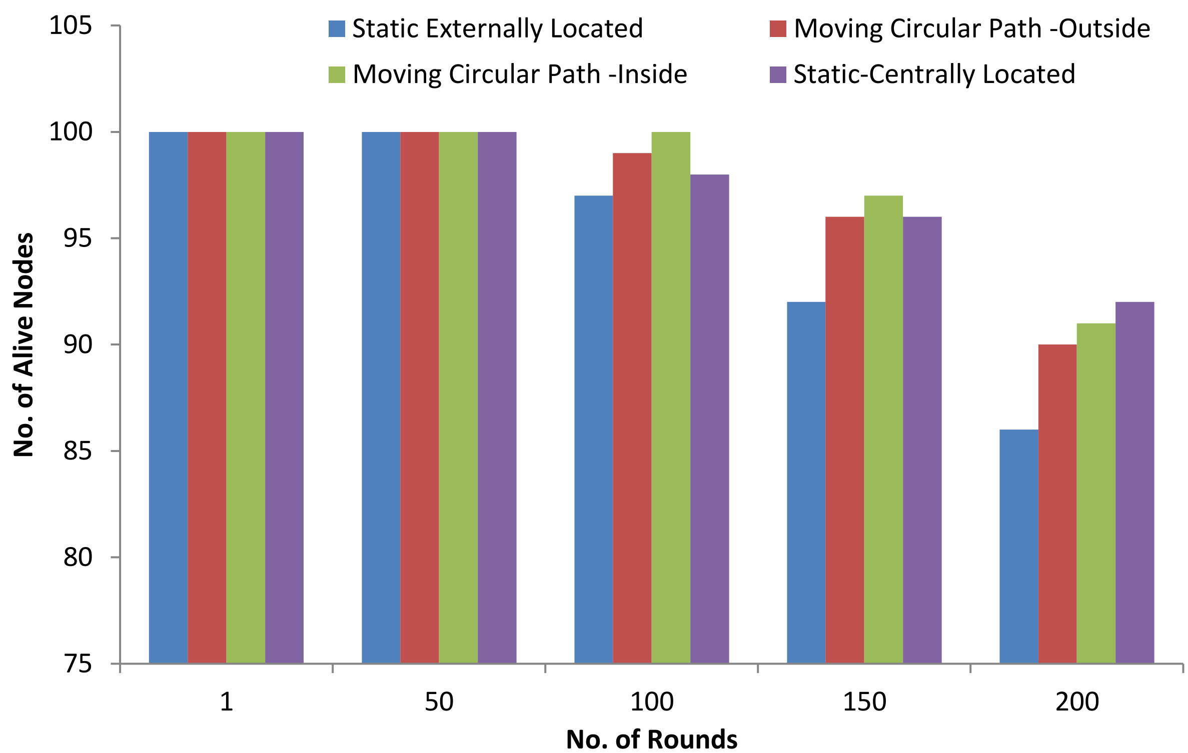


Figure 5.29: Comparison of Number of Alive Nodes [100 Nodes; 200 Rounds]

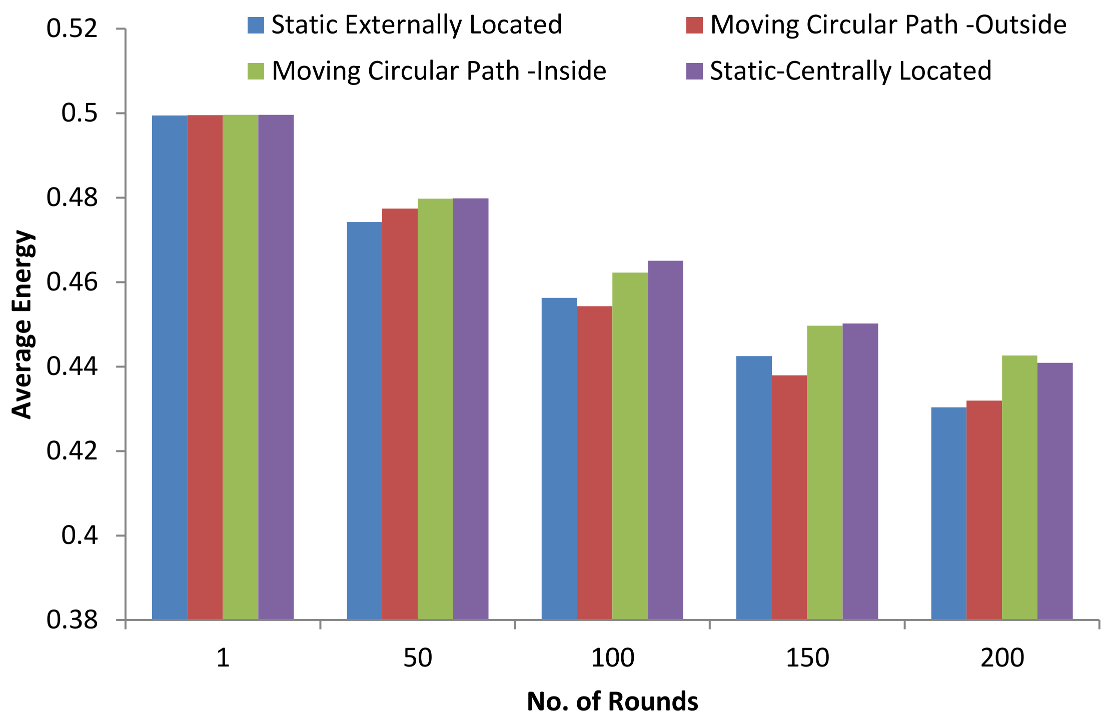


Figure 5.30: Comparison of Average Energy of Nodes [100 Nodes; 200 Rounds]

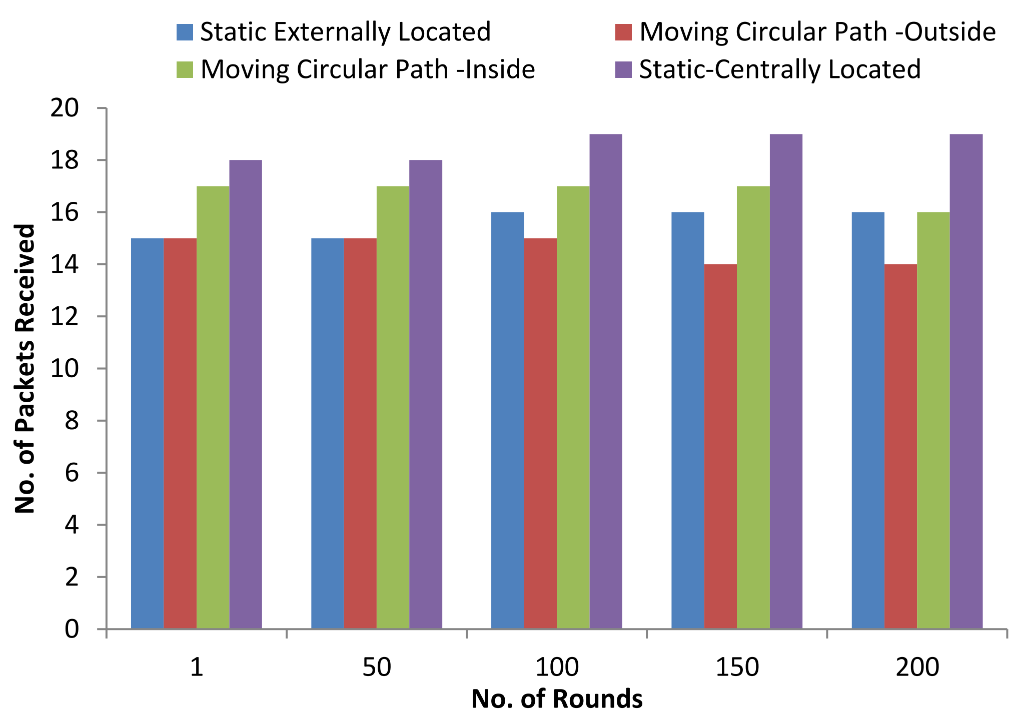


Figure 5.31: Comparison of Throughput [100 Nodes; 200 Rounds]

From the above simulations, it can be inferred that:

- Throughput of the network is more when the sink is statically placed with in the network deployment area.
- Number of alive nodes is more in case of a network with internally mobile sink instead of a network with internally static sink
- On comparing external mobile sink and internal mobile sink, the network with internal mobile sink has been found to have higher number of alive nodes, higher average network energy and better throughput.

5.8 SUMMARY

The chapter has introduced the proposed protocol Hibernated Clustering Wireless Sensor Networks (HC-WSN), for improving energy efficiency and lifetime of the network. HC-WSN has been designed considering the energy consumption aspects of sensor networks. The protocol proposes measures at various levels in wireless sensor network to overcome the limitations in existing clustering protocols.

The chapter also simulates the various measures proposed in fields like cluster head selection, hibernation, collision avoidance and sink mobility. From the simulation results it has been found that the overall performance of WSNs has considerably improved in comparison to the similar existing protocols.

CHAPTER VI

TEST-BED DESIGN AND IMPLEMENTATION

6.1 INTRODUCTION

The proposed protocol “HC-WSN” has been introduced and explained in detail in the previous chapter. The simulations have been carried out to establish the results of the proposed scheme. Though simulations give great flexibility in carrying out experiments but they do not reflect the real world scenarios. On the other hand test-beds have their own limitations of scale and cost involved for every modification. The test-bed implementations overcome inadequacies of mathematical modeling and provide outcomes based on real time physical environmental conditions.

This chapter discusses the test-bed requirement and test-bed design parameter for a Wireless Sensor Networks. The details of designing a new test-bed comprising of hardware components and associated software have been discussed. The chapter concludes with discussion on implementation of HC-WSN on newly designed test-bed.

6.2 NEED FOR TEST-BEDS

A Wireless Sensor Network Test-bed is a platform for experimentation of development projects. It allows rigorous, flexible, transparent and replicable testing of theories, computational tools and innovations. When compared to WSN simulators, WSN test-beds enable more realistic and reliable experimentation in capturing the subtleties of the underlying hardware, software, and dynamics of the wireless sensor network.

With recent advancements in wireless communications and MEMS technology, Wireless Sensor Networks (WSNs) are rapidly gaining increasing attention on the experimentation level as well as the application-deployment level. Affordability, ease of deployment, and ability to monitor phenomena that were impossible to monitor using other solutions are just few among many other reasons that make WSN such a preferred choice.

This rapid growth galvanizes educational and research institutions around the world to set-up their own wireless sensor network test-beds. These test-beds enable researchers to gain hands-on experience and to investigate variety of scenarios. It provides researchers with hands-on opportunity to experimentally investigate own innovation, and to test and evaluate its adaptability to real-world scenarios. Accordingly, such test-beds have become the basis for experimentation with wireless sensor networks in real-world settings; and they are also used by many researchers to evaluate specific applications pertaining to specific areas.

A test-bed typically consists of sensor nodes deployed in a controlled environment. Test-beds provide researchers with an efficient way to examine and evaluate their algorithms, protocols, applications, etc. Test-bed can be designed to support different features depending on the objective of the research. Among the important features of a Test-bed is that it can be designed to remotely configure, run and monitor experiments.

Even though WSN simulators are available, the need of a test-bed, which undeniably is a relatively costly solution, is felt. WSN simulators could be used for testing, evaluation and initial validation. WSN simulator is based on mathematical models that attempt to model the underlying characteristics of its physical system. Selecting the appropriate level of abstraction in simulation model is a complex problem. The accuracy of a simulator solely depends on its mathematical model. Accordingly, there is a trade-off between simulator's accuracy and computational complexity.

Complex simulation models demand excessive computational resources and time for execution. To improve upon the performance, such simulation models are made as simple as possible, causing loss of detailed information and conditions pertaining to real world scenarios. Most simulator designs focus on the specific higher layer protocols and ignore interaction between layers. At the time of designing simulation models, it is impossible to take into consideration all aspects of wireless channels. Therefore, considering these practical bottlenecks, the fidelity of simulators is always a concern. This inherent difficulty in faithful modelling has led to development of WSN test-beds.

Further, WSN test-bed provides the user exposure to complete WSN product development life cycle.

Though the role of simulation tools in providing affordable environment for initial design and testing cannot be underestimated. The role of simulation is not conflicting but rather complementary.

6.3 DESIGN CHALLENGES

In this section some of the significant features have been explained which are also key design challenges for Wireless Sensor Networks. These have been summarized with the help of Figure 6.1 below.

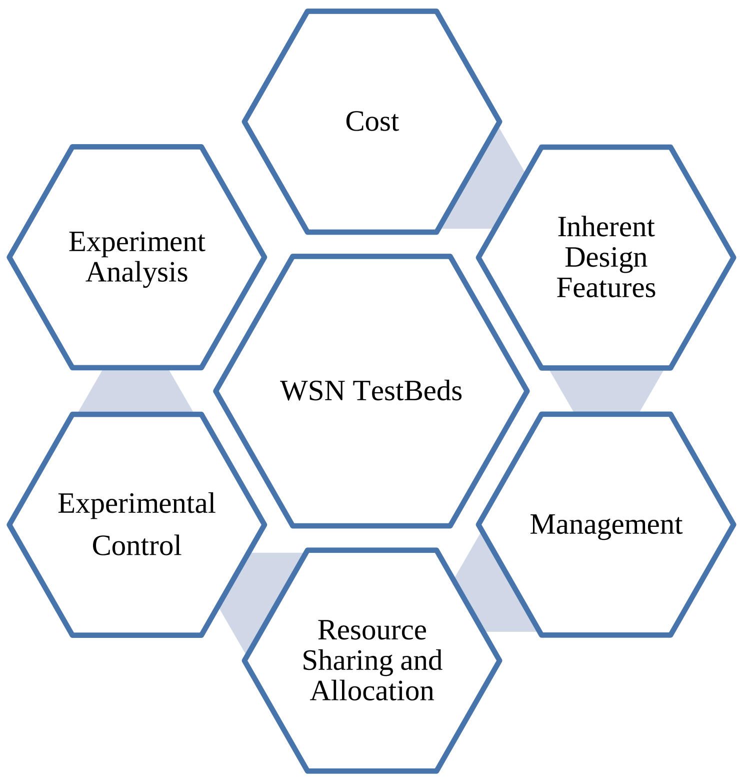


Figure 6.1: Design Challenges for WSN Test beds

A. Cost: In any of the hardware based real time experimenting platform, cost plays a significant role. It decides the flexibility of operation versus the scale and parameters to be considered. Adding on components though adds features but also adds on to the cost. There should be preference to optimize the test-bed to meet maximum expectation in an economical manner without compromising quality.

B. Inherent Design Features: The test-bed should be designed considering various inherent design features like use of open source hardware/ software, heterogeneity and scalability.

i. Open Source Technology: The design of a WSN test-bed could utilize open-source hardware and software for gaining flexibility, affordability, scalability, heterogeneity and support/ innovation from huge open source community.

ii. Heterogeneity: Heterogeneity refers to the ability of the WSN test-bed framework to accommodate and support heterogeneous mixture of test-bed hardware and software such as sensor nodes from different vendors with varying capabilities including different sensing ranges, varying sensor types, and different communication and computation capabilities. Heterogeneity inherently adds flexibility to the test-bed design. A heterogeneous and flexible test-bed can distinctively achieve design equilibrium through introducing a balance between cost and performance.

iii. Scalability: Scalability is a desirable property of a WSN test-bed design. It provides the WSN test-bed with the readiness required to handle expansion or growth in a graceful manner. For instance, a scalable WSN test-bed will have the ability to cover a bigger area for environmental monitoring through integrating the required additional hardware to the scalable framework. For a system to be scalable, scalability should be inherently implemented into its design. Subsequently, a scalability-management trade-off is always present and it has to be handled prudently.

C. Test-bed Management: In WSN applications, failures are common therefore maintaining a WSN test-bed's performance is a peculiar task which has to be achieved by controlling sensor nodes without any direct human intervention. The management functions integrate configuration, operation, administration, security, and maintenance of all elements and services of the test-bed.

D. **Resource Sharing and Allocation:** Designing a test-bed that could be shared by multiple users involves allocating a subset of sensor nodes from a pool to individual experiment or multiplexing experiments on each node. Once the user is granted access to the test-bed, it should enable them to configure their allocated resources to carry out specific experiments.

E. **Experimental Control:** Involves various aspects to control how the experiment is being conducted. It includes Topology Control, Application Configuration, Experiment Execution, and Network Debugging.

   i. Topology Control: The technique could be defined as reorganization and management of node parameters and modes of operation throughout the lifetime of the WSN network to modify the topology of the network with the goal of extending its lifetime while preserving important characteristics, such as network and sensing connectivity and coverage.
   ii. Application Configuration: The ways in which a user interacts with Test bed to setup their application either by writing own applications or by using a library of applications already provided by the WSN Test-bed developer.
   iii. Experiment Execution: The user should be able to initiate, pause, resume and terminate an experiment and able to view output at any point in time.
   iv. Network Debugging: WSN test-beds inherit debugging problems and difficulties from embedded and distributed systems. Should have tools to support uncover existing bugs and debug the error encountered.

