ENERGY-EFFICIENT CLUSTERING ALGORITHMS FOR EDGE-BASED WIRELESS SENSOR NETWORKS

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

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February, 2016

To my family

DECLARATION

By the Ph.D. Research Scholar

I hereby *declare* that the Research Thesis entitled **ENERGY-EFFICIENT CLUSTERING ALGORITHMS FOR EDGE-BASED WIRELESS SENSOR NETWORKS** which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy** in **Mathematical and Computational Sciences** is a *bonafide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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Date: February 18, 2016

CERTIFICATE

This is to *certify* that the Research Thesis entitled **ENERGY-EFFICIENT CLUSTERING ALGORITHMS FOR EDGE-BASED WIRELESS SENSOR NETWORKS** submitted by **MUNI VENKATESWARLU K.**, (Reg. No.: 100473 MA10F01) as the record of the research work carried out by him, is *accepted as the Research Thesis submission* in partial fulfillment of the requirements for the award of degree of **Doctor of Philosophy**.

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Chairman - DRPC

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ABSTRACT

A wireless sensor network (WSN) is a spatially distributed autonomous sensor nodes to monitor physical or environmental conditions, such as temperature, sound, pressure, etc. and to cooperatively pass their data through the network to a main location. Sensor nodes' resources have been a primary concern in designing any wireless sensor network application, since they are limited and non-renewable. Most of the current efforts on sensor network research have limited their design space solely to the sensor nodes themselves. Under such an approach, the burden of achieving complex networking functions all rests upon the sensor nodes. Thus, the search for alternative resources got much attention in sensor networks. Base station is one such resource abundant and constraint-free network component in wireless sensor network. By exploring base station's capabilities, functional complexities in existing and upcoming algorithms can be simplified. A *Base station Assisted Novel Network Design Space (BANDS)* is proposed to exploit edge-base-station capabilities to offer new possibilities to meet up-to-minute requirements. Experimental results prove that the proposed work conserves network resources by shifting control overhead from sensor nodes to the base station. Based on the proposed network design space, a *Zone-Based Routing Protocol (ZBRP)* is introduced to enhance sensor network lifetime. ZBRP uses random back-off timers having communication cost and neighborhood count as primary parameters to select cluster heads for each data forwarding round. From the simulation results, it is observed that the proposed routing protocol improves network lifetime by distributing energy consumption evenly among clusters. To overcome the problems that arise with uneven energy dissipation, a novel *Energy-efficient UnEqual Clustering algorithm (EUEC)* is proposed. It creates limited and equivalent number of clusters in each level, which allows energy to be consumed evenly among cluster heads. Also, a disjoint multi-hop routing mechanism is proposed to balance network routing load among data forwarding paths. Experimental results prove that the proposed algorithm overcomes hot-spot problem with uniform energy dissipation among clusters and elevates network lifetime.

A novel and extended scale-free clustering technique called, *Energy-efficient Hybrid Clustering Mechanism (EHCM)* is proposed to overcome hot-spot problem without scalability issues. EHCM creates *dynamic number of clusters* in different sizes based on sensor node's location information, which distributes energy dissipation uniformly among sensor nodes. From the simulation results, it is realized that the proposed work achieves hot-spot free network and prolongs network lifetime. Since the number of clusters are generated dynamically, the proposed algorithm is easily scalable.

Keywords: Wireless Sensor Network; Network Design Space; Energy Efficiency; Unequal Clustering; Load Distribution; Energy Dissipation; Lifetime.

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List of Symbols

Symbol	**Explanation**
ε_{fs}	Energy consumed by the amplifier to transmit at a shorter distance
ε_{mp}	Energy consumed by the amplifier to transmit at a longer distance
θ_i	Beam-width of i^{th} level
a_i	Area of i^{th} ring
A_i	Area of i^{th} level
BS	Base Station
C	Number of clusters
$d(D_{ch}, BS)$	Distance between downstream cluster head and base station
$d(F_{ch}, D_{ch})$	Distance between forwarding and downstream cluster head
D_{re}	Downstream relay cluster head residual energy
$d(S, BS)$	Distance between node S and base station BS
E_{amp}	Transmit amplifier
E_{CH}	Energy consumed by a cluster head
$E_{Cluster}$	Total amount of energy consumed by a cluster
E_{DA}	Energy consumed by a cluster head for data aggregation
E_{elec}	Energy consumed to transmit or receive the signal in electronic circuit
E_{init}	Initial energy
E_{mem}	Energy consumed by cluster members

Symbol	Explanation
E_{re}	Residual energy
$E_{Rx}(L)$	Energy consumed to receive L-bit message
E_{se}	Spent energy
$E_{Tx}(L,d)$	Energy spent to transmit L-bit packet over the distance d
F_{re}	Data forwarding cluster head residual energy
L_{total}	Total number of levels in the network
L_n	Level Number
N	Number of sensor nodes
N_{CHs}	Number of cluster heads
n_{tch}	Number of tentative cluster heads
NH_{count}	Number of neighborhood nodes
R	Radius of the network field
r_{ch}	Radius of a cluster head
R_{num}	Round number
r_i	Transmission power level of i^{th} ring
S_n	Sector Number
Z_j^i	j^{th} partition of i^{th} level
z_a	Area of a zone
Z_n	Zone Number
Z_t	Number of zones in a given level

Chapter 1

INTRODUCTION

1.1 WIRELESS SENSOR NETWORK

Wireless Sensor Network is a distributed collection of resource constrained multi-functional sensor nodes with wireless communication and computational capabilities deployed either inside the phenomenon or very close to it. The aim of wireless sensor network is to sense and collect data from the interested phenomenon, process and transmit it to a required place. Rapid development in the field of Micro Electro Mechanical Systems technology has provided small sized, low-power, low-cost and signal processing sensor nodes with the capability of sensing various types of physical and environmental conditions. Advances in computing and communication technology have made it possible to integrate sensing capabilities, wireless communication interfaces, and microprocessors into tiny devices that can be easily embedded in the environment with its computational power (Vogt, 2009).

The concept of Wireless Sensor Networks (WSNs) was originally proposed in 1999 about "smart dust" computers that can be sprayed on the wall, deployed anywhere throughout the environment and collaborate to solve big problems. Later on, sensor networks found their way into a wide variety of applications with vastly varying requirements and characteristics (Taherkordi, 2011). Wireless Sensor Network (WSN) improves the ability of human beings to monitor and control physical locations from far-off places. Since each sensor node works independently without any central control, failure of some sensor nodes does not affect sensor network activities. Wireless sensor network is the backbone for establishing smart environments (Bhattacharyya et al., 2010).

Wireless sensor network is a subset of Ad-hoc network as shown in Fig. 1.1. An ad-hoc network typically refers to any set of networks where all devices have equal status on a network and are free to associate with any other ad-hoc network device in link

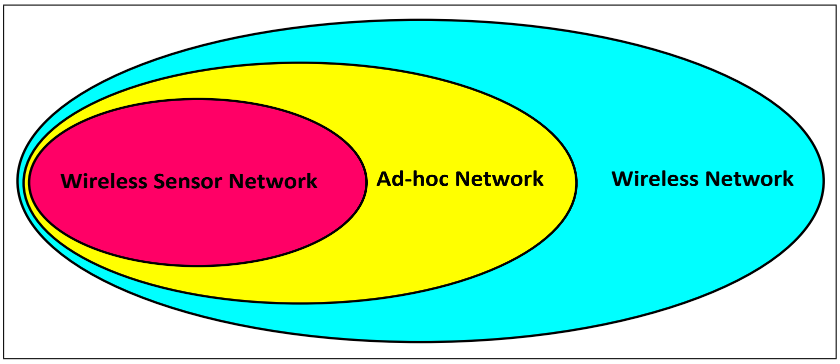


Figure 1.1 WSN as a subset of Ad-hoc network

range. Limitation on sensor node's energy, memory, processing power, etc, introduce several constraints on wireless sensor network compared to ad-hoc networks. Though many protocols and algorithms have been proposed for ad-hoc networks, they cannot be used due to the unique features and application requirements of wireless sensor networks (Kim Boon et al., 2006). Some of the key differences between sensor networks and ad-hoc networks are listed here:

(i) The number of sensor nodes in a sensor network will be larger than the number of devices in a wireless ad-hoc network.

(ii) Since sensor nodes are densely deployed, the data being sensed is highly redundant in sensor networks.

(iii) Sensor nodes will have limited power supply and replacement or recharging of battery is impractical. Whereas the batteries of ad-hoc network are rechargeable and replaceable.

(iv) Data transmission rate is very much low in sensor networks compared to the data rates in ad-hoc network.

(v) Sensor networks are strongly application specific and fault prone due to limited network resources.

1.1.1 Components of Wireless Sensor Network

Wireless sensor networks mainly consist of sensor nodes and one or more base stations as shown in Fig. 1.2.

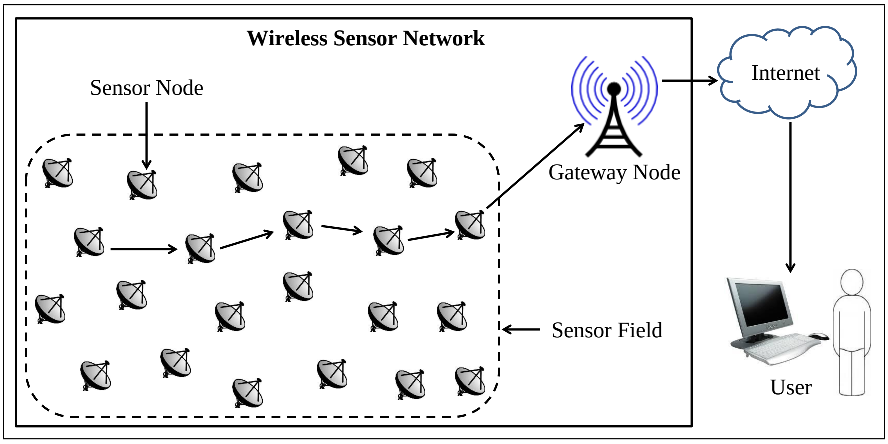


Figure 1.2 A Wireless Sensor Network

1.1.1.1 Sensor Node

A sensor node, also known as a *Mote*, is a node in a wireless sensor network that is capable of sensing, processing and communicating information to other connected nodes in the network. A mote is a node but a node is not always a mote. A mote consists of processor, memory, battery and Analog to Digital converter. It is connected to sensors and a radio transceiver to form a Sensor Node and is shown in Fig. 1.3 (Tripathi, 2012). Sensor nodes establish a wireless ad-hoc network and compose a distributed system to collaboratively sense physical phenomena and process sensed data, or to react to the environment based on the sensed data. These tiny nodes can be deployed at different kinds of environments to monitor both over space and time, the variations of physical quantities such as temperature, humidity, light, or sound.