F. **Experiment Analysis:** The test bed should have the features for efficient data collection, data fusion, data storage and impressive visualization.

6.4 AVAILABLE TEST-BEDS

Developing, testing, and evaluating network protocols and supporting architectures and services for WSNs can be undertaken through test-beds or simulation tools[104]. Due to the substantial cost of deploying and maintaining large-scale WSNs and considerable set time required for hardware test-beds, Simulation tools emerged as favorable tools of developing reliable and portable WSN applications. But with the increase in availability of economical hardware components, WSN test-beds are being deployed by Universities and different research organizations for near real time development and testing of WSN applications. Some of these test beds have been mentioned in the Table 6.1 below. Few salient features of these test beds are:

a. These test-beds support multiple network topologies and different network layer protocols.
b. They enable realistic experimentation in terms of Scale, Behavior, Functionalities, Environment and Constraints.
c. Most of these have been developed for user friendly experience and are flexible to support varied applications.
d. They are flexible enough to accommodate various permutations and combinations of parameters to test maximum possible scenarios.
e. They are economical and comparatively easy to maintain.

Table 6.1: Available Test-beds

Test-bed	**Hardware**	**Remarks**
TWIST	204 motes (102 TmoteSky + 102 eyesIFX) spread across 3 floors	Supports flat and hierarchical setups, node death and addition emulation, cost-effective and open solution which can be reproduced by others
INDRIYA	139 TelosB motes spread across 3 floors	Experiment prototyping with TOSSIM simulation environment, web-based interface designed based on Harvard's MoteLab interface, nodes replacement with Arduino motes
NetEye	130 TelosB motes, indoor	Static 3db attenuators are attached to mote antennas for multi-hop network and different power levels
DES-Testbed	95 nodes: embedded PC board with up to 3 802.11 cards, and wireless sensor	Virtualizer running several virtual machines that recreate the testbed topology and its lossy links. 1 mobile DES-Node node on a Roomba
Kansei	210 XSM motes: large grid-like structure of motes evenly distributed	Supports various platforms such as Extreme Scale Motes (XSMs), TelosB, Imote2 and Stargates, event injection at GW and mote level

6.5 TEST BED DESIGN

A test-bed having four sensing nodes and one base station has been designed[105]. The test bed design or creation involves developing both the hardware and the software components. The hardware comprises of the sensors, transceivers and the power source forming the nodes deployed in the field and a coordinator module connected to server (laptop in this case) which acts as Base station.

The software comprises of the firmware installed on the transceivers to function like a sensing node and on the RF module connected to the laptop to act like coordinator and finally on the base station to provide an interface to control the entire test-bed and finally process the collected data for necessary analysis and decision making. The sensor nodes are the building blocks of the sensor network. All the four sensor nodes forming the sensor network are of the same configuration and the coordinator communicates with these nodes in a star topology. From the test bed perspective, the design process has been divided into key steps represented in Figure 6.2.

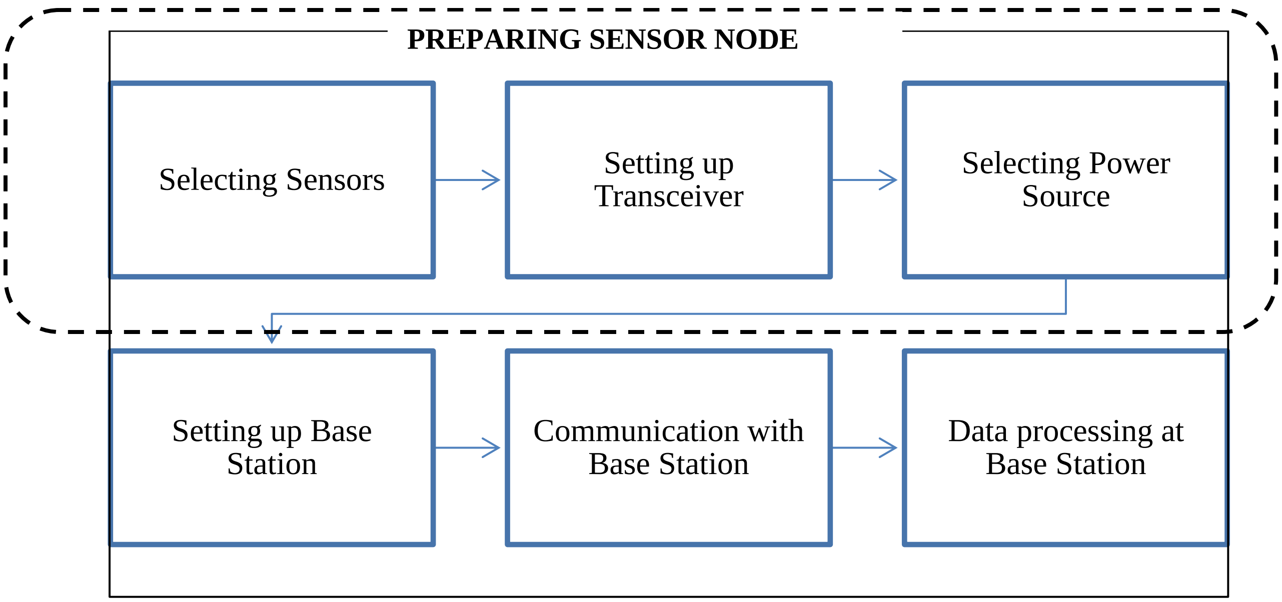
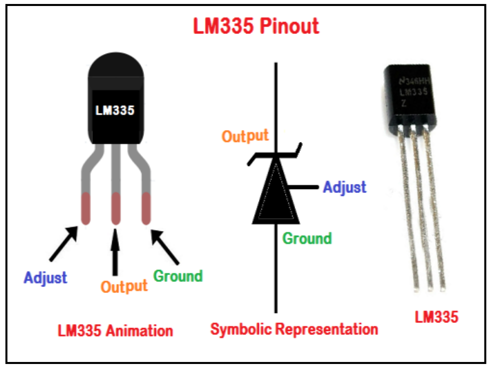
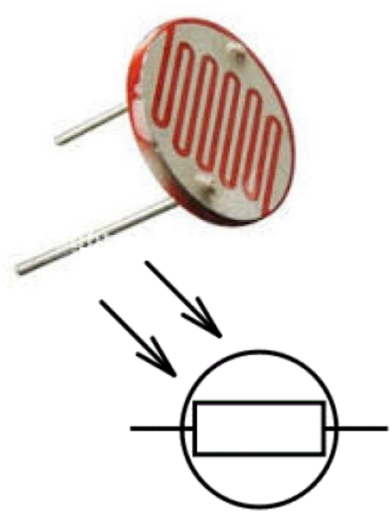


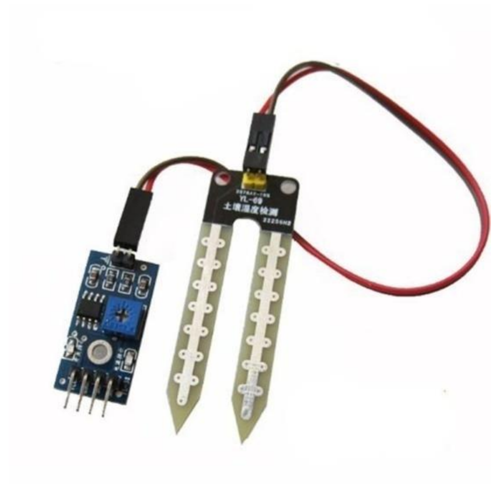
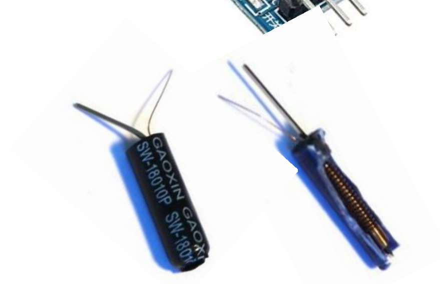
Figure 6.2: Test Bed Design

6.5.1 Selecting Sensors

The proposed test bed should be able to sense environmental parameters like Temperature, Light, Vibration and Moisture. Such a test bed will find utilization in applications like environment monitoring in buildings and monitoring status of industrial equipment for preventive maintenance etc. The details of the sensors selected for preparing the sensor nodes have been provided in the Table 6.2 below:

Table 6.2: Sensor Specifications

Temperature Sensor (LM335) ▪ Easily Calibrated/ Integrated Circuit based Temperature Sensors. ▪ Operates as 2 Terminal Zener having breakdown voltage directly proportional to absolute temperature at 10 mV/°K. ▪ Dynamic Impedance < 1Ω ▪ Operates over a current range of 400 µA to 5 mA. ▪ Has typically less than 1°C error over a 100°C temperature range. ▪ **Operating Range: −40°C to 100°C**	
Light Dependent Resistor (LDR) ▪ Is a device whose resistivity is a function of the incident electromagnetic radiation. ▪ Works on the principle of **photo conductivity -** an optical phenomenon in which materials conductivity is increased when light is absorbed by the material. ▪ Electrons get excited from valance band to conduction band when photons of enough energy fall on it and number of charge carriers is increased. ▪ Current: 75mA ▪ Operating Range: -60°C to 75°C	

<table>
<tr><th colspan="2">Sensor Specifications</th></tr>
<tr><td>Moisture Sensor
▪ Is a simple moisture sensor with Comparator LM393 chip
▪ Soil moisture module is most sensitive to the ambient humidity
▪ DO: Digital Output Interface (0 and 1)
▪ DO port output becomes high, when soil humidity exceeds a set threshold value
▪ AO: Analog Output Interface
▪ Analog output AO and AD module connected through the AD converter, give more precise values of soil moisture.
Operating voltage: 3.3V - 5V
Current: 15mA</td><td></td></tr>
<tr><td></td><td></td></tr>
<tr><td>Vibration Sensor (SW18010P)
▪ Is effectively just a delicate spring with a sturdy piece of metal in the middle.
▪ Static - Switch is open circuit (OFF) , When moved, the spring wobbles around and touches the metal, momentarily making contact.
▪ Conductive pick produces instant conductivity i.e. instant ON-state, when external force disappears, switches back to open circuit OFF-state
▪ Voltage: < 12 V, Current: <20mA
▪ Conductive time: 2ms</td><td>

</td></tr>
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6.5.2 Selecting Transceiver

After selecting the sensors, the important component is the transceiver for transmitting and receiving the sensed data. Though equipment based on wireless technologies like WiFi are easily available in Lab scenario, but in case of WSNs as the operation is required to be unattended for a prolonged duration, a transceiver with minimal power consumption is required. Therefore the ZigBee based transceivers which operate in low power applications with infrequent data transmission needs have been chosen. Though both WiFi and ZigBee can be used for similar applications as both are short range wireless technologies and share common ISM band of 2.4GHz. Both these technologies use same spread spectrum techniques. ZigBee Networks consume 1/4th of the power consumed by Wi-Fi networks. A comparison between WiFi and ZigBee has been provided in Table 6.3 below:

Table 6.3: ZigBee Vs WiFi

S. No.	ZigBee	WiFi
1.	**Operating Frequency:** 900-928 MHz and 2.4GHz. and a specific frequency of 868 MHz for European countries.	2.4GHz, 5GHz, as well as 60 GHz in some of the recent developments
2.	**Channel Bandwidth:** 1 MHz	0.3, 0.6 or 2MHz.
3.	**Network Range:** restricted to Wireless Personal Area Networks (WPAN), reaching 10-30meter in usual applications	Serve PAN and WLAN area networks with an average range between 30 to 100 meters.
4.	**Data Transfer speed:** only 250kbps	11mbps to 54 mbps
5.	**Bit Time:** 4 micro seconds	0.00185 micro seconds
6.	**Network Size:** Over 65,000 nodes in one network	Up to 2007 nodes in one network

XBee Transceiver: As discussed, ZigBee is a technical standard for communication using small, low power, digital radios for personal area networks (PAN), based on IEEE International Standard 802.15.4. It operates at 2.4 GHz and is often regarded as mini version of WiFi. XBee Transceiver is

Figure 6.3: XBee RF Module

an 802.15.4 RF module manufactured by M/s Digi International based on ZigBee technology. It is ideal for applications requiring low latency and predictable communication timing. It provides quick and easy, robust communication in point-to-point, peer to-peer, and multipoint/star configurations. The modules operate in two modes API and AT. The vital specifications of an XBee module are given at Table 6.4 below:

Table 6.4: XBee RF Module Specifications

Specification	**Value**
Range	40 m (Indoor), 120 m (Outdoor)
RF Data Rate	250 kbps
Operating Temperature	-40 to 85º C (industrial)
Operating Frequency Band	ISM 2.4 GHz
Transmit Power Output	2mW (+3dBM)
Supply Voltage	2.1 – 3.6 V
Operating Current (transmit)	35 mA (@ 3.3 Volts)
Operating Current (receive)	38 mA (@ 3.3 Volts)
Idle Current (receiver off)	15 mA
Power Down Current	< 1 µA @ 25ºC

Pin Out diagram of XBee RF Module: The Pin Out diagram of RF module is given at . As per the diagram:

- 10 Pins can be configured as Digital Inputs - for sensing switches
- Same 10 Pins can function as Digital Outputs :
- For controlling LEDs and small motors directly
- Larger loads can be operated using relays.
- First four pins can also work Analog Inputs – for sensing phenomenon that range over a scale like temperature, light etc.

- Many of these pins also perform optional duties (RSSI / ASSOC)

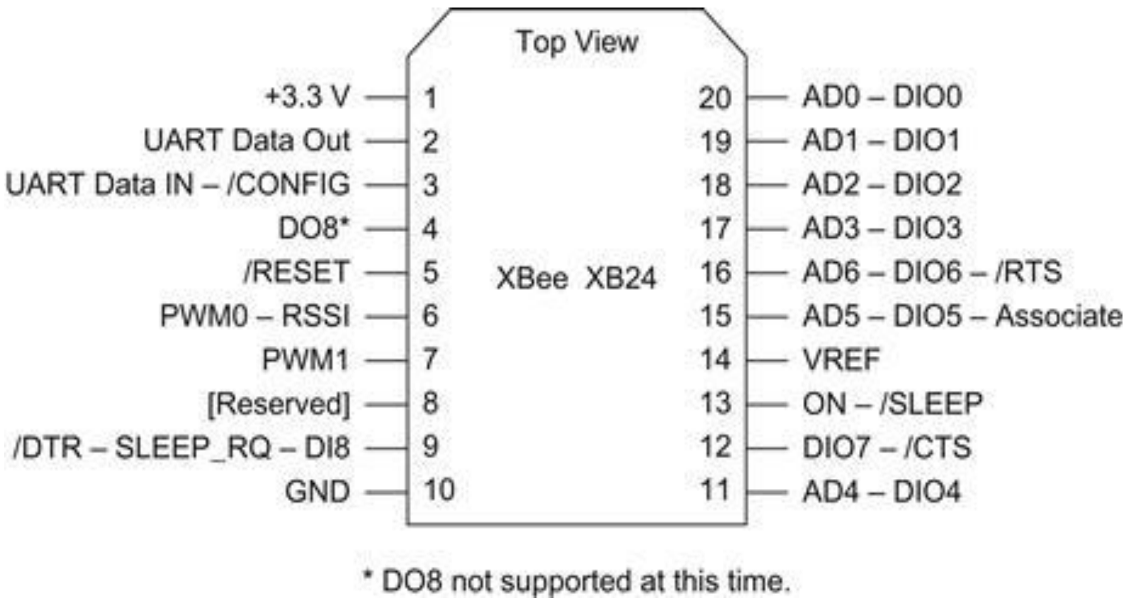

Figure 6.4: Pin –out Diagram of XBee RF Module

6.5.3 Selecting the Power Source

The criteria of selecting the Power source is that, it should have small battery size and long operating hours without sacrificing system performance. The power source should be inexpensive and similar for all the nodes. The operating voltage should be in the range of 2.1V to 3.6V.

The total energy requirement of the circuit considering the transmission and reception along with energy required by sensors can be mentioned as equation (1) below:

$$E_{TOTAL} = E_{TX} + E_{TEMP} + E_{LDR} + E_{MOIST} + E_{VIB} \quad (1)$$

In this research work two AA alkaline batteries have been used per node. The battery voltage is 1.5Volts and has a capacity rating of 2500mAh.

6.5.4 Schematic View of a Node

The detailed circuit diagram of newly designed sensor node along with all four sensors is given at Figure 6.5 below.

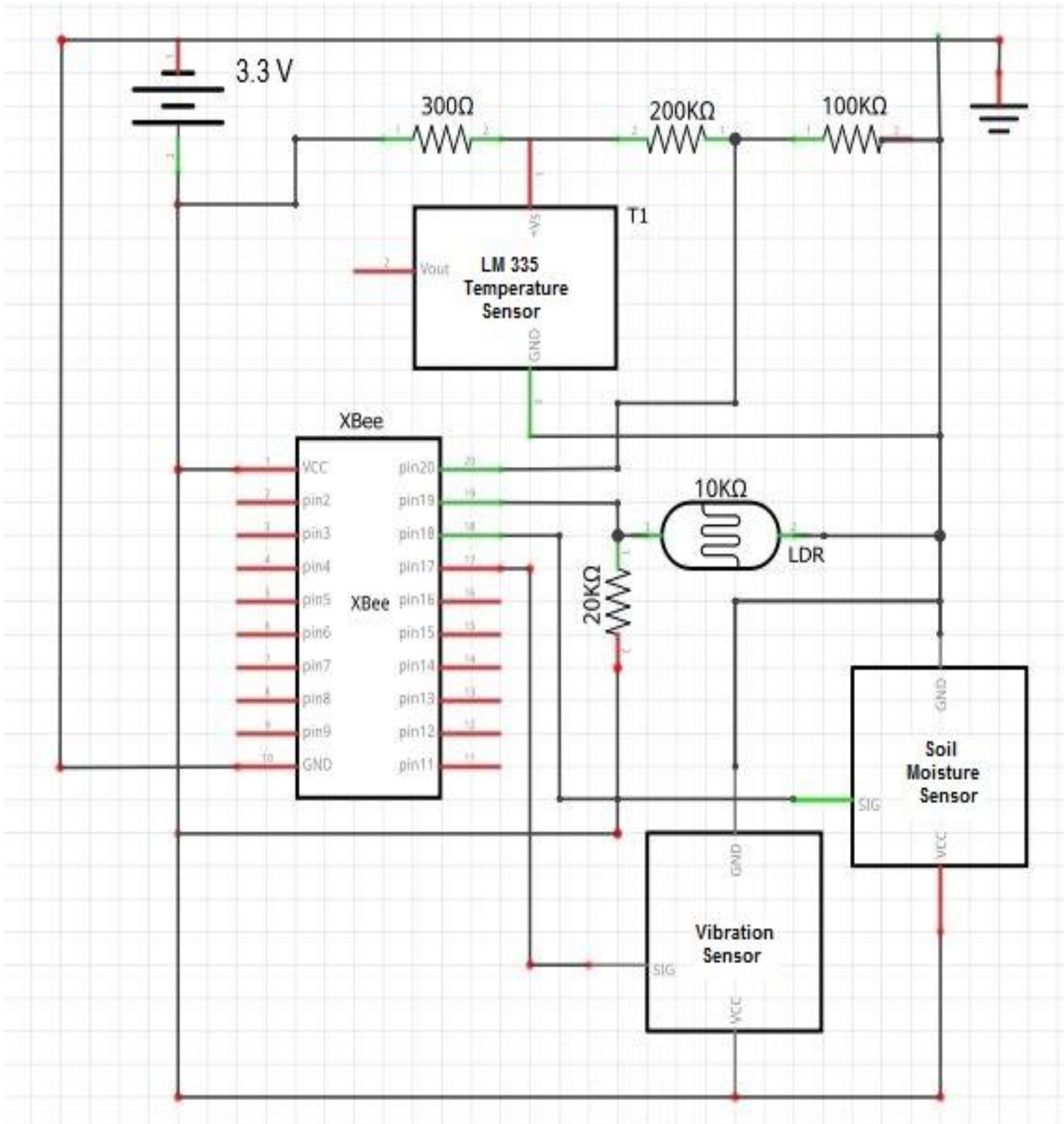

Figure 6.5: Schematic View of Sensor Node

6.5.5 Sensor Nodes in operation

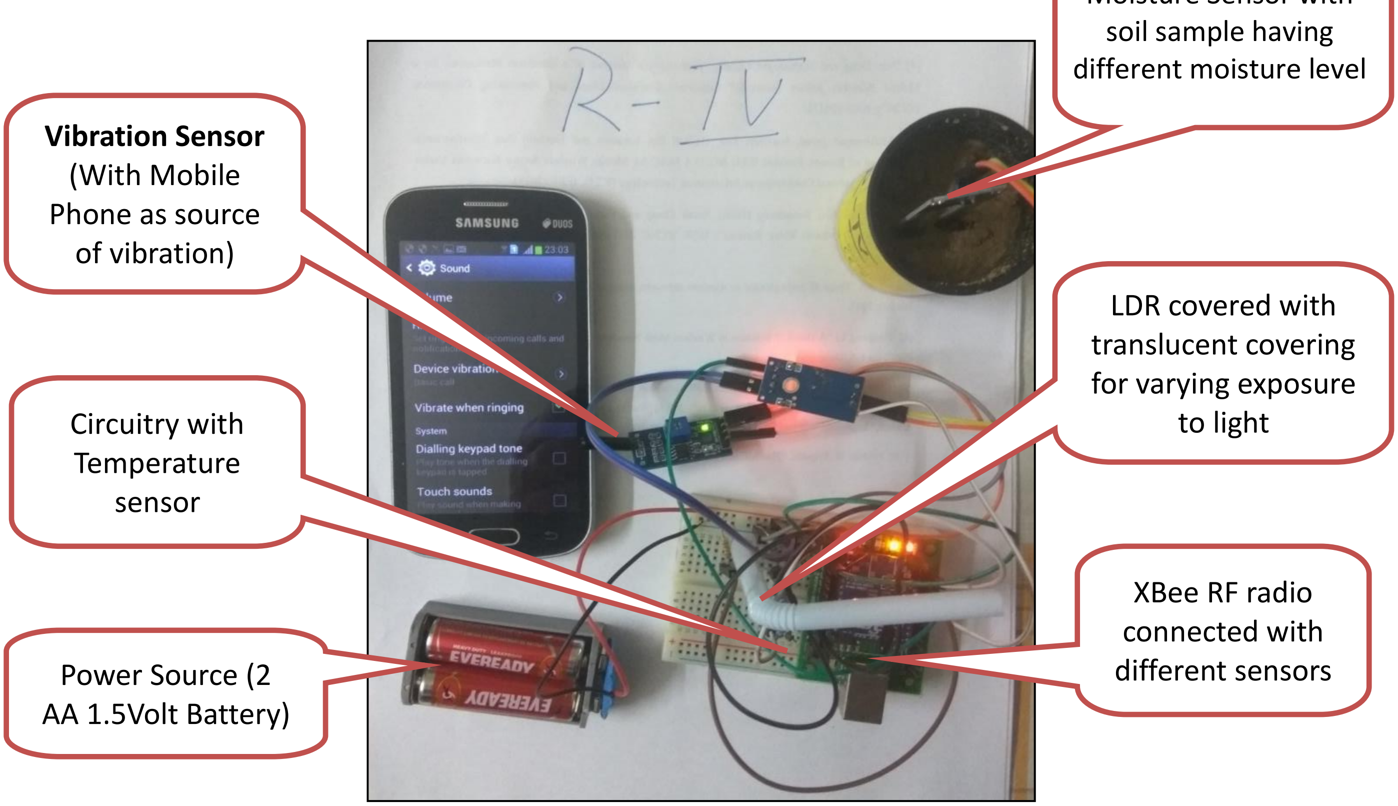

Figure 6.6: Sensor Node in Operation

Based upon the circuit diagram shown in Figure 6.5, the four sensor nodes have been prepared and have been deployed in a building to measure the values of different parameters at different locations.

- To measure the temperature difference, the nodes have been placed in different locations having varying temperature.
- For the purpose of moisture variation, probes have been dipped into containers with mud having different moisture content.
- The illumination on LDR has been varied using coverings of differing opacity.
- The vibration sensor has been activated using source of vibration like ringing phone at different locations.
- It may be noted that as the purpose of the test-bed is to evaluate the proposed energy efficiency algorithm, hence same has been focused in the research work.

6.5.6 Base Station

A Windows based laptop has been used as a base station. The laptop has been made the part of the sensor network by interfacing it with a XBee RF module which acts as a coordinator. The sensor nodes sense the data and pass it on to the coordinator. Further in the later part of the experiment, on cluster formation, the cluster heads are selected which collect the data from the sensor nodes and transmit the data to the base station.

The Figure 6.7 below shows the XCTU interface for configuring the RF modules as Coordinator, Router or End point. In the present research work, the coordinator has been interfaced using XCTU at COM4 to communicate with the program written in Java for handling test bed operations.

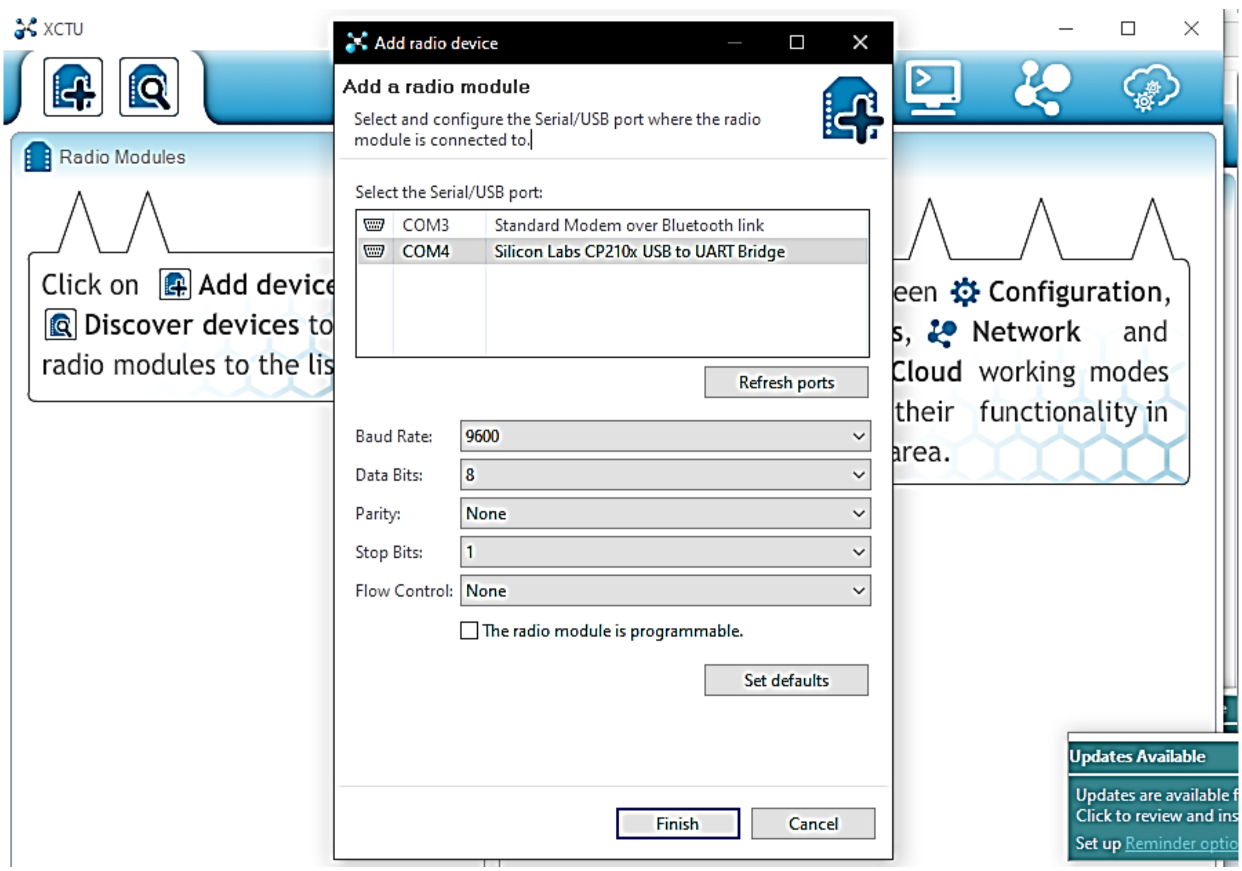

Figure 6.7: XCTU Interface for configuring XBee RF modules

6.5.6.1 Software Interface at Base Station

The test bed operations are handled through software interface prepared during the research work. The software has been developed using the Java programing language utilising the Digi XBee library available from the OEM for XBee RF modules. The software is executed on the base station and following main functions:

1. The software handles the network discovery of the nodes and enables the sensor nodes to form the sensor network.
2. The interface provides the functionality to operate the network in different modes and set custom parameter values.
3. The data collected by the sensor nodes i.e. the temperature, value of moisture, vibration, and light intensity along with the node id, residual battery voltage, node address, timestamp and destination details (Cluster head or sink) are transmitted to the base station.
4. The battery voltage level is recorded for each individual node, which is used for determining residual energy of the node. Based upon the residual energy the Cluster Head is selected in accordance to the proposed protocol i.e. HC-WSN.
5. After assignment of the cluster heads, the nodes transmit the data to the cluster head and subsequently to the sink.
6. The Hibernation mode is induced in the nodes with residual battery voltage below a lower and upper threshold values as per the HC-WSN.
7. The data regarding voltage level, sensing data along with timestamp is collected at the base station, which is stored in the form of text files on the hard disk of the laptop.

The data thus collected in different scenarios is analysed for evaluating the different energy efficient methodologies implemented on the test-bed.

The Figure 6.8 below shows the test-bed along with base station in operation with all the four sensor nodes communicating with the base station through RF transceivers.

Test-bed in operation

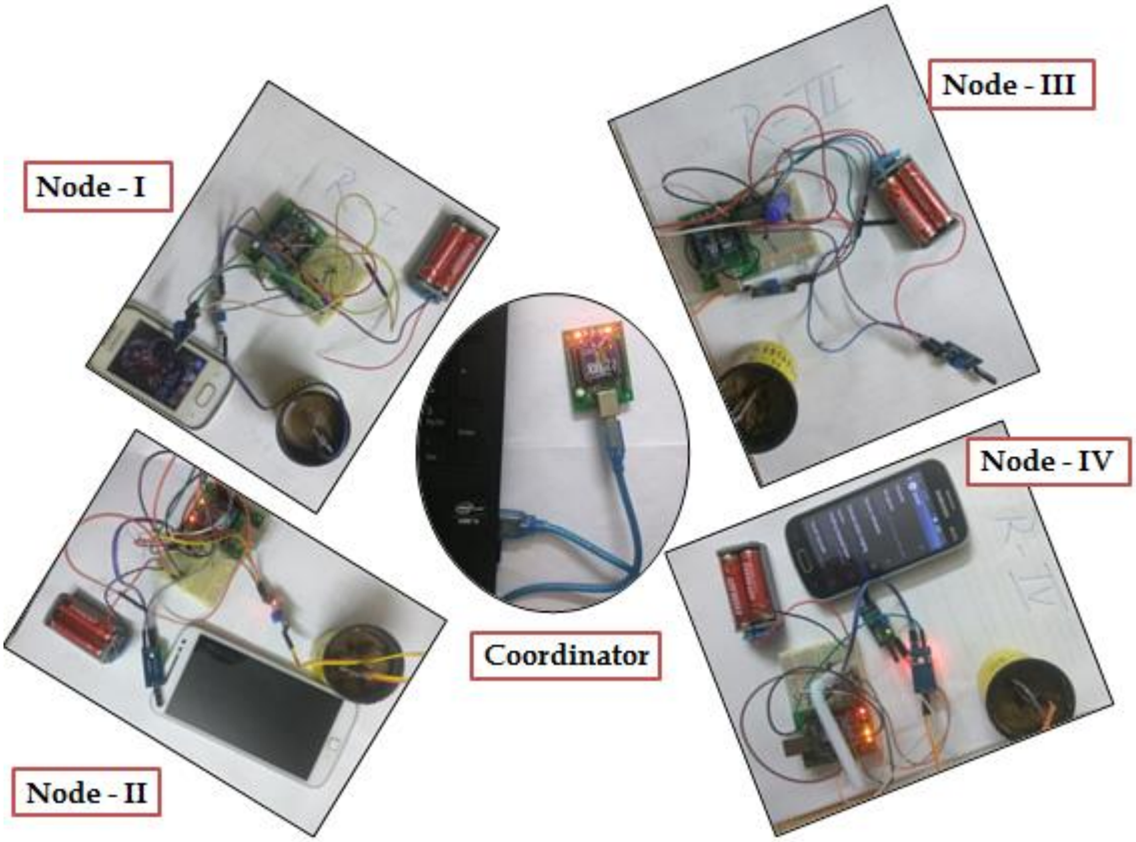

Figure 6.8: Test Bed in Operation

6.6 TESTBED IMPLEMENTATION

As both hardware and software are ready, the algorithms are implemented on the Test-bed to validate the results of the proposed algorithms. For this an implementation plan has been developed and entire implementation has been divided into four different scenarios. The details are:

Implementation Plan

- **Scenario – I : Network Discovery**
- **Scenario – II : Inducing the Sleep mode**
- **Scenario – III : Cluster Based Approach**
- **Scenario – IV : HC-WSN implementation**

6.6.1 Scenario – I : Network Discovery

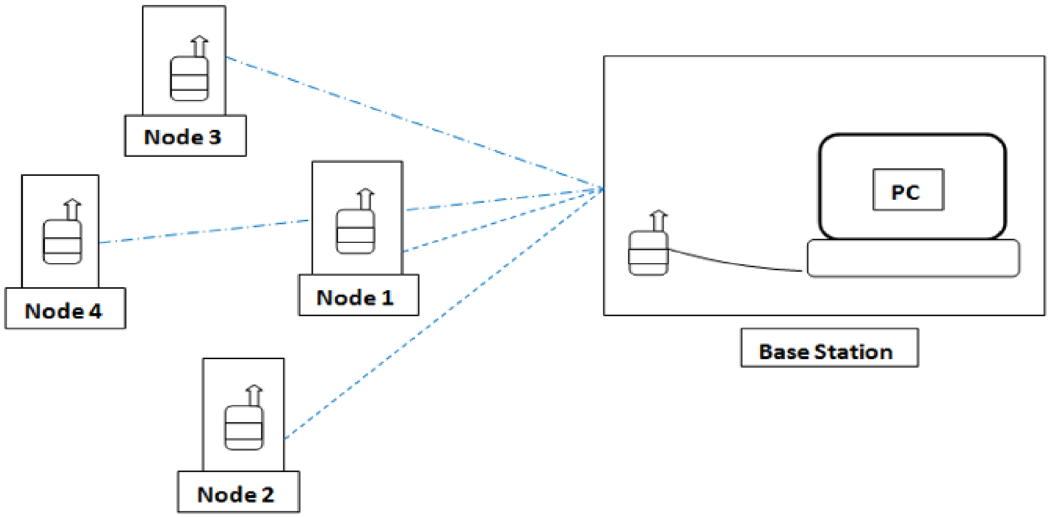

Figure 6.9: Scenario I: Node Discovery

Under Scenario – I, the nodes are spread into different locations in the building for sensing the environmental parameters of temperature, moisture, vibration and light. As soon as the node is powered on, the LED connected with the PIN-13 of the RF module lights on indicating the Power ON status. Node discovery process is initiated from the coordinator connected to the base station. As the node gets associated in the network the ASSOC indiacator (LED connected with PIN-15) starts blinking.