1.1.1.2 Base Station (Central Gateway Node)

Gateway node connects sensor network with the external world including third party systems, stand alone data loggers, local computers and networks, and, monitoring and alerting systems. Base station deployment is very important task as all the sensor nodes handover

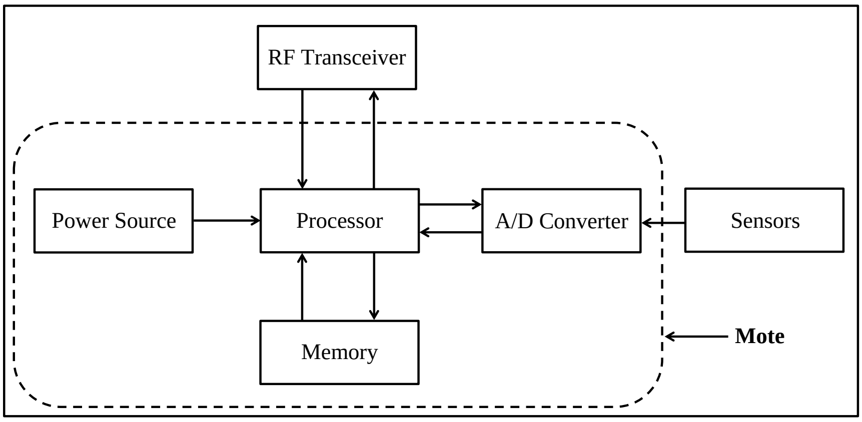


Figure 1.3 Typical architecture of a sensor node

their information to the base station for processing and decision making. In general, base stations are assumed to be static in nature to collect the data from sensor nodes. Unlike sensor nodes, base stations are usually resource abundant with unlimited power supply, huge storage capacity and huge communicational and computational capabilities.

1.1.2 Radio Model

The radio model which has been used in earlier works (Heinzelman et al., 2002; Li et al., 2005) is used in this thesis. For the radio hardware, the transmitter dissipates energy to run the transmitter radio electronics and power amplifier, and the receiver dissipates energy to run the receiver radio electronics as shown in Fig. 1.4.

Here, both free space ($d^2 powerloss$) and the multi-path fading ($d^4 powerloss$) channel models are used depending on the distance between the transmitter and the receiver. If the distance is less than the given threshold d_0, the free space (fs) model is used. Otherwise, the multi-path (mp) model is used.

In the radio model of Tx amplifier, we assume $\alpha = 2$ for free space and $\alpha = 4$ for multi-path model. The energy spent to transmit L-bit packet over the distance d is given as follows:

$$E_{Tx}(L,d) = \begin{cases} L.E_{elec} + L.\varepsilon_{fs}.d^2 & if d < d_0 \\ L.E_{elec} + L.\varepsilon_{mp}.d^4 & if d \geq d_0 \end{cases} \tag{1.1}$$

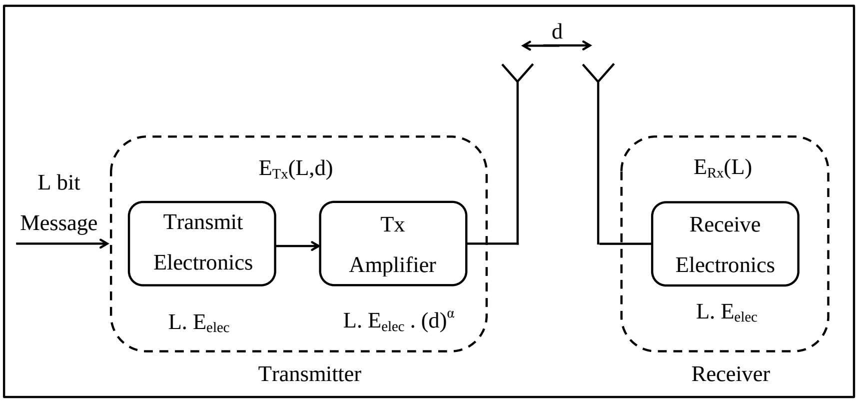


Figure 1.4 Radio Model

where E_{elec} is energy consumed to transmit or receive the signal in electronic circuit, ε_{fs} is energy consumed by the amplifier to transmit at a shorter distance, ε_{mp} is energy consumed by the amplifier to transmit at a longer distance and the threshold d_0 is calculated as

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \tag{1.2}$$

To receive L bits, radio spends $E_{Rx}(L)$ energy which is given below.

$$E_{Rx}(L) = L.E_{elec} \tag{1.3}$$

1.1.3 Types of Wireless Sensor Networks

Based on infrastructure, wireless sensor networks are categorized into two types (Yick et al., 2008):

(i) **Structured Wireless Sensor Networks:** Here, sensor nodes are densely deployed in a predetermined way and they are not easily manageable.

(ii) **Unstructured Wireless Sensor Networks:** In this, sensor nodes are randomly deployed in limited number and they are easily manageable.

Based on how the sensor readings are delivered to Base Station (BS), Wireless sensor networks are distinguished as follows (Schaffer, 2010):

(i) **Synchronous Wireless Sensor Networks:** Synchronous sensor networks send sensed information to destination in real-time using multi-hop wireless communication.

(ii) **Asynchronous Wireless sensor networks:** Asynchronous sensor networks deliver readings with some delay(e.g., once in a day or week or month) to sink node.

1.1.4 Applications

Wireless sensor networks have been developed for a wide range of applications such as military, agriculture, industry, target tracking, data collection, rescue missions, national security, monitoring disaster prone areas, flood detection, managing inventories, medical health care, home networks and environmental studies (Akkaya and Younis, 2005; Liu, 2012).

1.2 CLUSTERING MECHANISM

Clustering is a process of dividing network into sub-regions based on certain criteria as shown in Fig. 1.5 (Said Ben et al., 2012).

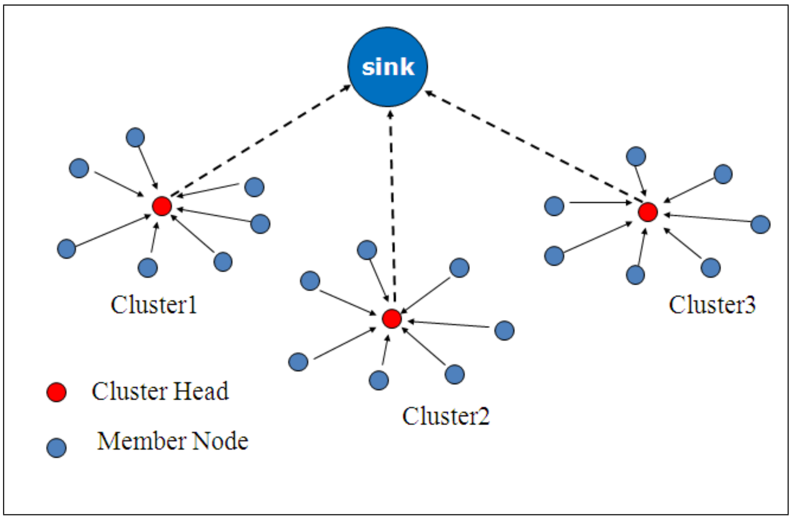


Figure 1.5 Clustering in Wireless Sensor Network

Communication via the on-board radio is the most expensive operation of a sensor node. Most of the sensor network applications operate without any human intervention and, sensor nodes batteries are non-replaceable and not-rechargeable. Therefore, sensor node's on-board energy should be utilized wisely to prolong sensor network lifetime. Protocols proposed in the literature such as LEACH (Heinzelman et al., 2002), PEGASIS (Lindsey and Raghavendra, 2002) and HEED (Younis and Fahmy, 2004) reduce energy consumption and increase the lifetime of the network. The basic idea here is to cluster sensors into groups, so that sensors communicate only to their cluster head. The cluster heads then communicate the aggregated information to the processing center. Clustering has been shown to greatly reduce power consumption, is easily scalable, and robust in case of node failures (Heinzelman et al., 2002). A good clustering scheme is one that takes into account one or more of the following: communication range, number and type of sensors, geographical location and remaining energy.

The cluster-based routing is an efficient way to reduce energy consumption within a cluster by decreasing the number of transmitted messages to the sink node. Hence, there have been many cluster-based routing protocols proposed in the literature. Clustering techniques are mainly developed to conserve every individual sensor node's energy (Liu et al., 2012). Well-organized clusters would enable uniform energy dissipation among cluster heads(CHs), and enhances wireless sensor network lifetime.

Hierarchical(Clustering) technique has numerous advantages like, it can localize the route setup, conserve communication bandwidth, avoid redundant message exchanges, cut on topology maintenance overhead, implement optimized management strategies to enhance network operations, schedule activities in the cluster, prevent medium access collision by limiting redundancy in coverage, decrease the number of relayed packets by aggregating data collected by sensors in the network, etc., (Abbasi and Younis, 2007).

Sensor nodes in a cluster transmit their sensed information only to their cluster head (CH). This communication significantly conserves the battery power of each individual sensor, which only needs to communicate with their respective CHs over relatively short distances. Each cluster head aggregates the collected data into a single fixed length data packet and forwards it towards sink node either directly or via multi-hop data routing paths.

In a cluster-based communication network, cluster heads spend their energy for intra-cluster communication and inter-cluster communication (Liu et al., 2012). The amount of energy consumed in intra-cluster communication depends on cluster size. Energy consumption rises with number of sensor nodes in a cluster. Cluster heads of even size clusters tend to consume uniform amount of energy for intra-cluster communication (Li et al., 2005). Since sensor nodes have limited transmission range, they transmit information to sink node using multi-hop data transmission model. In this, cluster heads act as relay nodes in data forwarding routes to deliver data between source and destination.

1.2.1 Energy Consumption Model

In a wireless sensor network, cluster heads are selected from the sensor nodes in the network. Each node chooses the nearest cluster head based on given criteria to forward data packets to Base station. All the sensor nodes attached to a cluster head, forms a cluster. Let there be N nodes uniformly distributed in an $M \times M$ area and C clusters in topology. There will be on an average $\frac{N}{C}$ nodes per cluster. Out of these, there will be one cluster head node and remaining $(\frac{N}{C} - 1)$ non cluster head nodes, called cluster members. The amount of energy consumed for a cluster member (E_{mem}) to transmit L-bits data to its cluster head is given as follows:

$$E_{mem} = L.E_{elec} + E_{amp}(L,d) \tag{1.4}$$

where E_{elec} is energy consumed to transmit or receive the signal and E_{amp} is transmit amplifier.