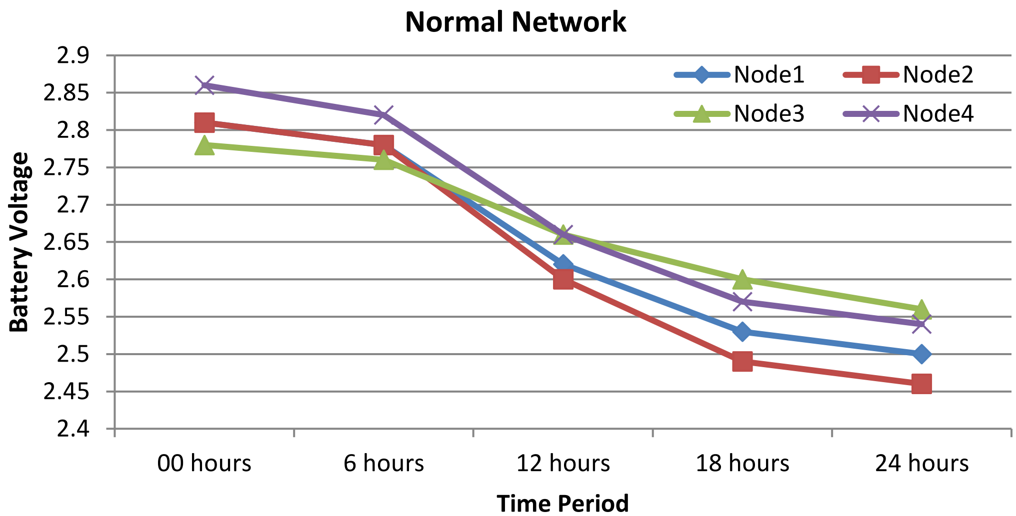

Figure 6.10: Scenario –I: Normal Network, Battery Voltage

A star topology as indicated in Figure 6.9 above is established and all the nodes start communicating directly with the sink through the coordinator. The nodes start sending data to the base station at fixed intervals.The sensed parameter values, residual voltage level of the power source and node Id is collected at the base station along with the time stamp.The timestamp vs residual voltage data for all the four nodes is processed for further analysis (Figure 6.10) and comparision with proposed energy efficiency algorithms. Further, Figure 6.11 below indicates the variation in residual Energy at individual nodes over period of time.

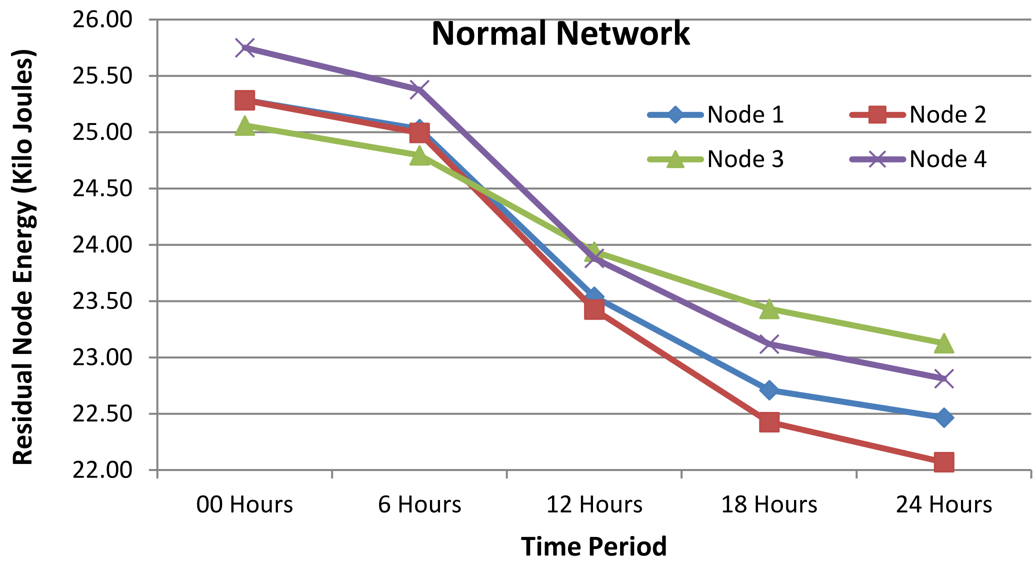

Figure 6.11: Scenario –I: Normal Network – Residual Node Energy

6.6.2 Scenario – II : Inducing the Hibernation(Sleep) mode

The implementation under Scenario – II has been undertaken to test the impact of sleep mode on the network. The experiment is strarted with set of fresh batteries for each node. Out of the four nodes, two nodes i.e. (Node 1) and (Node 2) have been induced the sleep mode and two operate in the normal mode.The sensing data along with residual voltage value at each node is transmitted to the base station.

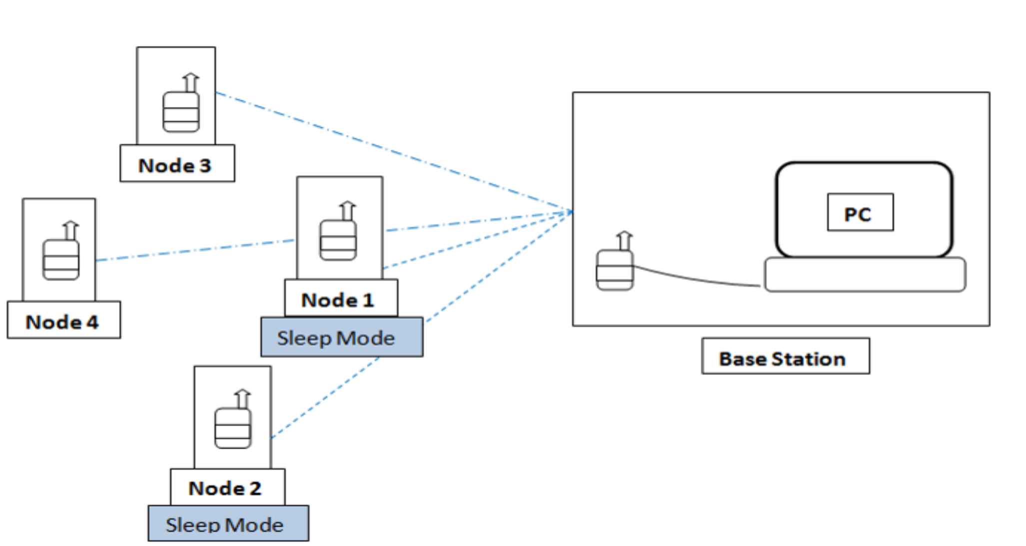

Figure 6.12: Scenario –II: Inducing Sleep Mode

The data collected at the base station is analysed and compared. A graph has been plotted for voltage versus time elepsed for all four nodes as per Figure 6.13 below. From the graph it has been seen that voltage level of the two nodes for which the sleep mode was not induced reduces at a much faster pace than the nodes in which the sleep mode was introduced.

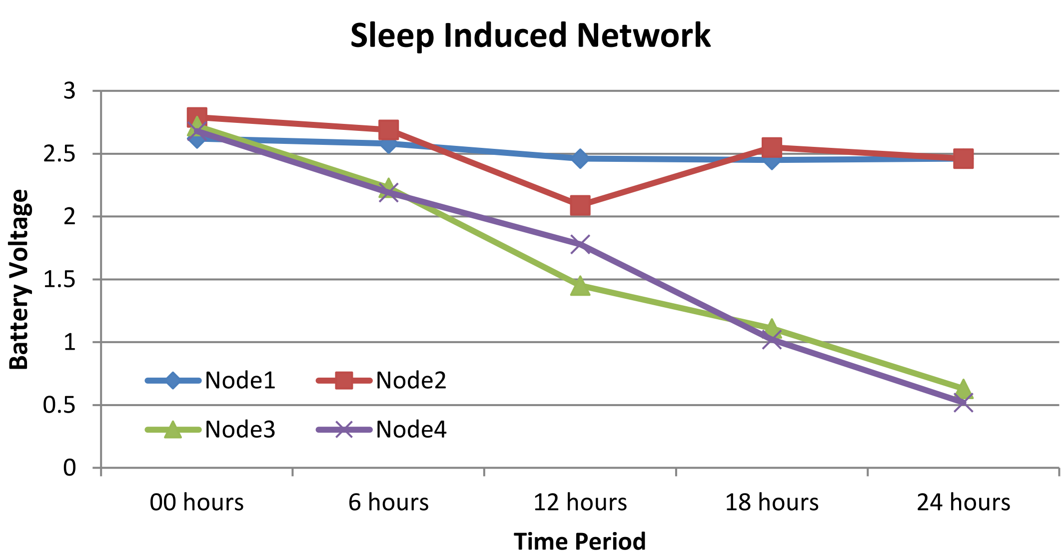

Figure 6.13: Impact of Sleep Mode, Battery Voltage

Further, Figure 6.14 below indicates the variation in residual Energy at individual nodes over period of time. This graph is similar to voltage level graph above and indicates that the residual energy of the two nodes for which the sleep mode was not induced reduces at a much faster pace than the nodes in which the sleep mode was introduced.

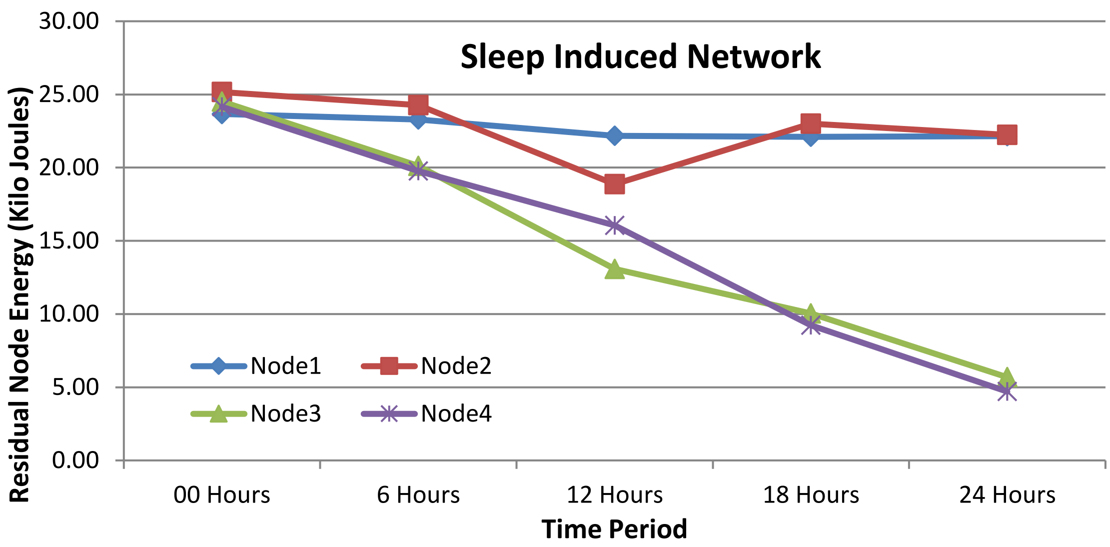

Figure 6.14: Impact of Sleep Mode– Residual Node Energy

6.6.3 Scenario – III : Cluster Based Approach

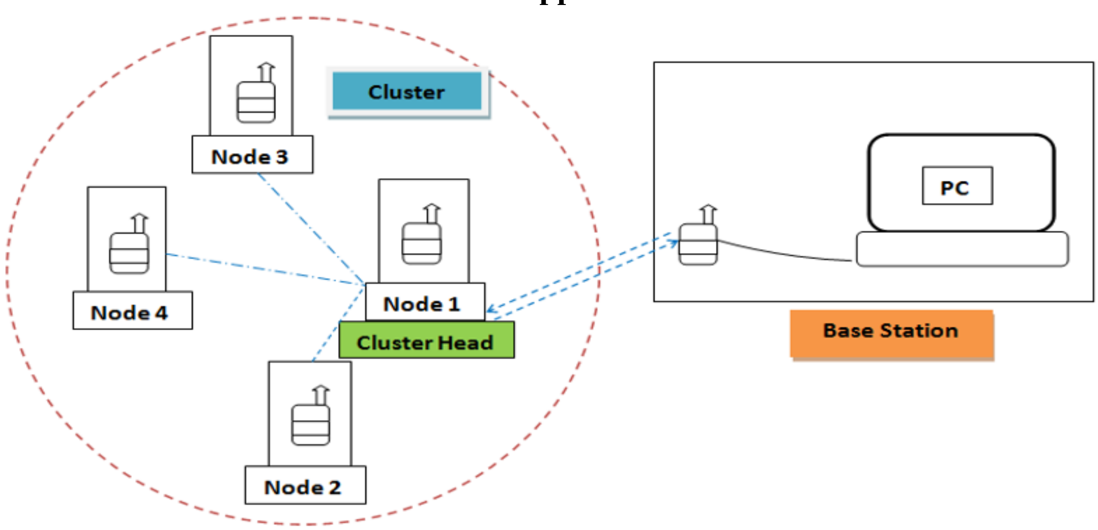

Figure 6.15: Scenario – III: Cluster Based Approach

In the Scenario –III, Clustering has been introduced in the existing network (with fresh batteries), maintaining the same topology.

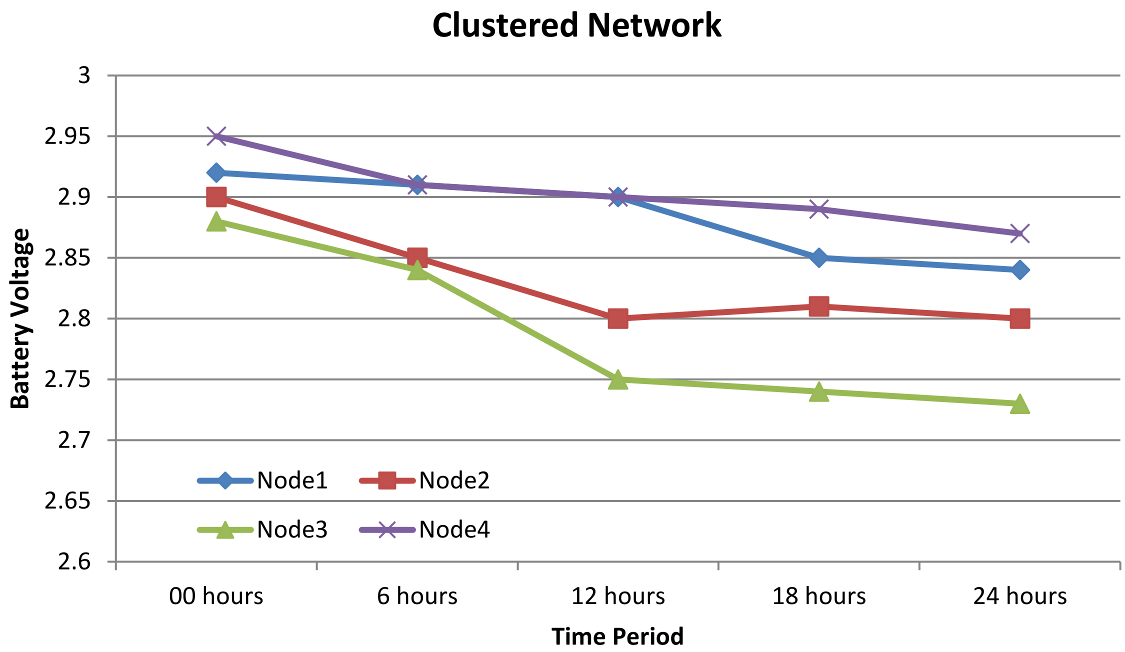

Figure 6.16: Impact of Cluster based approach

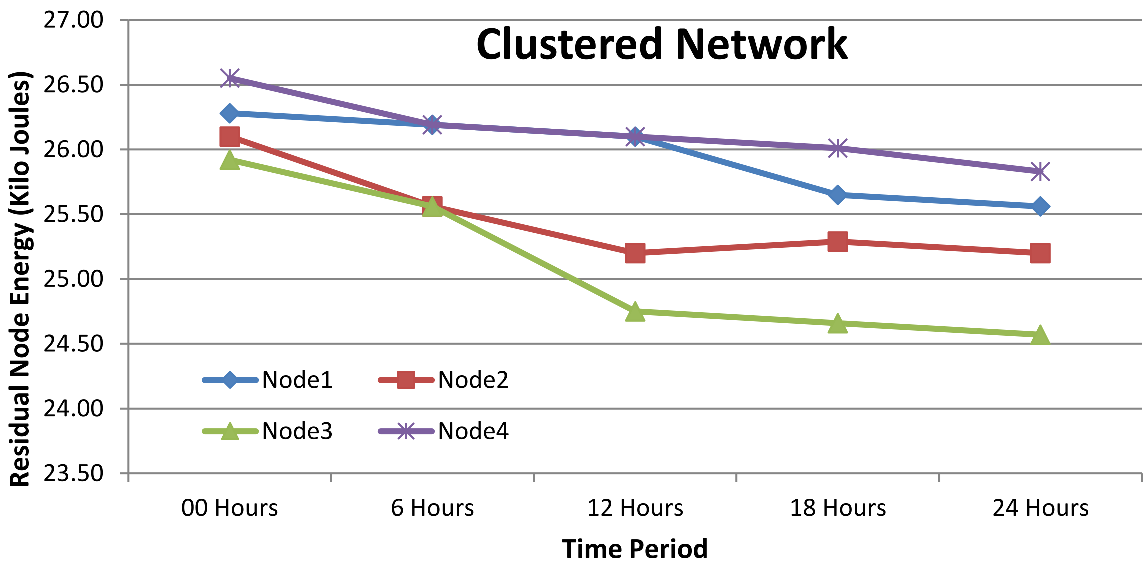

Figure 6.17: Impact of Cluster based approach on residual Energy of Nodes

As soon as the nodes are powered on, a network is formed after the Node Discovery from the Base station and sensor node wise battery voltage data is received at the base station. The battery voltage data is used to determine the node with the highest residual energy. The node with the highest residual energy is chosen as cluster head and the remaing three sensor nodes start transmitting the data to the cluster head. The cluster head transmits the sensing data received to the base station.The voltage level at different sensor nodes is measured after fixed interval of time and it has been found that the voltage at the nodes reduces at a much slower pace and life time of the network is enhanced.The cluster head selection is a continuous process and cluster head role is rotated across all the nodes. Figure 6.16 and Figure 6.17 show that residual voltage levels and residual energy levels are higher in a clustered network than in nomal network after the same time interval.

6.6.4 Scenario – IV : HC-WSN implementation

In this scenario, the sleep mode (Hibernation) has been introduced along with clustering to further minimise the energy consumption.The block diagram in Figure 6.18 demonstrates the stages of experiment.

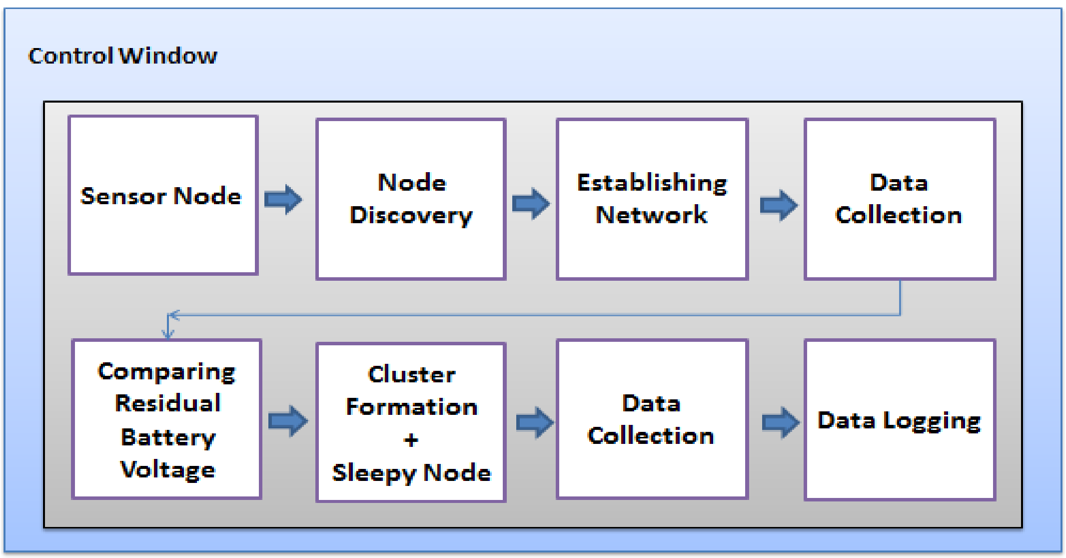

Figure 6.18: HC-WSN Implementation Block Diagram

As the nodes are powered on, node discovery takes place and the network is established. The node with the highest residual eenergy and voltage above upper threshold value is made the Cluster Head. On the other hand nodes with energy level below the lower threshold values are declared as dead.The nodes having the voltage level between the upper threshold and lower threshold values are the nodes which perform the sensing operation. Sleep or Hibernation mode is induced in these nodes for fixed number of rounds.

The cluster formation, cluster head selection and hibernation is a continuous process. The node wise residual voltage data is collected at the base station and node wise energy is worked out, graphs indicating analysis are shown in Figure 6.20 and Figure 6.21. It has been found that the energy consumption at nodes is further decreased leading to enhanced life time of the network.

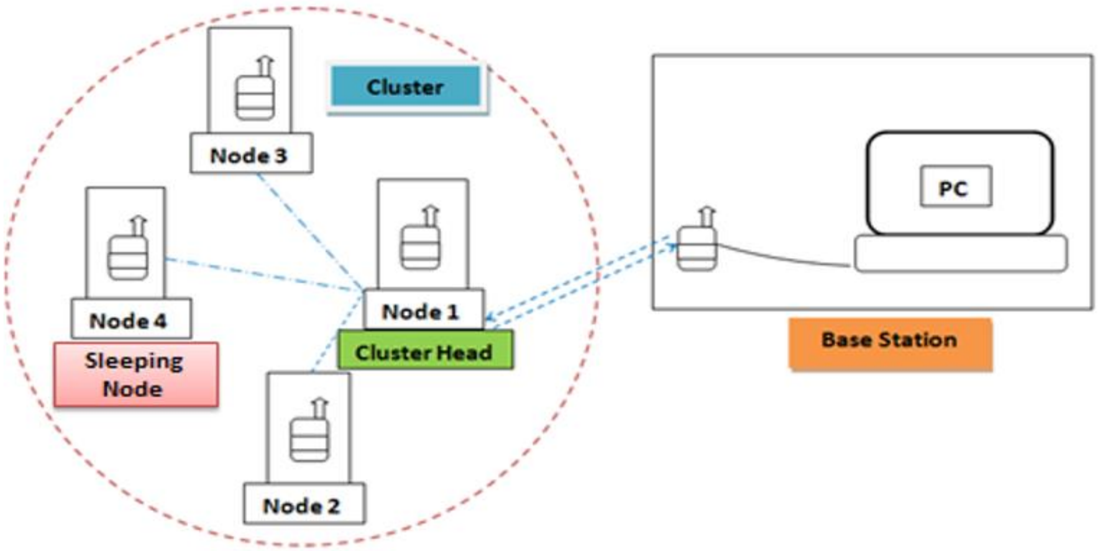

Figure 6.19: Setup Diagram for HC-WSN

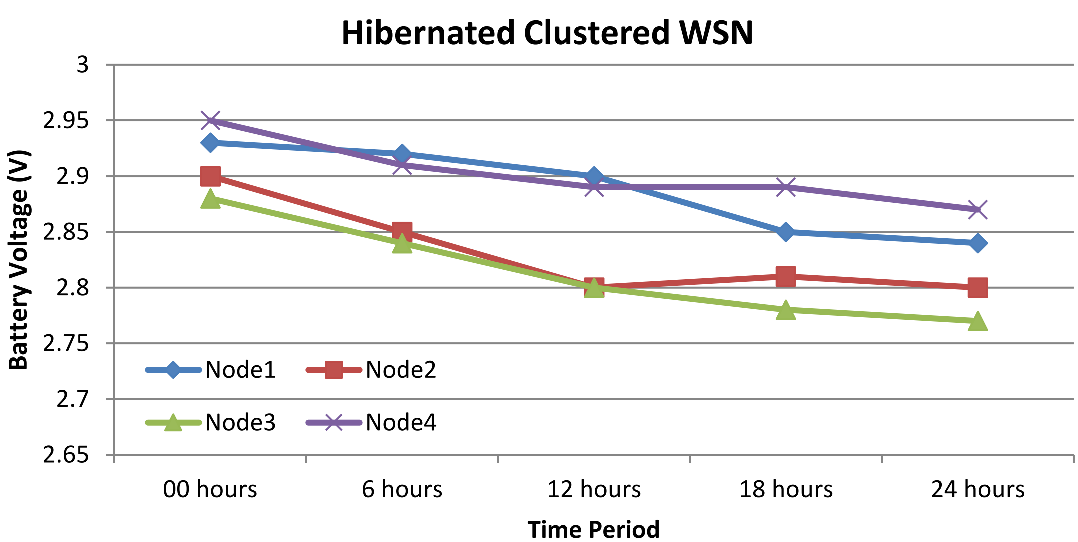

Figure 6.20: Impact of HC-WSN approach - Battery Voltage

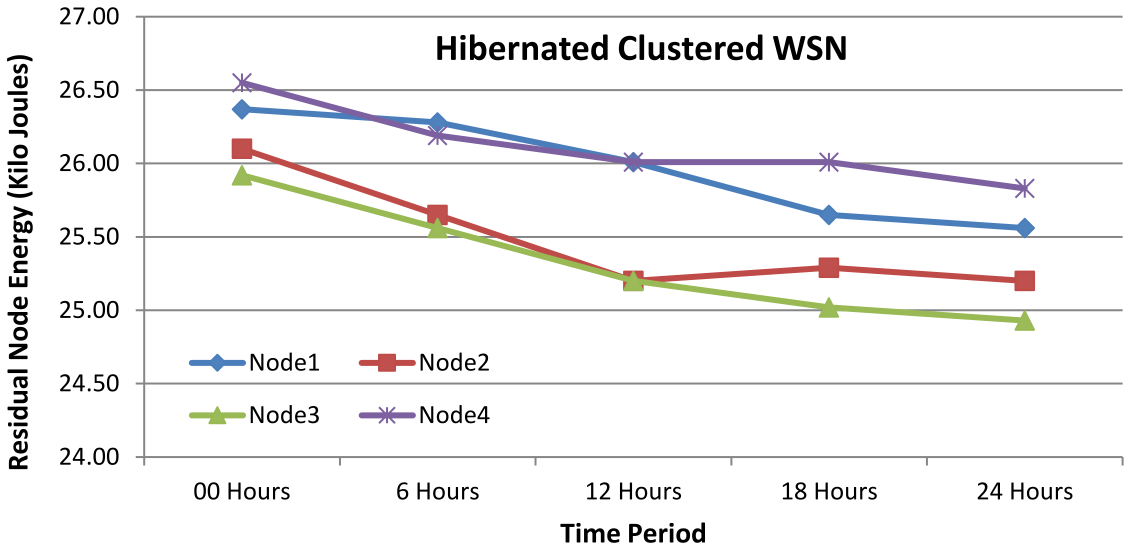

Figure 6.21: Impact of HC-WSN approach- Residual Node Energy

6.7 FINANCIAL ASPECTS

Cost or financial implication is an important aspect to consider while evaluating a proposed solution. The cost of hardware components for this experimental Test bed comprising of four nodes and coordinator has been presented in the Table 6.5: Cost of Hardware components for Test-bed below. Also, the approximate cost of individual sensor node has been arrived at Rs1575/- and the details are given in Table 6.6 below.

Table 6.5: Cost of Hardware components for Test-bed

S. No.	Components	Rate (Rs.)	Qty.	Amount
1	XBee Radio Module	850	5	4250.00
2	USB Adaptor for XBee Radio	250	4	1000.00
3	LM335 Temperature Sensor	25	4	100.00
4	LDR	10	4	40.00
5	Soil Moisture Sensor	150	4	600.00
6	Vibration Sensor	150	4	600.00
7	AA Battery Holder	50	4	200.00

8	AA Batteries	10	8	80.00
9	Breadboard	70	4	280.00
10	Resistances (Box)	30	1	30.00
11	Jumper Wires (Set)	50	1	50.00
12	USB Cable (A to B)	50	1	50.00
Total				**Rs.7280.00**

Table 6.6: Cost of single Sensor Node

S. No.	Components	Rate (Rs.)	Qty.	Amount
1	XBee Radio Module	850	1	850.00
2	USB Adaptor for XBee Radio	250	1	250.00
3	LM335 Temperature Sensor	25	1	25.00
4	LDR	10	1	10.00
5	Soil Moisture Sensor	150	1	150.00
6	Vibration Sensor	150	1	150.00
7	AA Battery Holder	50	1	50.00
8	AA Batteries	10	2	20.00
9	Breadboard	70	1	70.00
Total				**Rs. 1575**

6.8 SUMMARY

The chapter covers in detail development of an experimental test bed. All aspects starting with identifying the requirement, selection of components, assembly of components and development of sensor nodes has been covered. The proposed protocol HC-WSN has been implemented on this testbed and results are found to be in line with simulation outcomes.

CHAPTER VII

CONCLUSIONS AND FUTURE SCOPE

Research and innovation is a journey towards betterment of human existence. The present research work has been undertaken with the same spirit in order to make contribution to the society. In the present research work a new protocol – "*Hibernated Clustering Wireless Sensor Networks (HC-WSN)*" has been developed to improve energy efficiency in operations of wireless sensor networks. In the form of HC-WSN, an energy efficiency framework has been defined which takes into consideration the energy consumption aspects of a wireless sensor network and proposes measures to improve upon processes to bring in an energy efficient and long lasting wireless sensor network.

7.1 CONCLUSIONS

The research work was taken up with objectives in order to achieve the goal of "*Analysis and Implementation of Energy Efficient Wireless Sensor Networks*". At the onset of the research work, research challenges in the field of wireless sensor networks along with their need and applications have been understood to gain knowledge about specific characteristics of the technology, the challenges being faced in the implementation and prominent researches undertaken in the field have been studied.

Out of numerous constraints on WSN operations, the energy efficiency of the wireless sensor networks has been focused for this research work. It has been found that factors like node density, network topology, handling collisions, scalability and quality of service greatly impact the energy efficiency of these networks. A study of these factors along with energy consumption aspects at the level of sensor node has been done and it has been concluded that the energy consumption is maximum for communication operations.

As part of the literature survey, various research works undertaken in the field of improving energy efficiency have been reviewed and based on the energy consumption aspects, along with the work done, a new clustering-based routing protocol has been proposed. The proposed protocol HC-WSN has following key features:

1. It is a hierarchical clustering-based routing protocol for energy constrained wireless sensor network nodes.
2. It takes into account the heterogeneity of nodes in a wireless sensor network; therefore, it is not mandatory for the constituent nodes to have same initial energy (E_{0i}– indicates initial energy for i^{th} node in the network).
3. It follows distributed clustering, and nodes are free to form clusters based on their vicinity (inter node distance *d*) with each other.
4. The member nodes of the cluster select among themselves, a cluster-head which is a sensor node having maximum residual energy, higher than the pre-defined E_{UTH} (Upper Threshold Energy). In case of conflict, the choice of Cluster Head is based on First in First out (FIFO) method.
5. Formation of clusters minimizes number of transmit / receive operations by making respective cluster heads responsible to communicate with destination.
6. The member nodes in cluster are responsible for sensing operation. Hibernation (sleep) is induced in a fraction of member nodes to minimise energy consumption and enhance network life time. Such nodes become Active after a fixed interval.
7. Nodes having energy less than Lower Threshold value are declared as "Dead". Such nodes do not form the part of network and isolating them well in time save the network from unnecessary communication overheads.
8. To reduce the communication overhead on account of selection of cluster-heads; cluster heads for all the clusters are not selected afresh in each round. The new cluster formation method is initiated based upon the residual energy of the current cluster-head in comparison to the threshold energy E_{UTH} defined for cluster heads.
9. The proposed protocol attempts to address the issue of ideal positioning of sink as static or mobile on a circular path with in the observation field.
10. HC-WSN takes advantage of the node density to minimise energy consumption. In case of high node density, dynamic sub-clusters with in the clusters are formed. This eliminates the redundant sensing inputs and contributes towards improving overall network life time.