Amount of energy consumed for a particular cluster head E_{CH} to receive data from all its cluster members, data aggregation and transmission of aggregated data to base station is as follows:

$$E_{CH} = (\frac{N}{C} - 1)L.E_{elec} + \frac{N}{C}.L.E_{DA} + E_{Tx}(L,d) \tag{1.5}$$

where E_{DA} is energy consumed by a cluster head for data aggregation. Total amount of energy consumed for a given cluster($E_{Cluster}$) is given as

$$E_{Cluster} = E_{CH} + (\frac{N}{C} - 1)E_{mem} \tag{1.6}$$

1.3 ROUTING IN WIRELESS SENSOR NETWORKS

Transmission of data from a wireless sensor network to an observer raises numerous issues: wireless sensors are constrained by limited resources, in terms of energy, network data throughput and computational power. The communication module is particularly resource constrained since the amount of data that can be routed in the network is inherently limited by the network capacity. Also, wireless communication is an energy consuming task, identified in many situations as the primary factor of lifetime reduction (Borgne, 2009). While there have been numerous efforts at developing routing and communication protocols for wireless sensor networks, the primary concern is energy efficiency. This consideration potentially affects many aspects of the system design: hardware, physical layer, MAC layer, addressing and routing, topology control, synchronization, naming scheme, security mechanisms, etc. Numerous solutions have been proposed in this context, with each of them addressing one or more aspects of sensor network system design.

1.3.1 Classification of WSN Routing Protocols

Since the scope of routing is very huge in wireless sensor network, variety of classifications defined to represent sensor network routing protocols, which are given below:

1.3.1.1 Routing Protocols Categorized based on Nature of Routing

It is the traditional way of classifying routing protocols. This method gives a broad scope of classification. This way of classification is introduced in wired networks, later it is being implemented for wireless networks.

(i) *Proactive or table-driven routing*

In this type, data will be transmitted using predefined paths which are established in prior to network implementation. Constructed routes will be stored and updated periodically in the routing table, which is why it is also called Table-driven routing and can be termed as Static routing. Here, routing information will be maintained even though nodes do not have anything to communicate.

E.g: Destination-Sequenced Distance-Vector (DSDV) (Meghanathan, 2010)

(ii) *Reactive or On-demand routing*

Reactive routing protocols establish routes whenever a node has data to send. Routes will be created on demand, which is why it is also be called as On-demand routing and can also called as Dynamic routing. For every data transmission, it checks whether any route is available between source and sink, if exists that route will be used, otherwise a new route will be constructed. When compared with proactive routing, reactive routing uses considerable amount of energy for discovery, setup and maintenance of routes dynamically.

E.g: Dynamic source routing protocol (DSR) (Jamal and Kamal, 2004) , Ad hoc On-Demand Distance Vector (AODV) (Yang et al., 2009)

(iii) *Hybrid routing*

This method is the combination of proactive and reactive routing methodologies. The design of hybrid routing protocols is to combine the merits of proactive routing protocols and reactive routing protocols. This method of routing can be used as proactive or reactive or both, depending upon the application requirement.

E.g: Zone Routing Protocol (ZRP), Distributed Dynamic Routing algorithm (DDR), Hierarchical Cellular-Based Management (HCBM) (Yang et al., 2009)

1.3.1.2 Routing Protocols Classified based on Network Architecture

WSN routing protocols can be divided into three groups based on network structure.

(i) *Flat based routing*

In this type of routing, all nodes will be treated as equal either physically or functionally. No node is superior or inferior to other. These types of nodes are called Homogeneous nodes and these types of networks are called Homogeneous networks. Every node plays equivalent role in the network operations. Usually flat based routing involves many nodes for data transmission between the source and sink (Jing et al., 2009).

E.g: Sensor Protocols for Information via Negotiation (SPIN), Directed Diffusion (DD), Rumor routing, Gradient Based routing (GBR), Constrained anisotropic diffusion routing (CADR), COUGAR, ACQUIRE, Minimum Cost Forwarding Algorithm (MCFA), Information driven sensor querying (IDSQ), Energy Aware Routing (EAR) (Rajashree.V. et al., 2009; Jamal and Kamal, 2004).

(ii) *Hierarchical based routing*

Hierarchical routing is introduced for wired networks, later it is being proposed for wireless networks because of its advantages. In hierarchical based routing, few nodes are considered as powerful or higher energy nodes, which are used for data processing and transmission and the other category called low power or less energy nodes are used for sensing work. Here, powerful need not necessarily mean sensor node's battery power, it can be some other parameter also. These types of nodes are called Heterogeneous nodes and these types of networks are called Heterogeneous networks. Here sensor nodes will play different roles in the network operations. This type of routing uses clustering concept and nodes will be grouped into clusters to have some advantages like data aggregation, scalability, minimum routing overhead, efficient energy consumption etc in the network operations. Hierarchical routing has two levels of operations. In first level, cluster heads will be selected from the group of cluster, and in the second level, data will be routed to sink (Rajashree.V. et al., 2009).

E.g: Low-Energy Adaptive Clustering Hierarchy (LEACH), Power-Efficient Gathering in Sensor Information Systems (PEGASIS), Hierarchical PEGASIS, EAR, Threshold sensitive Energy Efficient sensor Network protocol (TEEN), APTEEN, Directed Query Dissemination(DirQ), Geographic adaptive fidelity (GAF), SPAN, Minimum Energy Communication Network (MECN), Small Minimum Energy Communication Network (SMECN), Self Organizing Protocol (SOP), Sensor Aggregate Routing (SAR), Virtual Grid Architecture Routing (VGA), Hierarchical Power-aware routing (HPAR), Two tier data dissemination(TTDD), Hybrid Energy-Efficient Distributed clustering (HEED) (Luis Javier Garca et al., 2009; Jamal and Kamal, 2004).

(iii) *Location based routing*

This routing approach uses nodes' geographical position to route the data between the nodes. This improves the performance of the network and it allows easy implementation of new strategies into the network. This method avoids flooding, but finding physical location of a sensor node using some techniques like Global Positioning System (GPS) introduces extra overhead on each and every sensor node (Rajashree.V. et al., 2009).

E.g: GAF, SPAN, GEAR, SPEED, GEAR, MFR, DIR, GEDIR, The greedy other adaptive face routing (GOAFR), MECN, SMECN, TBF, BVGF, GeRaF (Jamal and Kamal, 2004)

1.3.1.3 Routing Protocols Categorized based on Protocol Operation

Routing techniques are categorized into five groups depending upon protocol operations as follows. The protocol are:

(i) *multi-path Routing*

multi-path routing uses more than one path for data transmission, the number of paths to be used is application and protocol dependent, whereas single path routing uses only one path. If this path fails, new route discovery needs to be implemented, which consumes network resource there by reduces network lifetime. Multi-path routing enhances the performance of the network. In this routing, more than one route will be constructed during route discovery process. If one route, called primary path fails, the others, called alternate paths will be used to carry out network operations, which lessen the burden of re-discovering the paths. Because of this, the reliability of multi-path routing is high when compared to single path routing. As mentioned, multi-path routing forms multiple paths, say, n paths at one go, the number of paths to be used is again application dependent.

E.g: Sequential Assignment Routing (SAR), Maximum Lifetime Routing, Energy aware routing, Mesh Multi-path routing (M-MPR), DD, Sensor-Disjoint Multi-path, Braided Multi-path, N-to-1 Multi-path Discovery (Jamal and Kamal, 2004).

1.3.1.3.1 Types of Multi-path Routing

A multi-path routing protocol can choose to use either single path and keep the rest as backup, or it can use some or all the paths for the node communication. The most common criterion to distinguish a multi-path routing protocol is disjointedness of the path. Considering the nature of existing multi-path routing algorithms, we categorize them in to the following types (Zhenqiang et al., 2003):

(a) *Non-disjoint multi-path routing protocol*

This is the basic variety of Disjoint Multi-path routing protocol. In this, a node or link will be used more than once in a number of routes for data transmission between source and sink.

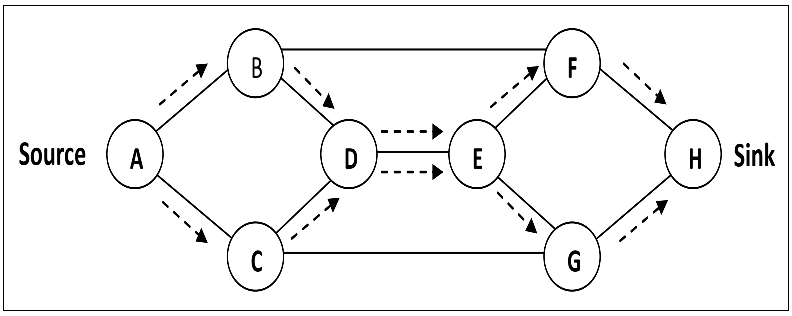


Figure 1.6 Non-disjoint multi-path routing

Fig.1.6 represents a simple example for Non-disjoint multi-path routing. From the Fig. 1.6 we have two routes, first one is A-B-D-E-F-H and the other is A-C-D-E-G-H. Here the nodes A and H represent Source and Sink respectively. If we observe nodes D and E, link DE are in common for both of the routes.

(b) *Node-disjoint multi-path routing protocol*

In this type of Disjoint multi-path routing protocols, different nodes will be used for establishing multiple routes between source and sink. One optimal path will be selected as Primary and others are alternate paths. Alternate paths should not intersect with primary path. No node is allowed to become a part of more than one route here. Fig.1.7 represents a simple Node-disjoint multi-path routing model.

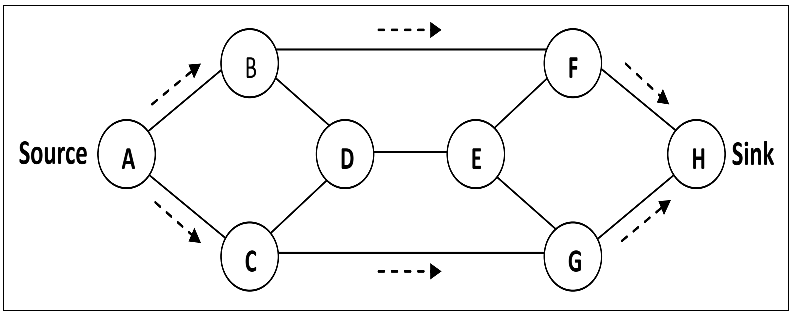


Figure 1.7 Node-disjoint multi-path routing

Here nodes A and H represents Source and Sink respectively. We have two routes in Fig.1.7, A-B-F-H and A-C-G-H, which use distinct nodes for communication between source and destination. It is clear that no node is in common to both of the routes. *E.g:* AOMDV, AODVM, SPIN, DD, LAND, Geographic multi-path routing protocol (GMP), energy-aware multi-path routing protocol (Ronghui and Haoshan, 2006).