To evaluate the proposed protocol, the need of simulating this proposed algorithm was felt. Accordingly various available simulation tools like QualNet, TOSSIM and MATLAB etc. were surveyed and MATLAB due to its user-friendly interface was selected. This approach has been compared with already established LEACH and recently proposed H-LEACH protocols.

Subsequently, to get real time experience on WSNs, a WSN test bed has been designed with the help of Zig Bee radios acting as transceivers, different sensors to detect environmental parameters and batteries as power source. The different phases undertaken to develop the proposed protocol have been implemented on this experimental testbed to gain practical insight into the working of WSN.

With this all the objectives laid down for this research work have been achieved.

7.2 CONTRIBUTION OF RESEARCH WORK

This research work contributes in multi-dimensional ways with following two tangible outcomes:

i. The work proposes a new energy efficient clustering-based routing protocol for improving life time of Wireless Sensor Networks.
ii. The work also provides with a prototype of sensor network test bed which can be used for carrying out experiments before making the changes in live / real time applications.

Apart from this, the research work has been a great learning experience with exposure to energy consumption aspects of Wireless Sensor Networks. Though the field is vast and is rapidly expanding, still the work done gives a good command over this amazing technology.

The work started with understanding the concepts of wireless sensor networks, their unique features like continuous unattended operation in inaccessible hostile environment. It covered study of numerous WSN applications to correlate the theory with the real time applications. It is worth mentioning that this work provides the much-needed motivation to dive deeper in the field of Wireless Sensor Networks with an objective to further improve operational efficiency, so that economical solutions can be innovated within the country itself for quick implementation of projects like Smart Metering and Internet of Things. These technologies can be truly termed as enablers for many good governance services in a large country like India.

7.3 SCOPE FOR FUTURE WORK

WSN will be one of the important components of the future automated offices, homes and factories. It will also be an important component of support systems for humans. Therefore, the field has immense research potential. Research contribution is required to be made in areas like improving the scalability and security of data transmission in Wireless sensor Networks.

- The current research work can also be improved further in terms of optimizing the cluster size and the predefined threshold values.
- In the future research work, the energy consumption in setup phase for cluster formation can be explored and optimized.
- During this research work, a need for automating test-bed reprogramming and experiment scheduling is felt which can be fulfilled by augmenting the test-bed with some job scheduling software, similar to the software for cluster computers which will enable concurrent access to multiple users.
- Areas like improving scalability and security of data transmission have immense research potential.
- In the near future variety and concentration of wireless devices is bound to increase and thus the requirement of low power wireless protocols
- The field of Wireless Sensor Networks has scope in upcoming technologies viz. Cognitive Sensing, Swarm Intelligence.

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BRIEF BIO DATA OF THE RESEARCH SCHOLAR

Sonam Khera (sonamkhattar23@gmail.com) received the M.Tech. and B.Tech. degrees in Electronics and Communication Engineering from Maharshi Dayanand University, Rohtak in the years 2007 and 2002 respectively. She joined J. C. Bose University of Science and Technology in the year 2008 as Assistant Professor in Department of Electronics Engineering. She is pursuing Ph.D in the field of Energy Efficient Wireless Sensor Networks. Her research interests include Security and Energy Efficiency of Wireless Sensor Networks, Wireless Communications and Internet of Things.

LIST OF PUBLICATIONS OUT OF THESIS

List of Published Papers in International Journals

S. No.	Title of Paper	Name of Journals	No.	Volume and Issue	Year	Pages
1	A practical approach to Energy Consumption in Wireless Sensor Networks ***Authors***: Sonam Khera, Dr. Neelam Turk, Dr. Navdeep Kaur	International Journal of Advanced Intelligence Paradigms, from Inderscience Publishers (**SCOPUS**)	ISSN online 1755-0394	Volume 16, Number 2, 2020 **DOI:**10.1504/IJAIP.2018.10009335	2020	190-202
2	MQTT protocol employing IOT based home safety system with ABE encryption ***Authors:*** Vatsal Gupta, Sonam Khera, Dr. Neelam Turk	Multimedia Tools and Applications from Springer **(SCIE)**	ISSN online 1573-7721	**DOI:**10.1007/s11042-020-09750-4	2021	-
3	Enhancing Network Coverage using Handoff Techniques in Mobile Wireless Sensor Networks ***Authors***: Sonam Khera, Dr. Neelam Turk, Dr. Navdeep Kaur	International Journal of Future Generation Communication and Networking (IJFGCN) under SERSC **SCOPUS and ESCI**	ISSN 2233-7857	Volume 10, Number 10, 2017 **DOI:**10.14257/ijfgcn.2017.10.10.02	2017	23-31
4	Energy Harvesting Aspects of Wireless Sensor Networks: A Review ***Authors***: Sonam Khera, Dr. Neelam Turk, Dr. Navdeep Kaur	International Journal on Recent and Innovation Trends in Computing and Communication (IJRITCC),	ISSN: 2321-8169	May 17 Volume 5 Issue 5	2017	875 – 878
5	Applications and Challenges in Wireless Sensor Networks ***Authors***: Sonam Khera, Dr. Neelam Turk, Dr. Navdeep Kaur	International Journal of Advanced Research in Computer and Communication Engineering (IJARCCE)	ISSN (Print) 2319 5940	Vol. 5, Issue 6, June 2016 **DOI**: 10.17148/IJARCCE.2016.5694	2016	448-451

List of Papers Presented in National/ International Conferences

S. No.	Title Paper and Authors	Name of Conferences	Remarks
1	Handoff Techniques in Wireless Sensor Networks ***Authors***: Sonam Khera, Dr.Neelam Turk, Dr. Navdeep Kaur	International Conference on Sustainable Development through Research in Engineering and Management (SDREM-16), YMCAUST, Faridabad (December 26-27, 2016)	
2	Energy Efficiency of Wireless Sensor Networks. ***Authors***: Sonam Khera, Dr.Neelam Turk, Dr. Navdeep Kaur	International Conference on Emerging Trends in Engineering and Management (ICETEM-12), SGI, Rohtak. (23-24 June, 2012)	
3	A Review of ZigBee Technology ***Authors***: Sonam Khera, Dr.Neelam Turk, Dr. Navdeep Kaur	International Conference on Paradigm Shift in Management and Technology (PSIMT-2015), YMCAUST, Faridabad (April 9-10, 2015)	
4	A Comparative Study of Simulation Tools For Wireless Sensor Networks ***Authors***: Sonam Khera, Dr.Neelam Turk, Dr. Navdeep Kaur	New Horizons in Technology For Sustainable Energy and Environment (NHTSEE-2017), YMCAUST, Faridabad (9-10 March, 2017)	
5	Future approach to Mobile Communication Technologies ***Authors***: Sonam Khera, Dr.Neelam Turk, Dr. Navdeep Kaur	Symposium on Nanotechnology: Interdisciplinary Aspects, YMCAUST, Faridabad. (December 12, 2016)	
6	Wireless Sensor Networks – An Energy Consumption Perspective ***Authors***: Sonam Khera, Dr.Neelam Turk, Dr. Navdeep Kaur	National Conference on Role of Science and Technology Towards 'Make in India' (RSTTMI-16) YMCAUST, Faridabad (March 05-07, 2016)	
7	Wireless Sensor Networks Security Issues ***Authors***: Sonam Khera, Dr.Neelam Turk, Dr. Navdeep Kaur	Workshop on Nanotechnology and Embedded Systems, YMCAUST, Faridabad. (23rd July – 3rd August,2012)	

ANALYSIS AND IMPLEMENTATION OF ENERGY EFFICIENT WIRELESS SENSOR NETWORKS

Summary of Thesis

Submitted in fulfillment of the requirement of the degree of

DOCTOR OF PHILOSOPHY

to

J.C. BOSE UNIVERSITY OF SCIENCE AND TECHNOLOGY, YMCA

by

SONAM KHERA

(Registration No. - YMCAUST/Ph 22/2011)

Under the Supervision of

Dr. NAVDEEP KAUR
Professor
SGGSWU, Fatehgarh Sahib

Dr. NEELAM TURK
Professor
J.C. Bose UST, YMCA, Faridabad

DEPARTMENT OF ELECTRONICS ENGINEERING
Faculty of Engineering And Technology
J.C. Bose University of Science And Technology, YMCA
Sector-6, Mathura Road, Faridabad, Haryana, India

October, 2021

CANDIDATE'S DECLARATION

I hereby declare that this thesis entitled "**ANALYSIS AND IMPLEMENTATION OF ENERGY EFFICIENT WIRELESS SENSOR NETWORKS**" by **SONAM KHERA** being submitted in fulfilment of the requirements for the Degree of Doctor of Philosophy in ELECTRONICS ENGINEERING under Faculty of ENGINEERING AND TECHNOLOGY of J.C. BOSE University of Science and Technology, YMCA, Faridabad during the academic years 2020-21 is a bona fide record of my original work carried out under guidance and supervision of **Dr. NEELAM TURK, PROFESSOR, DEPARTMENT OF ELECTRONICS ENGINEERING,** J.C.BOSE UNIVERSITY OF SCIENCE AND TECHNOLOGY, YMCA, FARIDABAD and **Dr. NAVDEEP KAUR, PROFESSOR, DEPARTMENT OF COMPUTER SCIENCE,** SGGSW UNIVERSITY, FATEHGARH SAHIB, PUNJAB and has not been presented elsewhere.

I further declare that the thesis does not contain any part of any work which has been submitted for the award of any degree either in this university or in any other university.

(Sonam Khera)

Registration No. - **YMCAUST/Ph 22/2011**

CERTIFICATE

This is to certify that this Thesis entitled "**ANALYSIS AND IMPLEMENTATION OF ENERGY EFFICIENT WIRELESS SENSOR NETWORKS**" by **SONAM KHERA,** being submitted in fulfilment of the requirement for the Degree of Doctor of Philosophy in **ELECTRONICS ENGINEERING** under Faculty of Engineering and Technology of J.C. BOSE University of Science and Technology, YMCA, Faridabad during the academic years 2012-2021, is a bona-fide record of work carried out under our guidance and supervision.

We further declare that to the best of our knowledge, the thesis does not contain any part of any work which has been submitted for the award of any degree either in this university or in any other university.

Dr. Navdeep Kaur
Professor
Department of Computer Science
Faculty of Engineering and Technology
SGGSW University
Fatehgarh Sahib, Punjab

Dated:

Dr. Neelam Turk
Professor
Department of Electronics Engineering
Faculty of Engineering and Technology
J.C. Bose UST, YMCA, Faridabad
Haryana.

Dated:

SUMMARY OF RESEARCH WORK

1. INTRODUCTION

Wireless Sensor Networks have opened up a new arena of applications, which are not only giving more information about the environmental phenomenon but have also given better control to make life easy. These applications work on the basis of the data captured by a number of sensors with varied capabilities. Whether it is the latest development in the field of Internet of Things, monitoring large industrial units, precision agriculture, remotely operating power plants, monitoring long-distance transmission lines, distant medicinal diagnostics, controlling forest fires, monitoring volcanoes or keeping an eye on the climate change all such applications utilize sensor network technologies in one way or the other.

A wireless sensor network (WSN) is a network of spatially distributed sensing devices called nodes that are specially designed to measure and monitor various physical parameters such as temperature, pressure, humidity, vibration, sound and motion etc. As shown in Figure – 1, WSNs find their application in variety of environments ranging from civil and military applications [1,2] to industrial sensing and diagnostics. These devices are equipped with receiving, storing, processing and transmitting abilities to capture the data from the deployment environment, processing it and transmitting it across to the base station. The sensor nodes are deployed in comparatively hostile environments where normal human intervention is minimum or not possible. The deployment of WSNs comprises of thousands of nodes spread across entire area under consideration with no or very less possibility of post deployment maintenance. The dense deployment of nodes though provides the much needed reliability and redundancy but at the same time poses a challenge for the limited bandwidth available. Due to such key factors of

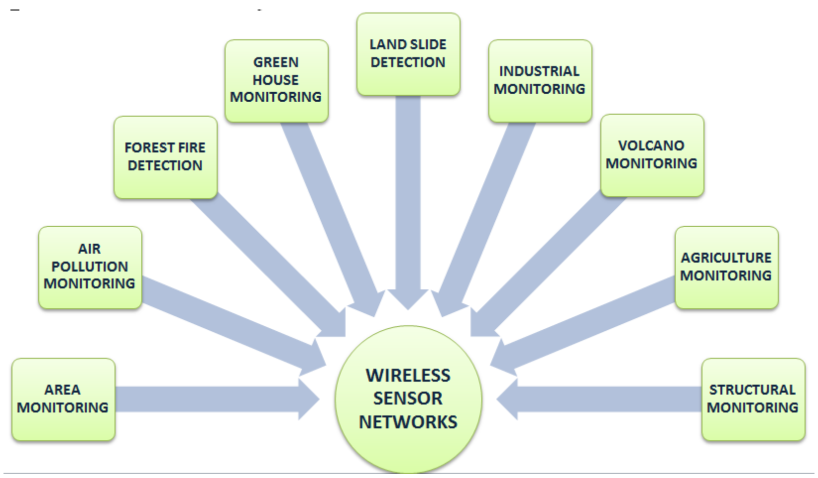

Figure 1. Applications of Wireless Sensor Networks

scale, economy and unattended operation for a longer duration, emphasis is laid on reducing the cost of sensor nodes, improving their energy efficiency along with efficient utilisation of limited available bandwidth.

With these challenges, lot of research work has been undertaken in this field with focus on reducing cost of manufacturing, deployment environment, hardware size, network topology, fault tolerance, scalability, power consumption, bandwidth availability and energy efficiency. Due to the huge size of proposed WSN deployments, researchers have focussed on development of numerous simulation tools to carry out research work on different aspects of sensor networks. Though simulation is essential to study WSN, it requires a suitable model based on appropriate assumptions and framework for proper implementation. The simulation results depend on the controlled environments under study and may not cover other realistic aspects which abruptly arise in physical deployments.

WSNs are specifically deployed to perform sensing operations in environments where human intervention is not possible. Thus once deployed, the WSN starts performing its functions and consumes the energy from the limited power source installed in sensor nodes. Due to inaccessibility of sensor nodes, these power sources are non-replaceable, (once the nodes are deployed in the physical environment). Therefore the energy consumption of sensor nodes plays significant role in determining the life of a WSN. During the research work various factors affecting the lifetime of a WSN have been studied with focus on improving the energy efficiency of the sensor nodes to ultimately enhance the network lifetime. It has been found that though there is rapid increase in the number of applications of WSN with increasing dependency on battery power, but there is not much development in the energy density of batteries.

The **motivation** behind this work is to find a methodology for reducing the energy consumption in the sensor nodes there by increasing their period of operation and thus improving the overall life time of the WSN. In addition to this the work involves developing a low cost WSN test bed that can be used for testing various scenarios considering the factors affecting the energy consumption in WSNs and to implement some of the techniques to increase network life time.

2. RESEARCH OBJECTIVES

Entire work has been divided into smaller research objectives which cover the step by step progress of the research work. These research objectives will be covered in detail to establish the understanding of the entire work undertaken. These research objectives are:

a) Literature review of various factors affecting the energy efficiency of Wireless Sensor Networks.
b) Proposing a protocol to enhance the life time of Wireless Sensor Networks by improving the energy efficiency.
c) Performance analysis of proposed protocol.
d) To design an experimental multi-node wireless sensor network test-bed hardware
e) To implement proposed protocol on experimental wireless sensor network test-bed and analysis of performance.

3. LITERATURE REVIEW

In the recent past numerous researches have been conducted and numerous physical test-beds have been setup by the researchers to verify their work. Reference [3] describes in detail a vast selection of WSN test beds developed over the past few years. The paper describes general architecture and highlights unique features of each test bed to choose the best test bed as per specific requirement. The test beds have been classified based on their designs. General Test beds are deployed indoors without any outside interference. Such test beds are deployed mainly by academic institutes. These test beds usually consist of a network of sensor nodes, channel for test bed management connectivity, a database for logging data and a management software with interactive user interface. The software is designed to handle scheduling of sensor nodes for experiments, controlling network topology, programming the nodes, debugging faulty networks, for analysis and visualisation of data.

On the other hand Server based Test beds have a centralised server based management. MoteLab [4] was one of the very first fully developed WSN test beds using MicaZ motes. It is an open source tool that is available on the Internet to any registered user. All Motelab code is available for institutions to build their own test beds. It consists of a MySQL database server, a PHP web server, a Java based data logger and a job daemon that assigns experiments to networked motes. The motes are connected through Ethernet interface to gain access to the back-channel. ORBIT [5] is a radio grid network test bed developed by Rutgers University, designed to serve as evaluation tool for wide range of wireless network protocols. It has multiple back-end services that can control the test bed through an Ethernet back-channel interface. The test bed supports mobile nodes and, is robust against failures. It can be used to test multiple radio technologies.

Another category of test beds comprise of the once that use a single PC as the central point of the test bed which takes care of all the data logging and the management functions. These arrangements use serial/USB back-channels to interface with the motes. These are flexible and can be easily adapted to different scenarios. But they have limitations regarding scalability and no simultaneous or remote user access. One such example is LabVIEW Test bed [6]. It uses off the shelf components to create a user friendly test bed along with management tool developed in LabVIEW environment. This interface program is installed on a central PC. Once motes are programmed individually through a RS-232 interface, the LabVIEW application can record and visualise all test bed data in real time. The test bed comprises of two sets of motes, the first is consists of 15 MicaZ motes in a multi-hop architecture and the second with 8 Cricket motes in a single hop configuration connected to the base station.

To harness the best of both the words, there are hybrid test beds in which a central management server is used but the test bed is dependent on separate gateway devices that perform control and data management functions and supply connectivity to motes. This approach is more scalable as new gateways can be added to extend the network capability. IBM WSN Test bed [7] is one such test bed developed at IBM's Zurich laboratory. The test bed evaluates various short range radio communication technologies. It can either be configured in a flat or meshed architecture. The sensor units are designed using FPGA and implement multiple sensors so that these can be interfaced with various radio nodes depending upon the experimental requirements. The wireless network thus created is connected with the enterprise network through a Power PC based gateway node. The data is derived from the network using a Java middle ware program and can be used for further analysis.

Another set of test beds address the limitation of confinement to single or fixed environment. Such multiple site test beds are deployed at multiple locations and are controlled from a central location. SensLAB[8] is one such very large scale open wireless sensor network test bed spread across 4 different sites in France. The objective of the test bed is evaluation of scalable wireless sensor network protocols and applications. SensLAB’s main and most important goal is to offer an accurate open access multi-users scientific tool to support the design, development, tuning, and experimentation of real large-scale sensor network applications. The SensLAB testbed is composed of 1024 nodes and it is distributed among 4 sites. Two sites offer access to mobile nodes. Every sensor node is also able to be configured as a sink node and can exchange data with any other sink node of the whole SensLAB testbed (locally or remotely) or any computer on the Internet.

Few test beds like SenseNeT [9] do not rely on any additional hardware like wired infrastructure or gateway nodes by using the existing wireless channel for node management and control purposes as well. This makes the testbed more scalable and reduces costs. A software component is installed on the motes, which is used to interact with the central servers through the existing wireless channel. Remote users can access the test bed through a web interface while an application and database server manages the test bed, reprograms nodes and records data. A base station node is used to interact between the management hardware and the network of MicaZ motes. The test bed has self-organising and self-healing properties that ensures depleted nodes can be replaced easily.

More work is being done and innovative enhancements are being added to the test bed architecture with an aim to improve upon resource allocation, scalability, control, accuracy, reliability, availability and improving user experience.

The research work involves study of various energy efficiency techniques and proposing a new methodology for better energy efficiency. Accurate prediction of sensor network lifetime requires an accurate energy consumption model. [10] There have been various attempts to model sensor node energy consumption. Some of the researches in the field are:

Heinzelman et al. [11] stated that the conventional protocols of direct transmission, minimum-transmission-energy, multi-hop routing, and static clustering may not be optimal for sensor networks, and proposed LEACH (Low-Energy Adaptive Clustering Hierarchy), a clustering-based protocol that utilizes randomized rotation of local cluster base stations (cluster-heads) to evenly distribute the energy load among the sensors in the network. LEACH uses localized coordination to enable scalability and robustness for dynamic networks, and incorporates data fusion into the routing protocol to reduce the amount of information that must be transmitted to the base station. In further enhancement to their work, [12] Heinzelman et al. developed and analysed LEACH protocol in considerably improving the system life time proposed a model that considered energy consumption only in microcontroller processing and radio transmission and receiving. Though, this model did not consider other important sources of energy consumption, such as transient energy, sensor sensing, sensor logging and actuation.

The model proposed by Millie and Vaidya [13] considers energy utilised in processing and communication along with transient energy, but it does not account for energy consumption of sensor sensing, sensor logging and actuation.The Zhu and Papavassiliou's model [14] takes care of the energy consumed in processing, communication and sensing but it does not consider energy consumption of transient energy, sensor logging and actuation. Reference [15] talks about radio as contributor to overall node energy consumption. It proposes adaptive radio low-power sleep modes based on current traffic conditions in the network. The paper covers in detail the Microcontroller Unit Energy, Listening Energy, Switching Energy i.e. the energy consumed for switching the radio state between states, including normal, power down and idle modes. The following equation defines the energy consumed for switching the radio from sleep mode α to active mode:

$$E_{switch}^{\propto} = \frac{(I_{active} - I_{\propto}) \times T_{\propto} \times V}{2} \qquad (1)$$

I_{active} - indicates the current draw of the radio in active mode, $I_{\propto}$ - is the current draw in sleep mode α, and $T_{\propto}$ is the time required by radio to switch from sleep mode α to active mode.

The work also covers the sleep time energy consumption which is the energy consumed when the radio is in low power mode and has been expressed as:

$$E_{sleep} = T_{rf}^{off} \times I_{\propto} \times \mathrm{V} \qquad (2)$$

Reference [16] Covers a very recent work in which a modified multi-path routing approach using artificial bee colony (ABC) has been proposed. The modified approach is based on fitness function which includes distance vector, reward factor, energy factor and latency of the path to be traversed. Reference [17] proposes a scheme for heterogeneous routing to achieve energy conservation in the network, by applying different strategies based on specific parameters at the same time inside different clusters. Each cluster can also adopt different strategies at different moments under different conditions.

From the review of routing protocols for WSNs, it can be concluded that the flat protocols may be an ideal solution for a small network with fixed nodes. However, in a large network they become infeasible because of link and processing overhead. The hierarchical protocols try to solve this problem and to produce scalable and efficient solutions. They divide the network into clusters and to efficiently maintain the energy consumption of sensor nodes and perform data aggregation and data fusion in order to reduce the number of transmitted messages to the sink. The clusters are organised based on the energy reserve of sensors and sensor's proximity to the cluster head. Thus, hierarchical protocols are suitable for sensor networks with heavy load and wide coverage area. On the other hand, the location based protocols may be useful for high dynamic networks as they do not need a state in routers nor in packet header and does not cause flood in the search. They use location information in order to calculate the distance among nodes, thus minimizing the energy consumption and extend the lifetime of the sensor network.

It is also evident that, low energy adaptive clustering hierarchy (LEACH) protocol has remained in the attention of research community ever since its inception. Numerous diverse modifications have been proposed by researchers over all these years. LEACH related protocols offer a promising improvement over conventional LEACH; however, there is still much scope for developing convenient and efficient LEACH variants.

4. RESEARCH METHODOLOGY

The strategy adapted to carryout research work has been depicted in Figure 2.

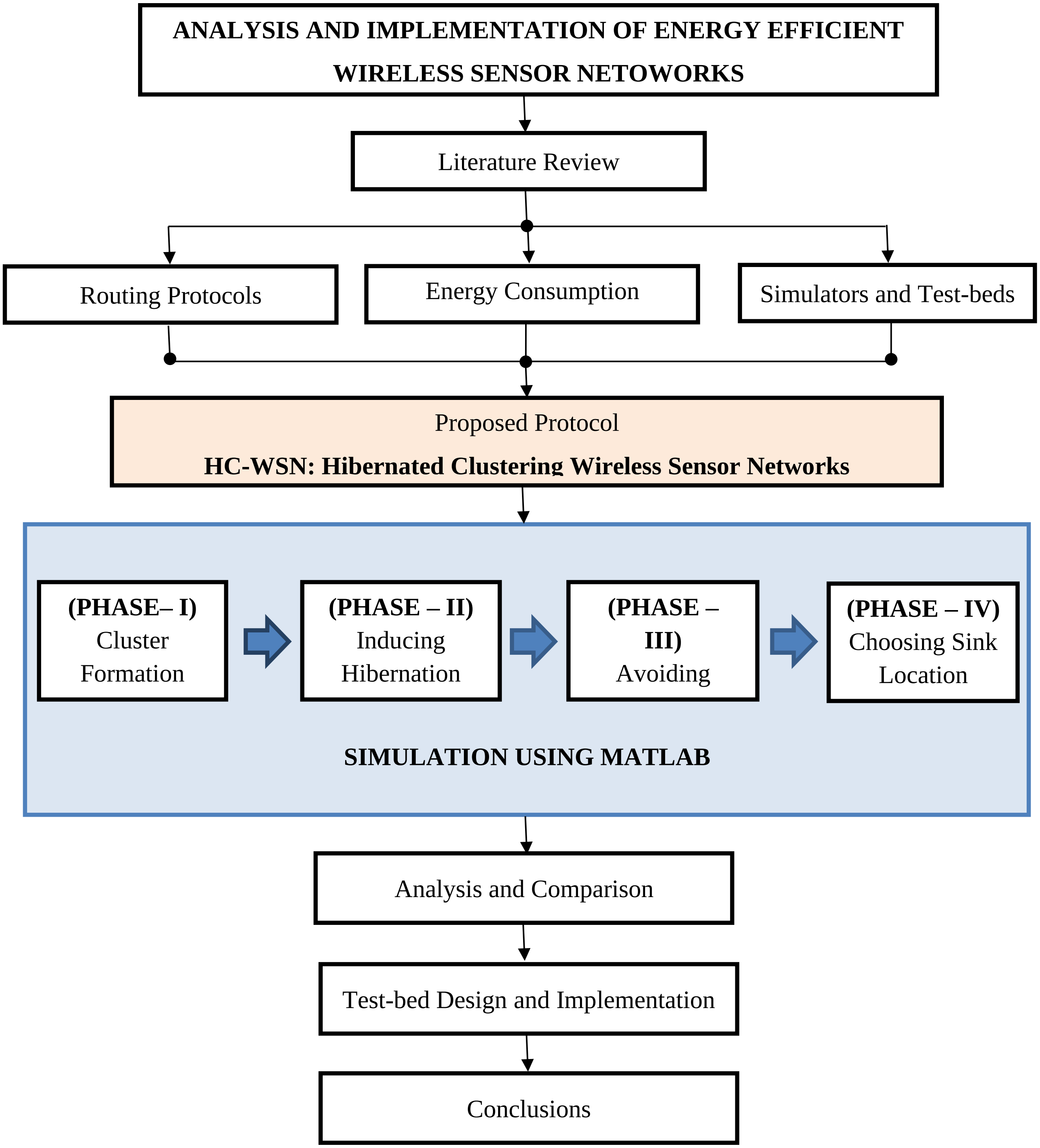

Figure2. Research Plan

As is evident from the research plan, extensive literature review has been carried out and, a new approach HC-WSN has been evolved to improve the energy efficiency. Subsequently, simulations are undertaken and hardware test-bed has been designed for implementing the proposed methodology along with features to customise the inputs for future experiments. Further sections provide a brief overview about the work.

Power Consumption in Wireless Sensor Networks: A sensor is a device that produces measurable response to a change in physical or chemical parameters. More specifically, a sensor is "a device that responds to a stimulus, such as heat, light, or pressure, and generates a signal that can be measured".

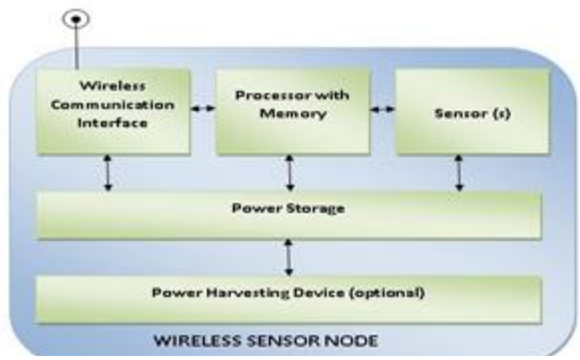

Figure3. Structure of a Sensor Node

Sensor Node: A sensor node is a small wireless device that is capable of sensing the data and transmitting the data wirelessly to one or many neighbouring nodes. The main components of a typical sensor node also known as mote are: microcontroller (with memory) a radio transceiver, external memory, power source and required sensors. Wireless sensor networks comprise of thousands of such nodes.

Figure 3 above shows the main components of a typical sensor node. It has processor with memory which is doing all the processing or calculations and the data captured is stored in the memory which is then transmitted to the base station through the network as per instructions via communication interface. For the functioning of the node energy is required which is available through the power source attached. Depending upon the usage, power is consumed from power source. Moreover the power sources in respective nodes are not replaceable. So it is needed to manage the load and reduce the battery power usage which in turn increases the network lifetime.

Out of the various functions performed by nodes, some are useful and some are wasteful. The power consumed by useful functions is called useful power consumption viz. transmitting or receiving the data, processing the query request, forwarding the query and data to neighbours. On the other hand the power consumed by wasteful functions like idle listening to the channel and waiting for the possible traffic, retransmitting because of collisions, overhearing and receiving packets not belonging to it, generating and handling control packets, over-emitting sensor receiving packets when it is not ready is called wasteful power consumption.

Building a wireless sensor network requires, constituting nodes to be developed and made available for maximum time. The sensor nodes perform numerous principal tasks – computation, storage, communication and sensing/actuation. Depending upon the application, the nodes might have to be small, inexpensive and energy efficient. They have to be equipped with right sensors, required memory and computational resources along with adequate communication facilities. For devising energy efficient routing algorithms, it is mandatory to understand the energy consumption in sensor nodes. As shown in Figure 4, the communication cost dominates the energy budget of any sensor node. Sensor nodes deploy RF circuitry for transmitting and receiving signals. By reducing the number of bits to be transmitted by doing processing locally, power consumption of a sensor network can be radically reduced. In most applications, for majority of the time there is nothing of interest to report, but still sensors need to be constantly vigilant for events. Therefore required duration of communication and distance of communication can be leveraged to lower the energy consumption at component level with in the sensor nodes.

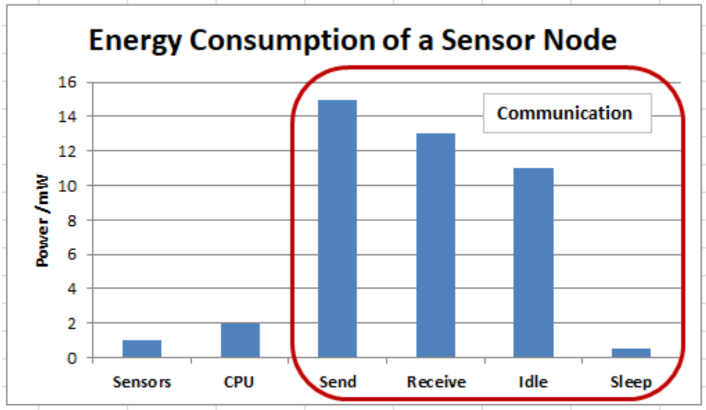

Figure 4. Energy Consumption of a Sensor Node

Reducing the energy consumption and improving energy efficiency: As per the literature survey, many schemes can be found, which have significant contributions in energy conservation. To improve energy efficiency and to increase the network lifetime, Sleep mode is introduced in the network**.** This is done by reducing the time where the sensor is idle. The entire operation of a sensor node can be divided into four modes as shown in the Figure 5.

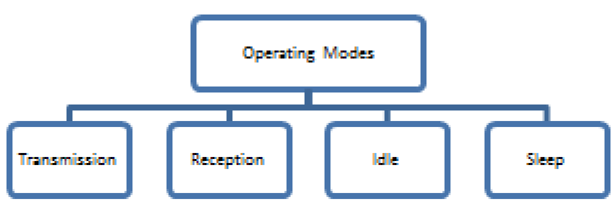

Figure 5. Operating modes of a Sensor Node

Transmission mode: Transmission mode means transferring of data between two nodes. In the transmission mode the energy is consumed in transmitting the data to the neighbouring nodes. In a sensor network each node is connected to the all the nodes by any of the path. Thus data can be transmitted to the neighbouring nodes in the network as per destination address assigned by the transmitting node.

Reception mode: Reception mode means receiving of data between two nodes. In the reception mode the energy is consumed in receiving the data from the various neighbouring nodes. In this the data is received by the node if its address matches the destination address assigned by the transmitting node.