(c) *Link-disjoint multi-path routing protocol*

In this type of multi-path routing protocols, different links will be used for establishing multiple routes between source and sink. No link is allowed to become a part of more than one route (Alka and Suresh, 2011). But, different routes can use same node for data transmission, which is shown in Fig.1.8.

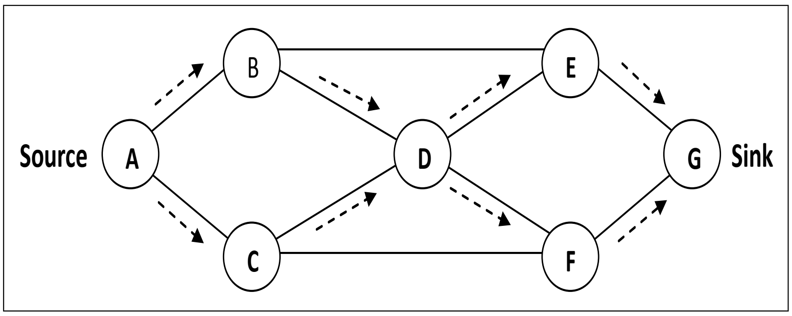


Figure 1.8 Link-disjoint multi-path routing

From Fig.1.8, node D is being used by two routes, A-B-D-E-G and A-C-D-F-G, but no link is in common for these routes. *E.g:* AOMDV, SPIN, DD, Split multi-path routing (Sung-Ju and mario, 2001).

(d) *Zone-disjoint multi-path routing protocol*

It is observed that if any two Link-disjoint or Node-disjoint multi-path routes are physically close enough to interfere with each other, then the sensor nodes compete with one another to access the shared medium. This leads to severe performance drop. Therefore, sometimes Unipath routing will perform better than multi-path with less energy cost and low routing overhead. Zone-disjoint multi-path routing has been introduced to overcome this problem.

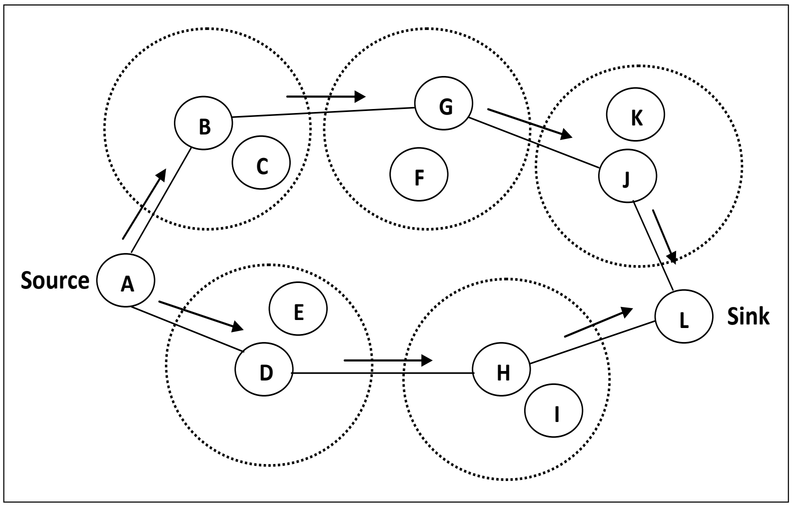


Figure 1.9 Zone-disjoint multi-path routing

Zone-disjoint multi-path routing protocols establishes multiple paths in such a way that no intermediate nodes of one path located in the neighborhood of intermediate nodes of another path. This means, the coupling factor of Zone-disjoint multiple paths is Zero and these two paths will not interfere while transmitting data between the nodes (Sung-Ju and mario, 2001).

E.g: Zone Multi-path Dynamic Source Routing (CZM-DSR), Multi-path Distance Vector Zone Routing Protocol (MDVZRP), Cluster-Based Multi-Path Routing (CBMPR) (Meghanathan, 2010).

(ii) *Negotiation based routing*

Negotiation based routing protocols use meta data called data descriptors to avoid redundancy during data transmission by negotiation among the sensor nodes. The main aim of this routing method is to overcome the drawbacks of flooding methodology and to avoid redundant data transmission. The negotiation between the sensor nodes will be done based on the descriptors that they use (Luis Javier Garca et al., 2009).

E.g: SPIN family protocols (Heinzelman et al., 1999).

(iii) *Query based routing*

In this method of routing, sink node sends query to interested area of network, nodes from that region reply back the sink with sensed data.

E.g: Rumor Routing (RR) (Jamal and Kamal, 2004)

(iv) *Quality of Service (QoS)*

Correspondence should be maintained between quality of data and network resources in QoS routing. This method of routing protocols should use minimum energy and provide high data quality (Akkaya and Younis, 2005).

E.g: SAR, SPEED, Energy aware routing, Energy aware QoS routing protocol

(v) *Network Flow*

This category of protocols are based on the flow of network activities. The network flow will be different from one application to another and the implementing routing technique should have the knowledge of network dynamics (Akkaya and Younis, 2005).

E.g: Maximum lifetime energy routing, Maximum lifetime data gathering, Minimum cost forwarding

1.3.1.4 Routing Protocols Classified based on Route Initiation

(i) *Source Initiated routing*

Here, source initiates route discovery process whenever it has data to send. This is one type of On-demand routing (Heinzelman et al., 1999).

E.g: SPIN (Jing et al., 2009)

(ii) *Destination Initiated routing*

In this case, destination initiates route discovery process when it needs data from the sensor nodes. It is one kind of query driven routing methodology (Jamal and Kamal, 2004).

E.g: Directed Diffussion (DD), LEACH (Heinzelman et al., 2002)

1.3.1.5 Routing Protocols Categorized based on Protocol Design Principle

(i) *Node-centric*

In this type, destinations are given identifiers or numerical addresses, using which sensor nodes send data. Giving such identifiers is not entertained in wireless sensor networks, therefore node-centric routing is not suggested for sensor network applications.

E.g: LEACH.

(ii) *Data-centric*

Query driven data model is one of the best examples for data-centric routing. Usually, WSN has huge number of sensor nodes deployed and sensor node cannot be given global identification, so, the data-centric concept came into existence. Here, destination sends queries to interested regions of the network to get data from the sensor nodes.

E.g: SPIN, Direct diffusion, COUGAR, ACQUIRE, SPEED, SAR, Rumor Routing, EAD, Information-Directed Routing, Gradient-Based Routing, Energy-Aware Routing (EAR), Information-Directed Routing, Quorum-Based Information Dissemination, Home Agent Based Information Dissemination, Flooding and gossiping, Gradient based routing, CADR (Akkaya and Younis, 2005).

(iii) *Geo-centric*

Geo-centric routing is also known as Location based or Location aware routing. Here, nodes use geographical location for routing operations. Geographic location will be given to sensor nodes by using techniques like Global Positioning System

(GPS), which plays important role in influencing network performance and use non flooding method for routing. New strategies and services like resource discovery, data dissemination etc can be implemented easily using physical location in this method of routing (Luis Javier Garca et al., 2009).

E.g: Geographic adaptive fidelity (GAF) (Xu et al., 2001)

(iv) *Mobility based routing*

Mobility of sensor nodes has to be taken good care of while designing a routing protocol for wireless sensor network. Mobility patterns will be varied from application to application. Developing a routing protocol for mobile sensor node networks is a very challenging task.

E.g: SEAD, TTDD, Joint Mobility and Routing, Data MULES, Dynamic Proxy Tree-Base Data Dissemination (Shio Kumar et al., 2010).

(v) *Heterogeneous*

There are two types of sensor nodes available: one, nodes with energy constraint and nodes without energy constraint. If a network has both types of nodes then it could be considered as Heterogeneous network. Designing a routing protocol for Heterogeneity network is much difficult than homogeneity networks, where all nodes are of same type.

E.g: IDSQ, CADR, CHR (Shio Kumar et al., 2010).

1.4 ORGANIZATION OF THE THESIS

Chapter 1 discusses fundamentals of wireless sensor networks and highlights important issues in designing and implementation of sensor network applications. Organization of the thesis is presented at the end of the chapter.

Chapter 2 presents related literature work concerned to this thesis along with their limitations. High level list of goals set to achieve with the research work are given and are briefly explained at the end of the chapter.

Chapter 3 introduces *Base station Assisted Novel network Design Space* for edge-based wireless sensor networks. It points out the importance and advantages of edge-base-station to meet up-to-the-minute requirements of wireless sensor network. Mathematical and conceptual model of proposed network design space is presented in this chapter. Simulation results are furnished to evaluate the behavior of the proposed network design space in comparison with existing network architectural models. The role of edge-base-station in post deployment operations is highlighted at the end of this chapter.

Chapter 4 presents a *Zone-Based Routing Protocol* for edge-based wireless sensor networks. This chapter discusses the importance of clustering technology and network architectural models. The proposed routing protocol is discussed in detail and its cluster head selection mechanism is explained. Simulation results are presented at the end this chapter to illustrate the characteristics of the proposed routing protocol.

Chapter 5 proposes an *Energy-efficient UnEqual Clustering algorithm* for edge-based wireless sensor networks. This chapter presents disadvantages of existing unequal clustering mechanisms and explains characteristics of EUEC. Also, a disjoint multi-hop routing protocol is proposed to distribute network load uniformly among different data transmitting routes in the network. Last section presents extensive experimental results of EUEC in comparison with another well known existing unequal clustering algorithm, EEUC.

Chapter 6 describes an *Energy-efficient Hybrid Clustering Mechanism* for edge-based wireless sensor networks to overcome scalability issues. This chapter details the importance of cluster size on network performance and explains EHCM implementation in detail. The detailed simulation results are illustrated at the end of the chapter to infer the behavioral characteristics of proposed clustering scheme over existing algorithms.

Chapter 7 concludes and summarizes the research work along with the recommendations for further possible directions in the research field. List of research publications are given at the end of this chapter.

Chapter 2

LITERATURE REVIEW

2.1 RELATED RESEARCH WORK

In this section, topics related to wireless sensor network design spaces, routing and clustering algorithms are reviewed in connection with the present work. Many clustering algorithms and cluster based routing protocols are proposed for wireless sensor networks in the literature. In the recent past, many algorithms were proposed specially towards effective data communication and data processing with optimal resource usage in sensor networks.

2.1.1 SPIN (Heinzelman et al., 1999): The basic idea of SPIN is to name the data using high-level descriptors called $Meta-data$ instead of sending all the data that is collected, which is the key feature of SPIN. By eliminating redundant data, sensor nodes operate more efficiently and conserve energy resources. Before sending a message, sensor node broadcasts an advertisement message containing a descriptor of the information. If a neighbor is interested in that data, it sends a request message to sender for the information and it is sent to this neighbor node. This process repeats for every interested neighbor node and will get a copy of the data. SPIN avoids redundant message transmission of flooding, overlapping of sensing areas and resource blindness by the meta-data negotiation. By this, SPIN achieves energy efficiency with reduced redundant data transmission in the network. Furthermore, the topological changes are localized since each node needs to know only its single-hop neighbors. However, the data advertisement mechanism of SPIN does not guarantee reliable data delivery process. For instance, if a node is interested in the data is far away from source node and the relay nodes between source and destination are not interested in that data, then the data will not be delivered to the interested node.

2.1.2 TEEN (Manjeshwar and Agrawal, 2001): Threshold sensitive Energy Efficient sensor Network protocol (TEEN) is a hybrid protocol of hierarchical clustering and data-centric approaches designed for time-critical applications, which responds to sudden changes in the sensing field. The network architecture is based on a hierarchical grouping where closer nodes form clusters and this process continues to second level and higher levels until base station is reached. Once the clusters are formed, cluster heads broadcast two thresholds values to their cluster members: Hard and soft thresholds. A sensor node will report data only if the sensed value is beyond the hard threshold or the change in the value is greater than the soft threshold. Using this, the number of data packets transmitted is controlled by adjusting the hard and soft threshold values. However, TEEN is not suitable for applications where data is delivered periodically, because the values of the attributes may not reach the threshold at all. In TEEN, the messages are transmitted using multi-hop cluster head to cluster head communication. If a cluster head is not in the radius of other cluster head's transmission radius, the data packet will be dropped. An AdaPtive Threshold sensitive Energy Efficient sensor Network protocol (APTEEN) (Manjeshwar and Agrawal, 2002) is proposed as an extension of TEEN to overcome periodic data collection and react to time-critical events.

2.1.3 GAF (Xu et al., 2001): Geographical Adaptive fidelity (GAF) is an energy-aware location-based routing algorithm for mobile ad-hoc networks. Each node is equipped with Global Positioning System (GPS) to associate itself with a given point in the virtual grid. Nodes with same point on the grid are considered to be equivalent in terms of cost of data packet routing. GAF establishes a collaboration between the nodes to play different roles in each zone. There are three states defined in GAF: Discovery of neighbors in the grid, active reflecting participation in data routing and sleep when the radio is turned off. The sleep time and related parameters are application dependent and can be fine tuned while routing data packets. The sleeping neighbors adjust their sleep time by using routing fidelity and load balancing. With this, GAF improves network lifetime as the number of nodes increases in the network field. To handle the mobility, each node in the grid computes estimated leaving time of grid and sends this to its neighboring nodes, which keeps the network connected by maintaining a active cluster header always for each zone on its virtual grid. However, cluster header in GAF does not support data aggregation as in the case of other hierarchical protocols.

2.1.4 GEAR (Yu et al., 2001): Geographic and Energy Aware Routing (GEAR) use geographic information for disseminating queries to required parts in the network since data queries often include geographic attributes. With this, GEAR restricts the number of interests in directed diffusion by considering a certain region rather than sending the interests to the whole network. Each node maintains an estimated cost and a learning cost to reach destination through its neighbors. The estimated cost is a combination of residual energy and distance to destination and, learning cost is a refinement of the estimated cost that accounts for routing around holes in the network. A hole occurs when a node does not have any closer neighbor to the target region than itself. If there are no holes, the estimated cost is equal to the learned cost. The learned cost is propagated one hop back every time a packet reaches the destination so that route setup for next packet will be adjusted. But, the maintenance cost of estimated cost and learning cost brings additional overhead to the network.

2.1.5 SPAN (Chen et al., 2001): SPAN is a power saving technique for multi-hop ad-hoc wireless networks that reduces energy consumption without diminishing connectivity of the network. Based on nodes position, it selects few nodes as coordinators. It activates only a fraction of nodes in a certain area at any given point of time. The selected coordinators form the network backbone used to forward messages while data is being forwarded. A node becomes a coordinator if two neighbors of a non-coordinator node cannot reach each other directly or via one or two coordinators. However, the energy consumption increase in SPAN as the number of nodes raises in the network.

2.1.6 LEACH (Heinzelman et al., 2002): The Low-Energy Adaptive Clustering Hierarchy (LEACH) is one of the most popular distributed cluster-based routing protocols for wireless sensor network. Sensor nodes organize themselves into clusters with one node acting as the cluster head. LEACH utilizes the randomized rotation of cluster heads to balance the energy dissipation of nodes. The cluster heads not only collect data from their clusters, but also aggregate the collected data to reduce the amount of messages to send to the base station, which enhances the network lifetime. Each node has a certain probability to become cluster head for each data forwarding round, and the task of being a cluster head is rotated among the nodes. The cluster head decision made is independent of other nodes to minimize overhead in cluster head selection mechanism. Each node first chooses a random number between 0 and 1. A sensor node becomes a cluster head for the current data forwarding round if the selected number is less than the following threshold:

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

where $P =$ desired percentage of cluster heads, $n =$ given node, $r =$ current round and $G =$ set of nodes that have not been cluster-heads in the last $\frac{1}{P}$ rounds.

The elected cluster head broadcasts an advertisement to its neighboring nodes. Non-cluster head nodes join the current round cluster head based on the received signal strength of the broadcasted message. Then, the cluster head creates TDMA slots for each cluster member and broadcasts the same to all its members. The cluster head role in LEACH is rotated in regular intervals of time among sensor nodes, which makes LEACH completely distributed. However, LEACH is single-hop routing algorithm, where each node communicates directly with cluster-head and the sink. Therefore, it does not serve the requirement of real world applications. Furthermore, the cluster head rotation incurs extra control overhead on energy resources of sensor nodes.

2.1.7 PEGASIS: Lindsey and Raghavendra (2002) introduced a chain-based clustering routing protocol, Power-Efficient Gathering in Sensor Information Systems (PEGASIS). This routing protocol is considered as an improvement over LEACH routing algorithm. The main aim of PEGASIS is to minimize the intra cluster communication overhead of LEACH protocol. The key idea of PEGASIS is to form chains with close by neighboring nodes using greedy approach. Each chain chooses a leader node to forward data to base station. Like LEACH, PEGASIS is also a single hop routing protocol.

2.1.8 Directed Diffusion (Intanagonwiwat et al., 2003): Directed diffusion uses attribute-value pairs for data and queries sensor nodes based on demand by using those pairs. The sink node requests for data by broadcasting interest through its neighboring nodes. Node which receives the interest will do caching for sink node in later stages. The intermediate nodes aggregate data using data's name and attribute-value pairs. Sensor node that receives the interest sets-up a gradient value toward the sensor nodes from which it receives the interest. The gradient includes data rate, duration and expiration time. By using, interest and gradients, paths are established among sources and destination. The sensed information is then forwarded in the reverse path of the interested nodes. Directed diffusion is different from SPIN in terms of the on-demand data querying mechanism. Directed diffusion use neighbor-to-neighbor communication model with no need for a node addressing mechanism. Since it is on demand and there is no need for maintaining global network topology, directed diffusion is energy efficient. But, the matching process for data and queries might incur some additional overhead on sensors resources. Also, it is highly application dependent due to its naming schemes which should always be defined in prior.

2.1.9 GeRaF (Zorzi and Rao, 2003): Geographic Random Forwarding (GeRaF) provides a complete solution combining the features of routing and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism as Media Access Control (MAC) layer. But, to find data relaying node GeRaF requires location information of sensor nodes' and their neighbors'. Therefore, GeRaF consumes more power and increases network latency.

2.1.10 HEED: Younis and Fahmy (2004) introduced Hybrid Energy-Efficient Distributed clustering (HEED), a multi-hop wireless sensor network clustering algorithm. Unlike LEACH, HEED does not select cluster heads randomly. In HEED, cluster heads are elected based on two parameters: residual energy and intra-cluster communication cost. Every node elects least communication cost cluster head to join it. But, HEED cluster head selection strategy creates more number of cluster heads than expected and this leads to variation in energy consumption in the network. Also, this may result in poor network coverage. Since HEED does several iterations to form clusters, network lifetime decreases with increased energy dissipation. Cluster heads near base station may die sooner because of heavy relay traffic. This is known as the *Hot-spot problem* (Liu, 2012).

2.1.11 EEUC: To address hot spot problem, Li et al. (2005), introduced an unequal clustering mechanism, Energy Efficient Unequal Clustering (EEUC) to balance energy consumption among cluster heads. EEUC is a competitive distributed unequal clustering algorithm, where cluster heads are selected based on residual energy and distance from the base station. EEUC forms small clusters near base station and the size of clusters increases as the distance progresses. Thus, the cluster heads close to base station preserve energy for inter-cluster communication. EEUC is a probabilistic clustering algorithm, where in each cluster head rotation round, each node generates a random number between 0 and 1 to decide whether it is going to participate in the cluster-head competition or not. The author also proposed an energy aware multihop routing protocol for inter-cluster communication in EEUC mechanism. Besides, EEUC creates huge and varied number of cluster heads based on parameters like r_{comp}, c etc from round to round and does not guarantee different cluster head nodes for each round.

2.1.12 UCS: Soro and Heinzelman (2005) proposed Unequal Clustering Size (UCS) network organization model for sensor networks. The main aim of UCS is to enhance the network lifetime by distributing the load uniformly among cluster heads, whose positions are predetermined. Having base station at center of the network, the cluster heads are arranged symmetrically in concentric circles in two levels called, Layers. Respective clusters in their respective layers are of same size and shape with cluster heads at center. But, the cluster size and shape differ from layer to layer. The aggregated data from cluster heads will be delivered to sink node through cluster head to cluster head communication. Moreover, predefined positions for cluster heads is not advisable for real-time applications. Also, layered approach proposed does not suite large scale networks.