Idle mode: In the idle mode the node remains in idle state. In this state the channel is ready to receive but is not doing so. In this mode some of the hardware functions are switched off and thus the energy consumption is little bit less.

Sleep mode: In sleep mode the node is not active or the significant parts of transceiver are switched off, thus consuming lesser power. Sleep time is set optimal so as to avoid the delay of information. Sensor networks use a fixed low-power radio mode for putting the radio to sleep. The reduction of the battery usage is caused by the sleep mode operation while at the same time it maximizes the network lifetime by introducing the sleep control.

Proposed Methodology- Hibernated Clustering Wireless Sensor Networks (HC-WSN): The proposed methodology aims at improving the energy efficiency of the sensor nodes and the wireless sensor network as a whole thus improving the network lifetime. In most of the research literature available, the sensor networks have been assumed to comprise of homogenous nodes and prominent algorithms like LEACH, PEGASIS and HEED have been proposed accordingly. An in-depth analysis advocates that each and every node forming the sensor network is unique in its own way, whether it is the location of deployment, energy levels or the energy depletion rates; each node is different from the other. So while proposing a technique impacting the network as a whole a generalised and wider perspectives should be considered. Due to this very basic design constraint, the algorithms based on homogeneous clustering have a poor performance in real world scenarios [6]. Also it has been found that most of the research works undertaken for improving energy efficiency of the WSNs [10], have considered nodes as either energy rich or energy optimum, the proposed methodology instead of classifying the nodes in two discrete categories tends to use the varying energy levels of the nodes to decide upon the state of nodes in this cluster based routing protocol.

Salient Features

The proposed methodology "HC-WSN" has been designed for efficient energy consumption with an objective to achieve maximum network lifetime by overcoming shortcomings of the existing cluster based routing protocols. The salient features of the proposed HC-WSN scheme are:

1. It is a hierarchical clustering based routing protocol for energy constrained wireless sensor network nodes.
2. HC-WSN assumes that the radio channel is symmetric i.e. energy required to transmit from A to B is same as energy required for B to A transmission for given SNR.
3. It assumes that all sensors are sensing the environment at fixed rate and thus have data to send to the end user.
4. It takes into account the heterogeneity of nodes in a wireless sensor network; therefore it is not mandatory for the constituent nodes to have same initial energy (E_{0i} – indicates initial energy for i^{th} node in the network).
5. It follows distributed clustering, and nodes are free to form clusters based upon their vicinity (inter node distance d) with each other.
6. The member nodes of the cluster select among themselves, a cluster-head which is a sensor node having maximum residual energy, higher than the pre-defined E_{UTH} (Upper Threshold Energy). In case of conflict, the choice of Cluster Head is based on First in First out (FIFO) method.
7. Formation of clusters minimizes the number of transmit / receive operations by making the respective cluster heads responsible to communicate with destination.
8. The member nodes in cluster are responsible for sensing operation. Hibernation (sleep) is induced to minimise energy consumption and enhance network life time. Such nodes become Active after a fixed interval.

9. Before entering into subsequent iteration, the residual energy of the member nodes is compared against predefined minimum energy value E_{LTH} (Lower Threshold Energy) and nodes not fulfilling the minimal criteria are declared as "Dead". Such nodes do not form the part of network and isolating them well in time save the network from unnecessary communication overheads.
10. To reduce the communication overhead on account of selection of cluster-heads; cluster heads for all the clusters are not selected afresh in each round. The new cluster formation method is initiated based upon the residual energy of the current cluster-head in comparison to the upper threshold energy E_{UTH} defined for cluster heads.
11. The proposed methodology also attempts to address the issue of ideal positioning of sink as static or mobile on a circular path with in the observation field.

Simulation and Analysis

In this research work, the proposed methodology has been evolved through continuous improvement in phased manner. The entire process has been divided into four phases, for phase wise induction of new aspects in the proposed methodology for further improvement and maximizing energy efficiency. The phase wise analysis has been done through MATLAB simulations. To evaluate the proposed methodology, following parameters have been monitored and have been compared with their value in earlier phase to assess the impact.

1) Number of Alive nodes.
2) Average Energy of the network
3) Throughput (Packets received at Base Station)

To verify the proposed methodology, HC-WSN has been compared with LEACH and Hybrid LEACH. Further HC-WSN has been simulated with varying location of Sink to see the impact of its location with respect to sensor nodes.

HC-WSN vs LEACH: In this scenario the proposed HC-WSN is compared with LEACH protocol. The simulation has been set up with 50 nodes for 100 rounds. The nodes are randomly spread over the deployment area and clusters are formed based upon vicinity in case of HC-WSN and on the basis of probability in case of LEACH. It has been found that average energy of network with HC-WSN is better than network with LEACH.

Another prominent variant of LEACH, called H-LEACH (Hybrid LEACH) has been proposed by Razaque et al. The Hybrid LEACH has been found to be better than LEACH with presence of live nodes for longer duration. Further the proposed methodology "HC-WSN" has been compared with Hybrid LEACH. The comparison has been done in terms of number of alive nodes, average energy of the network and throughput.

To further optimise HC-WSN, sink position, node density and number of rounds have been varied and simulations have been carried out in following experimental setups:

1) Node density scenario (Varying the number of nodes)
2) Time variation scenario (Varying number of rounds)
3) Varying position of Base Station (Static and Mobile- outside and inside)

It has been observed that:

- Throughput of the network is more when the sink is statically placed with in the network deployment area.
- Number of alive nodes is more in case of a network with internally mobile sink instead of a network with internally static sink
- On comparing external mobile sink and internal mobile sink, the network with external mobile sink has been found to have higher number of alive nodes, higher average network energy and better throughput.

Experimental Test bed

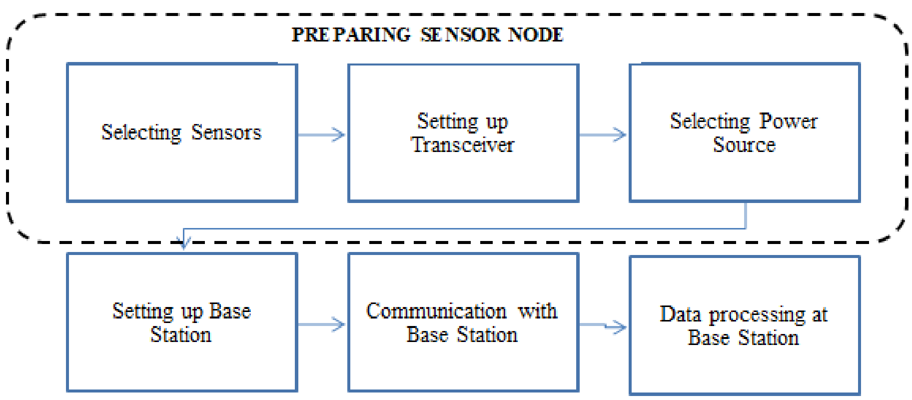

Figure 6 Test Bed Design

A test-bed has been prepared as part of the research work. The test bed design or creation involves developing both hardware and software components. The hardware comprises of the sensors, transceivers and the power source forming the nodes deployed in the field and a coordinator module connected to server (laptop in this case) which acts as Base station.

The software comprises of the firmware installed on the transceivers to function like a sensing node and on the RF module connected to the laptop to act like coordinator and finally on the base station to provide an interface to control the entire test-bed and process the collected data for necessary analysis and decision making. From test bed perspective, the design process can be represented as in Figure 6.

The four sensor nodes have been prepared and have been deployed in a building to measure the values of different parameters at different locations.

- To measure the temperature difference, the nodes have been placed in different locations having varying temperature.
- For the purpose of moisture variation, probes have been dipped into containers with mud having different moisture content.
- The illumination on LDR has been varied using coverings of differing opacity.
- The vibration sensor has been activated using source of vibration like ringing phone at different locations.
- It may be noted that as the purpose of the test-bed is to evaluate the proposed energy efficiency algorithm, hence same has been focused in the research work.

The node wise residual voltage data is collected at the base station and residual energy at nodes is worked out. It has been found that the energy consumption at nodes is further decreased leading to enhanced life time of the network.

5. Organisation of Proposed Thesis

To give an in-depth, in-sight into the research work undertaken, the thesis has been divided into seven chapters.

Chapter – I: Introduction

Chapter – I gives introduction to the thesis and research challenges in the field of Wireless Sensor Networks have been covered in detail. The chapter also covers in detail the motivation for the research, scope of work, contribution and objectives of the research. A pictorial representation of research plan has been given for better understanding.

Chapter – II: Literature Review

Chapter –II covers necessary background on fundamental concepts in Wireless Sensor Networks, their characteristics and applications, findings from the extensive literature review undertaken during the research work. It also reviews the published research in the field of improving energy efficiency of wireless sensor networks and provides details about the available simulation environments and test-bed technologies available for experiment with Wireless Sensor Networks.

Chapter –III: Energy Consumption Perspective of Wireless Sensor Networks

This chapter discusses the components of a WSN and elaborates constituents of a typical sensor node; it focuses on the various parameters of energy consumption and discusses in detail various factors influencing it. Aspects of useful power consumption and points of wasteful power consumption have been covered in detail.

Chapter – IV: IEEE 802.15.4: The Standard For Wireless Sensor Networks

It includes study of IEEE 802.15.4 standard for LR-PANs and covers the network architecture model of WSNs. The ZigBee standard for WSNs has also been discussed in detail.

CHAPTER –V: Proposed Protocol: Hibernated Clustering - Wireless Sensor Networks (HC-WSN)

This chapter takes inference from the works already under taken in the field of cluster based routing algorithms for improving energy efficiency by various researchers. A new protocol has been proposed to enhance the energy efficiency and network life time. Features of this proposed protocol have been discussed in detail along with simulation using MATLAB and analysis of results.

Chapter – VI: Test-Bed Design and Implementation

This chapter discusses in detail the available test-beds and sensor nodes; it focuses on the requirement and benefits of proposed experimental test-bed. The components used, their characteristics and mode of operation is discussed in detail. This chapter covers the different stages of implementation of proposed protocol including various experimental scenarios which have ultimately led to the proposition of HC-WSN. The network life time estimated on the basis of residual battery capacity of different sensor nodes in four different scenarios is discussed and analysed to validate simulation outcomes of HC-WSN.

Chapter – VII: Conclusions and Future Scope

This chapter covers the benefits that can be derived from the research work undertaken like development of applications for upcoming technologies like Internet of Things, Smart Metering for Energy Consumption and better understanding of practical aspects of WSNs. The chapter concludes the entire research work in terms of the protocol proposed, its analysis and immediate benefits. The chapter discusses the future scope of the work including improvement in data security of network with respect to proposed HC-WSN protocol.

6. Proposed Outcomes of the Research

- In this work, an extensive literature review pertaining to the state of issue to increase the energy efficiency of WSN is presented. Various research papers, books and application notes have been referred which take into consideration various aspects of understanding of sensor nodes and how wirelessly they form the network. This work focuses on the current research efforts in the area of wireless sensor Networks. The work also presents challenges anticipated in the years to come and enlists future scope for research. A full description of various techniques or methodologies is beyond the scope of this work, the focus is on providing developments that have taken place in the area of network lifetime.

- In this research work, various recent research papers were referred to understand the various factors affecting the energy efficiency of Wireless sensor networks. Various factors include: Type of Service, Quality of Service, Fault Tolerance, Lifetime, Scalability, Wide range of densities, Programmability, Maintainability.
- During the research work, various available simulation environments were reviewed and it was found that though simulation environments provide ease of conducting experiments in terms of scale and flexibility but have limitations in incorporating the practical aspects. For a better understanding and hands-on experience of the working of WSNs, the development of hardware testbed has been undertaken.
- In this research work, the practical aspects and learning from implementing a test bed and techniques for reducing power consumption in wireless sensor networks have been covered. The designed test bed has been used to measure different environmental parameters at four different locations using four different nodes. The effect on residual battery voltage with time is measured and graphically analysed.
- For improving node life and thus overall network lifetime, sleep mode has been induced in two nodes. It has been found that two nodes which are working with sleep mode induced in them, have more battery available than other two nodes during same time.
- To further improve upon the network life time, a clustered approach was adapted and it was found that the network life improved substantially in clustered scenario, when one node (cluster head) was communicating with sink instead of each and every node communicating directly with the sink.
- The Clustered scenario has been even further improved (HC-WSN) and to increase the network life by strengthening the weakest nodes, the nodes with minimum residual battery voltage (above a threshold value) was made to sleep so as to preserve the energy and participate in the network for a longer period of time thereby enhancing the life time.
- Such hands-on study has provided an in house physical environment to experiment with different aspects of Wireless Sensor Networks. This has given a better idea for implementing upcoming technologies like Internet of Things with applications in Smart grids, home automations and advanced surveillance systems etc.

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8. List of Publications

S. No.	Title of Paper	Name of Journals	No.	Volume and Issue	Year	Pages
1	A practical approach to Energy Consumption in Wireless Sensor Networks ***Authors***: Sonam Khera, Dr. Neelam Turk, Dr. Navdeep Kaur	International Journal of Advanced Intelligence Paradigms, from Inderscience Publishers (**SCOPUS**)	ISSN online 1755-0394	Volume 16, Number 2, 2020 **DOI:**10.1504/IJAIP.2018.10009335	2020	190-202
2	MQTT protocol employing IOT based home safety system with ABE encryption ***Authors:*** Vatsal Gupta, Sonam Khera, Dr. Neelam Turk	Multimedia Tools and Applications from Springer **(SCIE)**	ISSN online 1573-7721	**DOI:**10.1007/s11042-020-09750-4	2020	-
3	Enhancing Network Coverage using Handoff Techniques in Mobile Wireless Sensor Networks ***Authors***: Sonam Khera, Dr. Neelam Turk, Dr. Navdeep Kaur	International Journal of Future Generation Communication and Networking (IJFGCN) under SERSC **SCOPUS and ESCI**	ISSN 2233-7857	Volume 10, Number 10, 2017 **DOI:**10.14257/ijfgcn.2017.10.10.02	2017	23-31
4	Energy Harvesting Aspects of Wireless Sensor Networks: A Review ***Authors***: Sonam Khera, Dr. Neelam Turk, Dr. Navdeep Kaur	International Journal on Recent and Innovation Trends in Computing and Communication (IJRITCC),	ISSN: 2321-8169	May 17 Volume 5 Issue 5	2017	875 – 878
5	Applications and Challenges in Wireless Sensor Networks ***Authors***: Sonam Khera, Dr. Neelam Turk, Dr. Navdeep Kaur	International Journal of Advanced Research in Computer and Communication Engineering (IJARCCE)	ISSN (Print) 2319 5940	Vol. 5, Issue 6, June 2016 **DOI**: 10.17148/IJARCCE.2016.5694	2016	448-451

List of Papers Presented in National/ International Conferences

S. No.	Title Paper and Authors	Name of Conferences	Remarks
1	Handoff Techniques in Wireless Sensor Networks ***Authors***: Sonam Khera, Dr.Neelam Turk, Dr. Navdeep Kaur	International Conference on Sustainable Development through Research in Engineering and Management (SDREM-16), YMCAUST, Faridabad (December 26-27, 2016)	
2	Energy Efficiency of Wireless Sensor Networks. ***Authors***: Sonam Khera, Dr.Neelam Turk, Dr. Navdeep Kaur	International Conference on Emerging Trends in Engineering and Management (ICETEM-12), SGI, Rohtak. (23-24 June, 2012)	
3	A Review of ZigBee Technology ***Authors***: Sonam Khera, Dr.Neelam Turk, Dr. Navdeep Kaur	International Conference on Paradigm Shift in Management and Technology (PSIMT-2015), YMCAUST, Faridabad (April 9-10, 2015)	
4	A Comparative Study of Simulation Tools For Wireless Sensor Networks ***Authors***: Sonam Khera, Dr.Neelam Turk, Dr. Navdeep Kaur	New Horizons in Technology For Sustainable Energy and Environment (NHTSEE-2017), YMCAUST, Faridabad (9-10 March, 2017)	
5	Future approach to Mobile Communication Technologies ***Authors***: Sonam Khera, Dr.Neelam Turk, Dr. Navdeep Kaur	Symposium on Nanotechnology: Interdisciplinary Aspects, YMCAUST, Faridabad. (December 12, 2016)	
6	Wireless Sensor Networks – An Energy Consumption Perspective ***Authors***: Sonam Khera, Dr.Neelam Turk, Dr. Navdeep Kaur	National Conference on Role of Science and Technology Towards 'Make in India' (RSTTMI-16) YMCAUST, Faridabad (March 05-07, 2016)	
7	Wireless Sensor Networks Security Issues ***Authors***: Sonam Khera, Dr.Neelam Turk, Dr. Navdeep Kaur	Workshop on Nanotechnology and Embedded Systems, YMCAUST, Faridabad. (23^{rd} July – 3^{rd} August,2012)	