2.1.13 BeamStar: Mao and Hou (2007) have introduced a novel edge-based routing protocol, called BeamStar for wireless sensor networks. The aim of BeamStar is to reduce the size and cost of the sensor node. This protocol utilizes infrastructure potential provided by an edge based network to carry out the network operations. It assumes that, the network is equipped with a directional antenna with power control capabilities. The power controlled capability base station scans the complete network with different power transmission levels in different angles to provide location information for the nodes. With this location information, sensor nodes can en-route sensed data to base station using controlled broadcasting mechanism. The data is forwarded by using simple forwarding rules provided by the base station. As flooding is being used for data transmission, it does not guarantee data delivery and causes energy wastage. The control overhead involved for regular network health check-up is very high.

2.1.14 EEDUC: Lee et al. (2008), have proposed another unequal clustering algorithm, Energy-Efficient Distributed Unequal Clustering (EEDUC) algorithm, in which cluster heads are distributed by using their waiting time. The waiting time is computed using the parameters, residual energy and number of neighbors. EEDUC is an extension of EEUC (Li et al., 2005) mechanism. Here also, clusters closer to the base station have smaller size than those farther away from the base station. It considers relay traffic for selecting cluster head to forward data towards base station. Since EEDUC uses traffic load to determine relay node, it may not guarantee a reliable data path.

2.1.15 PEZ: Bai et al. (2009) introduced a multi-hop unequal clustering algorithm, Power-Efficient Zoning Clustering Algorithm for wireless sensor network (PEZ), to extend network lifetime by minimizing energy consumption. It is developed based on two most popular clustering protocols, LEACH and PEGASIS. PEZ divides its network into fan-shaped regions placing the base station at the center. Each region is considered as a cluster. Multi-hop data communication delivers data to BS. Like UCS, PEZ also uses layered network model which limits its applicability to small scale networks. Due to the lack of control on clusters formation, PEZ forms randomly varied number of clusters and causes uneven energy dissipation among sensor nodes.

2.1.16 CHIRON: Kuong Ho et al. (2009) proposed a routing protocol for edge-based wireless sensor networks, called, CHIRON. It is developed based on one of the most popular hierarchical routing protocols, PEGASIS (Lindsey and Raghavendra, 2002). Also, it uses the same technique as that of BeamStar (Mao and Hou, 2007) to provide location information for the nodes in the network. It outperforms BeamStar with respect to delay time and network lifetime. CHIRON's data transmission process is same as PEGASIS (Lindsey and Raghavendra, 2002) routing protocol. However, the data forwarding mechanism used is unreliable as it forwards data randomly towards the destination node. Also, increase in the network growth results long chain formation and causes adverse effect on network performance.

2.1.17 Cluster based BeamStar (CBS): To overcome the drawbacks of BeamStar, Li and Yang (2009) proposed a routing protocol for edge-based wireless sensor networks called, Cluster-based BeamStar. It uses the same concept of BeamStar to provide location information for sensor nodes with refined sensing process. CBS outperforms BeamStar in efficient usage of power, inter-node communication and scan time. CBS uses LEACH (Heinzelman et al., 2002) routing protocol to transmit data among nodes and node with maximum residual energy will be elected as cluster head, just like CHIRON (Kuong Ho et al., 2009). But, the radius selection strategy used creates huge number of rings with increase in network size. As a result, CBS forms several clusters and clogs the sensor network.

2.1.18 EDUC: An Energy-Driven Unequal Clustering (EDUC) (Yu et al., 2011) uses uneven competition ranges to build uneven size clusters. Clusters far away from base station have smaller sizes to preserve some energy for inter-cluster communication. Cluster head roles are rotated depending upon the energy reserves of cluster heads to minimize energy dissipation. Each node acts as a cluster head no more than once during its network lifetime. The energy levels are computed accurately in cluster head rotation mechanism based on the assumption that, the cluster heads have single-hop communication route from the base station, which is not always an appropriate for real time applications. Also, the energy levels estimation scheme proposed in this paper does not suit for multi-hop data transmission environment.

2.1.19 EBCAG: Liu et al. (2012) introduced Energy-Balancing Clustering Approach for Gradient-based Routing (EBCAG) in wire less sensor networks. It aims at achieving the energy balance among cluster heads, decreasing the total energy consumption of a network, and prolonging the lifetime of the network. It sets up a gradient value for each sensor node according to the minimum hop count towards the sink. In order to balance the energy consumption at different cluster heads, the network will be organized via unequal clustering. The data gathered from the cluster members should follow the direction of descending gradient to reach the sink. Gradient based data routing process would result in difference in load distribution among data forwarding routes, there by causing uneven energy dissipation in the network.

2.1.20 HMCR: Zeng and Dong (2016) present an encoding method for harmony memory based on the characteristics of WSNS routing. The paper has introduced a dynamic adaptation for the parameter Harmony Memory Considering Rate(HMCR) to avoid the prematurity in early generations and strengthen its local search ability in late generations. The adjustment process of harmony search algorithm has been discarded to make the proposed routing algorithm contain less parameters. Also, an effective local search strategy is proposed to enhance the local search ability, so as to improve the convergence speed and the accuracy of routing algorithm.

2.1.21 EELB: A novel load balancing scheme that balance the energy consumption of the sensor nodes and maximum network lifetime by load balancing applying the sub-network management in wireless sensor networks is proposed in (Kim, 2016). The proposed scheme takes into account load balancing of individual nodes to maximize the system lifetime. Then, the authors propose a scheme using analytical models to compare the results with previous research works. These result shows that the sensor nodes operate together for full network lifetime and it indicates maximum utilization of the usable energy of the wireless sensor network.

2.1.22 UCRA: A distributed underwater node self-deployment algorithm is proposed in (Jiang et al., 2016). Here, each node begins the uneven clustering based on the distance on the water surface. Each cluster head node selects its next-hop node to synchronously construct a connected path to the sink node. Then, the cluster head node adjusts its depth while maintaining the layout formed by the uneven clustering and then adjusts the positions of in-cluster nodes. The algorithm originally considers the network reliability and energy consumption balance during node deployment and considers the coverage redundancy rate of all positions that a node may reach during the node position adjustment. Simulation results show, compared to the connected dominating set (CDS) based depth computation algorithm, that the proposed algorithm can increase the number of the nodes near the sink node and improve network reliability while guaranteeing the network connectivity rate.

2.1.23 EBCADD: Zheng et al. (2016) propose an Energy-Balanced Clustering Algorithm based on Distance to the base station and neighbor Distribution (EBCADD) to generate clusters in wireless sensor networks with random distribution. In order to minimize the energy consumption of entire network, a cluster has a larger cluster size as increasing distance from the base station. The optimal node became cluster head on the basis of the residual energy and neighbor distribution in cluster head election process. Besides the algorithm controls the size of cluster based on threshold size in terms of the number of the nodes per cluster to form an appropriate architecture of the network topology. Simulation results demonstrate that the new algorithm can establish more balance-able clustering structure effectively in uniform and nonuniform distribution of nodes, and prolong the network life.

2.1.24 ELEACH: An Efficient LEACH(ELEACH) protocol is proposed in (Deshmukh and Gawali, 2016). ELEACH selects CHs based on results on Voronoi tessellations from stochastic geometry and remainant energy in the member node devices. A novel method is used in the proposed protocol to choose the CHs wherein the CHs and member nodes of clusters are distributed as two independent homogeneous spatial Poisson Point Processes (PPPs). Probability of selecting the CHs and threshold is derived using results from spatial statistics. The Proposed algorithm selects optimum number of CHs leading to reduction in total energy spent in the network compared to conventional LEACH and other such algorithms. The network life is measured by number of rounds. Monte-Carlo simulations are carried out for performance analysis of LEACH, TEEN and other PPP based protocols. Furthermore, total energy dissipated in the network for each round is fairly constant throughout the network life.

2.1.25 NFEACS: In (Julie and Selvi, 2016), a neurofuzzy energy aware clustering scheme (NFEACS) is proposed to form optimum and energy aware clusters. NFEACS consists of two parts: fuzzy subsystem and neural network system that achieved energy efficiency in forming clusters and cluster heads in WSN. NFEACS used neural network that provides effective training set related to energy and received signal strength of all nodes to estimate the expected energy for tentative cluster heads. Sensor nodes with higher energy are trained with center location of base station to select energy aware cluster heads. Fuzzy rule is used in fuzzy logic part that inputs to form clusters.

2.1.26 CCM: Tang et al. (2010) propose a routing algorithm called CCM (Chain-Cluster based Mixed routing), which makes full use of the advantages of LEACH and PEGASIS, and provide improved performance. CCM divides a WSN into a few chains and runs in two stages. In the first stage, sensor nodes in each chain transmit data to their own chain head node in parallel, using an improved chain routing protocol. In the second stage, all chain head nodes group as a cluster in a self-organized manner, where they transmit fused data to a voted cluster head using the cluster based routing.

2.1.27 DEEH: A new decentralized hierarchical cluster-based routing algorithm for WSNs is proposed in (Sabet and Naji, 2015). The most of energy consumption occurs due to transmission of messages, such as data and control packets. In our new approach clustering and multi hop routing algorithms are performing at the same stage to decrease control packets. According to non-uniform energy consumption among nodes, clusters are formed in such a way that cluster heads have the most competency in forwarding task of intra-cluster and inter-cluster transmission tree. Energy consumption, adjustment degree and the exact distance that each data traverses to reach the base station are three main adjustment parameters for cluster heads election.

2.1.28 EEADC: In Yu et al. (2012), a cluster-based routing protocol for wireless sensor networks with nonuniform node distribution is proposed, which includes an energy-aware clustering algorithm EADC and a cluster-based routing algorithm. EADC uses competition range to construct clusters of even sizes. At the same time, the routing algorithm increases forwarding tasks of the nodes in scarcely covered areas by forcing cluster heads to choose nodes with higher energy and fewer member nodes as their next hops, and finally, achieves load balance among cluster heads.

2.2 GAP ANALYSIS

From the literature review, the following points have been noted.

1. It is observed from the literature that, most of the current efforts on sensor network research have limited their design space solely to the sensor nodes themselves.
2. In the previous efforts, control overhead is heavy on network resources when performing control and managerial operations in the network.
3. Network architecture based routing protocols proposed previously are tightly coupled to their network design spaces.
4. Control overhead involved in rotating cluster head role among sensor nodes and formation of clusters is high in the existing clustering algorithms.
5. In unequal clustering mechanism, clusters are constructed using variable transmission power levels, which would create coverage holes with poor selection of network parameters.
6. Uneven size clusters formation causes construction of irregular number of clusters in each data forwarding round. Random number of clusters in different cluster sizes for each data transmission round leads to uneven energy dissipation among sensor nodes in the network.
7. Lack of control on number of clusters built in unequal clustering mechanisms, introduce scalability problems as the network size varies.
8. Further more, as cluster formation depends on base station distance in unequal clustering techniques, it doesn't guarantee a fully connected network.

2.3 MOTIVATION

In wireless sensor networks, sensor nodes are often equipped with one or more low powered sensors, a processor, less memory, a power supply, a radio and an actuator (Ren and Yu, 2005). Limited and non-renewable energy resource of a sensor node has been a primary concern in design and development of sensor network applications (Lee et al., 2011). Additionally, the sensor network bandwidth is much lower than wired communications and radio operations are relatively expensive compared to pure computation. The sensor networks are less reliable than common network systems. Depending upon the configuration of network and environment circumstances, wireless links may become degraded or unviable. These factors make the design of sensor network applications very special and different from other networking technologies (Taherkordi, 2011).

Growth in the usage of sensor network applications introduces several new requirements. Since sensor nodes operate mostly in environments that are human unattended and vary dynamically, the need for timely adaptations, raise significant challenges for enabling sensor zest behavior. To address these requirements, one needs to study the fundamental issues of sensor network reconfiguration, sensor node software up-gradation, dead node distribution, etc. to enable dynamicity in sensor network. To meet the requirements, sensor network has to sacrifice most of its energy resources to exchange a lot of control information among sensor nodes. It is observed that most of the current efforts on sensor network research have limited their design space solely to the sensor nodes themselves. Under such an approach, the burden of achieving complex networking functions (for example, topology control, routing, localization, synchronization, and so forth) all rests upon the sensor nodes in the network core (that is, a core-based paradigm).

Sensor nodes are resource constrained with limited computational and communicational capabilities, whereas a base station is resource abundant and constraint-free network component in wireless sensor network. The potential properties like, unlimited energy sources, huge memory, high computational power, constraint free network operations, unrestricted behavioral characteristics make base station as a valuable asset for wireless sensor network. Therefore, by exploiting the base station characteristics, the functional complexities in existing and upcoming algorithms and protocols can be simplified. This prompts us to explore complete functionalities of wireless sensor network base station to achieve overhead-free control and managerial operations, and, implement less-complex clustering and routing algorithms.

2.4 RESEARCH OBJECTIVES

The high level research objectives of this dissertation are listed below.

1. To propose a novel network design space for edge based wireless sensor networks to explore and exploit full capabilities of edge-base-station.
2. To design a cluster-based routing protocol for wireless sensor networks to enhance network lifetime.
3. To develop an energy-efficient unequal clustering algorithm to enable uniform energy dissipation across the network.
4. To propose an energy-efficient and easily scalable clustering algorithm for wireless sensor networks to elevate network lifetime.

2.5 RESEARCH CONTRIBUTION

This section briefly explains the research objectives.

2.5.1 Towards Research Objective 1: A Novel Edge-based Network Design Space

To explore and exploit edge-base-station capabilities, a *Base station Assisted Novel Network Design Space (BANDS)* is proposed for edge-based wireless sensor network in Chapter 3. In this thesis, sensor network is called *Edge-based Wireless Sensor Network* because the base station is located at one corner of the network. Also, the base station is termed as *Edge-base-station* since it is located at one edge of the network (this is, an edge-based approach). The proposed network design space reduces control overhead burden on sensor nodes to perform control and managerial functions using edge-base-station. It has the potential to simplify complex operations in upcoming algorithms and protocols by offering new possibilities to meet emerging application requirements. The proposed network model assumes that the base station in the network is equipped with a power controlled capability directional antenna. Unlike sensor nodes, the base station is resource abundant in-terms of energy, memory, processing power and communication abilities. The proposed network design space exploits functionalities of edge-base-station to meet up-to-the-minute requirements of WSN. The edge-base-station can reach any part of the network by varying its transmission power level and beam width. Using this advantage, network administrator can perform tasks like, updating routing information, giving identities to sensor nodes, querying for data, patching software updates, cluster formation, identifying communication holes, distributing dead nodes etc., with little control overhead on sensor nodes. The proposed network partitioning scheme divides sensor network into several equally spaced partitions called, *Zones*. Base station provides identities to sensor nodes in each zone by changing its transmission power levels in different angles during network deployment phase. Nodes in each zone will be assigned with unique identity with which sensor nodes can be distinguished from one zone to other. The proposed network architectural model helps network to form clusters and perform data transmission with little network cost. Experimental results prove that the proposed network design space shifts control overhead from sensor nodes to base station and conserves network resources.

2.5.2 Towards Research Objective 2: A Zone based Routing Protocol

Several cluster-based routing algorithms have been developed in the last few years, (Mao and Hou, 2007; Kuong Ho et al., 2009; Li and Yang, 2009; Soro and Heinzelman, 2005; Bai et al., 2009; Liu et al., 2012) based on different network architectural models focusing on either one or more design aspects of WSN applications. Routing algorithm and its network model are tightly dependent on each other which means, change in network architecture requires corresponding modification in routing algorithm also. And, each technique will incur significant additional cost on sensor node to perform network control operations. Based on the proposed network design space, BANDS, a *Zone-Based Routing Protocol (ZBRP)* is proposed for edge-based wireless sensor networks in Chapter 4. The proposed network design space divides sensor network into several equally spaced zones. With uniform node deployment, ZBRP creates even size clusters with no extra burden on network resources. The proposed multi-hop routing protocol uses random back-off timers in which communication cost is the primary parameter to select cluster heads for each data forwarding round in every cluster. For multi-hop data transmission, cluster head from downstream close to base station having high residual energy with less number of packets relayed will be chosen as a relay node. From the simulation results, it is observed that the proposed routing protocol conserves network resources and improves network lifetime.

2.5.3 Towards Research Objective 3: An Energy-efficient Unequal Clustering Algorithm

In multi-hop data transimmison model, even size clustering causes *Hot-spot problem* due to uneven energy consumption among cluster heads. Unequal clustering mechanism balances energy consumption among inter cluster communications but not in intra-cluster communication. It will introduce several other problems like, poor network coverage in large and sparsely populated wireless sensor networks, dynamic size clusters rise the hop count between source and destination, irregular cluster sizes cause uneven energy consumption among sensor nodes in intra-cluster communication, high control overhead is involved in cluster formation and route maintenance due to random sizes and zig-zag route patterns, etc. To overcome these problems, an *Energy-efficient UnEqual Clustering algorithm (EUEC)* is proposed for edge-based wireless sensor networks in Chapter 5. The primary goal of the proposed algorithm is to avoid hot-spot problem with uniform energy dissipation among cluster heads. For this, it creates limited and equivalent number of clusters across different levels of the network. This will limit number of clusters it forms and enables consistent hop count between the source and destination. EUEC uses the proposed network design space to form initial level clusters in the network. Even number of clusters in each level ensures concentrated clusters near base station to avoid heavy relay burden on cluster heads. Uniform number of clusters in each level promotes invariable energy dissipation among cluster heads across different levels. Data communication is one of the heavy energy consuming operations observed in wireless sensor network. To balance network load among different data forwarding routes, a disjoint multi-hop routing mechanism is proposed. In this model, source node chooses a relay cluster head which has greater residual energy and, minimum hop-count with base station and itself in the downstream. This distributes network load uniformly among cluster heads in different data forwarding routes. Simulation results show that the proposed unequal clustering algorithm avoids hot-spot problem with uniform energy dissipation among the limited number of clusters it forms and enhances network lifetime. From the results, it is observed that the proposed multi-hop routing protocol distributes network load evenly among data forwarding routes and balances energy consumption among cluster heads.

2.5.4 Towards Research Objective 4: An Energy-efficient and easily Scalable Clustering Mechanism

Cluster size is one of the most important factors that influences network operations directly, because large number of clusters will congest the network field with small size clusters and a very small number of clusters will exhaust the cluster heads with large amount of messages transmitted from cluster members. Therefore, the number of clusters to be formed should be decided carefully to minimize the trade-off between intra and inter cluster communication. In the previously proposed clustering model, number of clusters needed raises with network size or with poor network radius selection causes *scalability issues*. To overcome hot-spot problem without scalability issues, a novel unequal clustering technique called, *Energy-efficient Hybrid Clustering Mechanism (EHCM)* is proposed for edge-based wireless sensor networks in Chapter 6. EHCM combines features of equal and unequal clustering techniques to propose hybrid clustering mechanism to achieve hot-spot free network with minimum number of clusters. It creates *dynamic number of clusters* based on sensor node location information i.e., level number and zone number. EHCM constructs both equal and unequal clusters at each level to distribute network load uniformly across the network. Like EUEC, EHCM creates small size clusters near base station in limited number to avoid hot-spots in the network. Experimental results prove that the proposed hybrid clustering algorithm achieves uniform energy consumption among cluster heads and enables hot-spot free network with optimal number of clusters in the network. It is also inferred from the results that, EHCM elevates network lifetime without scalability issues.

2.6 SUMMARY

This chapter summarizes well-known clustering and routing algorithms for wireless sensor networks along with their drawbacks. Based on the limitations discussed, the gap between the previous and present research work has been presented and, the motivation for this research work has been detailed. At the end of the chapter, the high level list of research goals are given and are briefly explained.

Chapter 3

BASE-STATION ASSISTED NOVEL NETWORK DESIGN SPACE

Emerging wireless sensor network applications introduce several new requirements like, network reconfiguration in regular intervals to meet future unpredictable needs, remote maintenance of sensor software, adapting up-to-the-minute functionality changes in heterogeneous environments, and remote patching of sensor software to handle after-deployment faults. To address these requirements, one needs to study the fundamental issues of wireless sensor networks like network reconfiguration, sensor node software up-gradation, dead node distribution etc., to enable dynamicity in sensor network (Taherkordi, 2011). Sensor nodes on-board energy resources are limited and non renewable. Constrained sensor nodes' resources have been a primary concern in designing every sensor network application. Wireless sensor network sacrifices most of its energy resources to exchange control and managerial information among sensor nodes to meet up-to-the-minute requirements of applications. Numerous number of algorithms and protocols have been developed in the last few years, to achieve high energy efficiency and increase network scalability. However, what has been lagging behind in the progress is the complexity and control cost on a sensor node. It is observed that most of the current efforts on sensor network research have limited their design space solely to the sensor nodes themselves. Under such an approach, the burden of achieving complex networking functions (for example, topology control, routing, localization, synchronization, and so forth) all rests upon the sensor nodes in the network core (that is, a core-based paradigm). Sensor nodes are resource constrained with limited computational and communicational capabilities, whereas a base station is resource abundant and constraint-free network component in wireless sensor networks. By exploiting base station characteristics, the functional complexities in existing and upcoming algorithms and protocols can be simplified. Mao and Hou (2007) have proposed a routing protocol called, BeamStar, to reduce complexity burden on sensor nodes by tapping into base station capabilities. In the same context, many clustering algorithms and routing protocols ((Kuong Ho et al., 2009; Li and Yang, 2009; Bai et al., 2009; Liu et al., 2012)) have been proposed in the recent past. But, all the previous efforts have not fully explored the advantages of base station.

To explore and exploit full capabilities of edge-base-station, a *Base station Assisted novel Network Design Space (BANDS)* is proposed for edge-based wireless sensor network in this chapter. The main aim of BANDS is to reduce control overhead on sensor nodes using edge-based capabilities while performing control and managerial functions like, network reconfiguration, dead node distribution, patching information etc. It is assumed that the base station in the network is equipped with power controlled capability directional antenna. By varying directional antenna's transmission power level and beam width, base station can reach any part of the network. Using this advantage, one can, provide identities to sensor nodes, query for sensed data, update software of sensor nodes, reconfigure the network, update routing information, schedule timers, etc., with little burden on sensor nodes resources.

3.1 PRELIMINARIES

This section presents the list of assumptions made in the thesis and set of goals to be achieved using the proposed novel network design space.

3.1.1 Assumptions

The following assumptions are made for the research work presented in this thesis.

1. All sensor nodes are homogeneous with same capabilities.
2. Nodes are not equipped with Global Positioning System (GPS) capable unit and are location unaware.

3. The base station in the network is equipped with power controlled capability directional antenna and is located at one corner of the sensing field.
4. Every node is capable to change its transmission power level depending upon the receiver distance.
5. Network has data to send continuously and there is only one sink node in the network to receive the information.
6. All communication links are symmetric. Based on received signal strength, nodes compute approximate distance with base station.

3.1.2 Goals of the Proposed Work

The proposed network design space will achieve the following goals.

1. To conserve network resources by shifting control overhead from sensor nodes to base station during control and managerial function.
2. To simplify cluster formation process with little burden on sensor node resources.
3. To supply identities and other control information to sensor nodes with less network cost.
4. To provide a simplified platform to make up-to-minute adaptions.
5. To guarantee well connected and good coverage network.

3.2 BASE STATION ASSISTED NOVEL NETWORK DESIGN SPACE

The conceptual model of the proposed novel network design space is detailed in this section.

Most of the wireless sensor network applications are developed in association with sensor nodes physical location. In general, GPS enabled devices are used with sensor nodes to provide physical information. But, use of GPS is uneconomical and not recommended in most of the real time applications due to sensor node design issues. Therefore, need for alternate techniques to acquire sensor node physical position has got much attention. Many localization algorithms are proposed in this context in the literature (Bulusu et al., 2000; Wang and Xu, 2010; Xu et al., 2001). But, all these attempts incur extra burden on network resources to provide location information.

Proposed network design space uses intelligent location discovery process to provide identity information to sensor nodes. The base station is equipped with power controlled capability directional antenna and the area covered for each transmission power level is called a *Sector*. The transmission power level gives radius R of a given sector and beamwidth θ provides span of the sector. Area covered by the base station for a given transmission level is illustrated in Fig. 3.1. The base station can reach any corner of the network field by adjusting directional antenna's transmission power level and beam width.

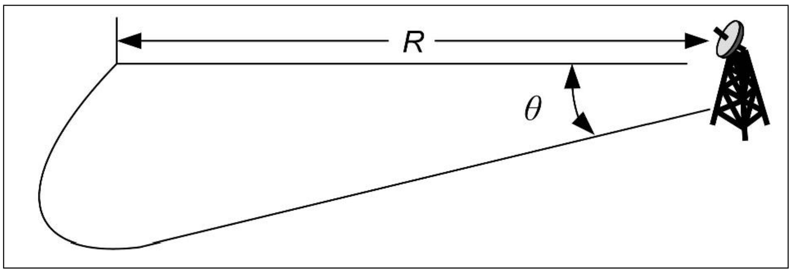


Figure 3.1 Sector formed by Power Controlled Directional Antenna

Wireless sensor network comprising N homogeneous sensor nodes deployed randomly in a quadrant of a circular network field within the radius R from the base station is considered. The network is divided into a number of levels and each level is scanned by the given transmission power level r_i. This provides Level Number (L_n), one of the two values of location information, that uniquely identifies location of a sensor node in the network. After level-wise scan, by varying beam width θ, each sector will be scanned to provide a Sector Number (S_n) to sensor nodes in each level. The tuple (L_n, S_n), gives location information of a sensor node in the network field.

Let L_{total} be the total number of levels in the network, then we have

$$r_1 = \frac{R}{L_{total}} \tag{3.1}$$

where R is radius of the network field and r_1 is radius of the first level.

Let r_i be the transmission power level of i^{th} ring and be calculated as follows

$$r_i = i \times r_1, \qquad \forall i = 1,2,3,...,L_{total} \tag{3.2}$$

Let θ_i be the beam-width of i^{th} level in degrees and be calculated as follows

$$\Theta_i = \frac{90}{2i-1}, \qquad \forall i = 1,2,3,...,2i-1 \tag{3.3}$$

By varying θ_i value, each time we scan a sector of i^{th} level.

Using r_i, we get area of i^{th} ring a_i as follows,

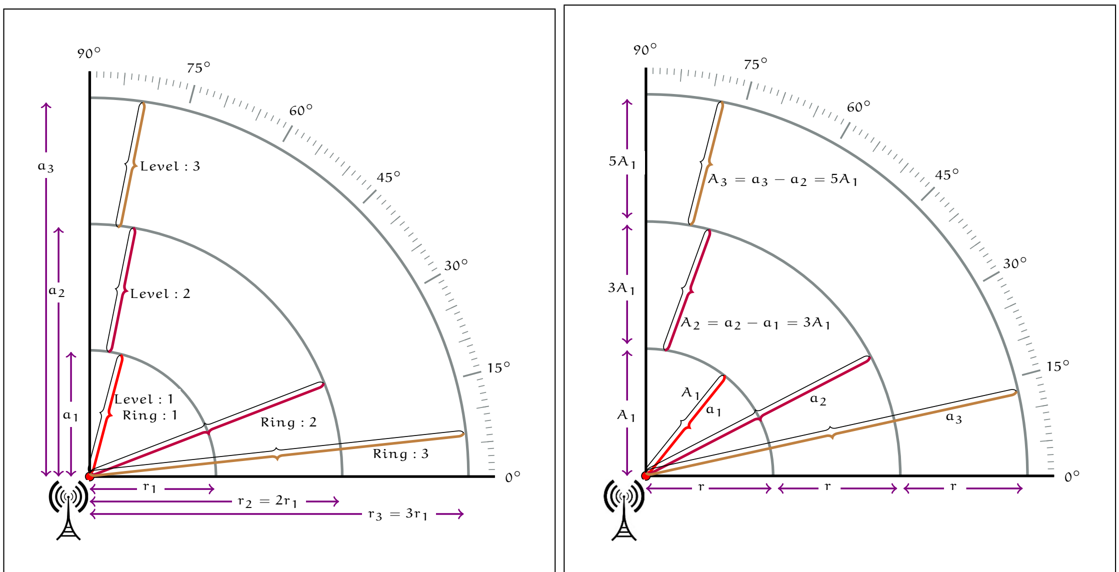
$$a_i = \frac{1}{4}\Pi r_i^2 = i^2 a_1, \qquad \forall i = 1,2,3,...,L_{total} \tag{3.4}$$

From the above equation (3.4), we get area of i^{th} level A_i as follows,

$$A_i = (2i-1)A_1, \qquad \forall i = 1,2,3,...,L_{total} \tag{3.5}$$

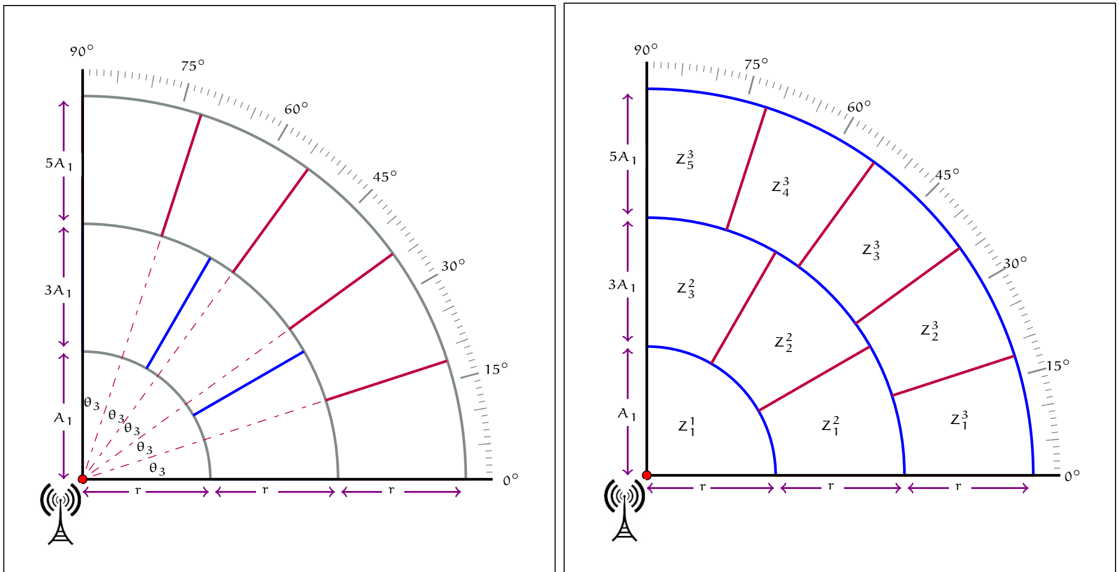
Form the equation (3.5), each level i can be divided into $(2i-1)$ equal partitions called, *Zones*. Each zone is identified as Z_j^i, where i represents level number and j represents partition number of that level.

Fig. 3.2 describes step-by-step network partitioning process of the proposed novel network design space. Fig. 3.3 explains network scanning process to provide location information to sensor nodes in the network. Fig. 3.3(b) to 3.3(e) illustrate level-wise scanning process to provide Level Number (L_n) to each sensor node. Varying the directional antenna's beam width θ (as given in Equation (3.3)), each sector is scanned to provide Sector Number (S_n) for each level. The tuple, (L_n, S_n), gives sensor node's zone information in the network. A 3-level sample network of the proposed network design space is presented in Fig. 3.4.



(a) Level-wise processing

(b) Area calculation for each level



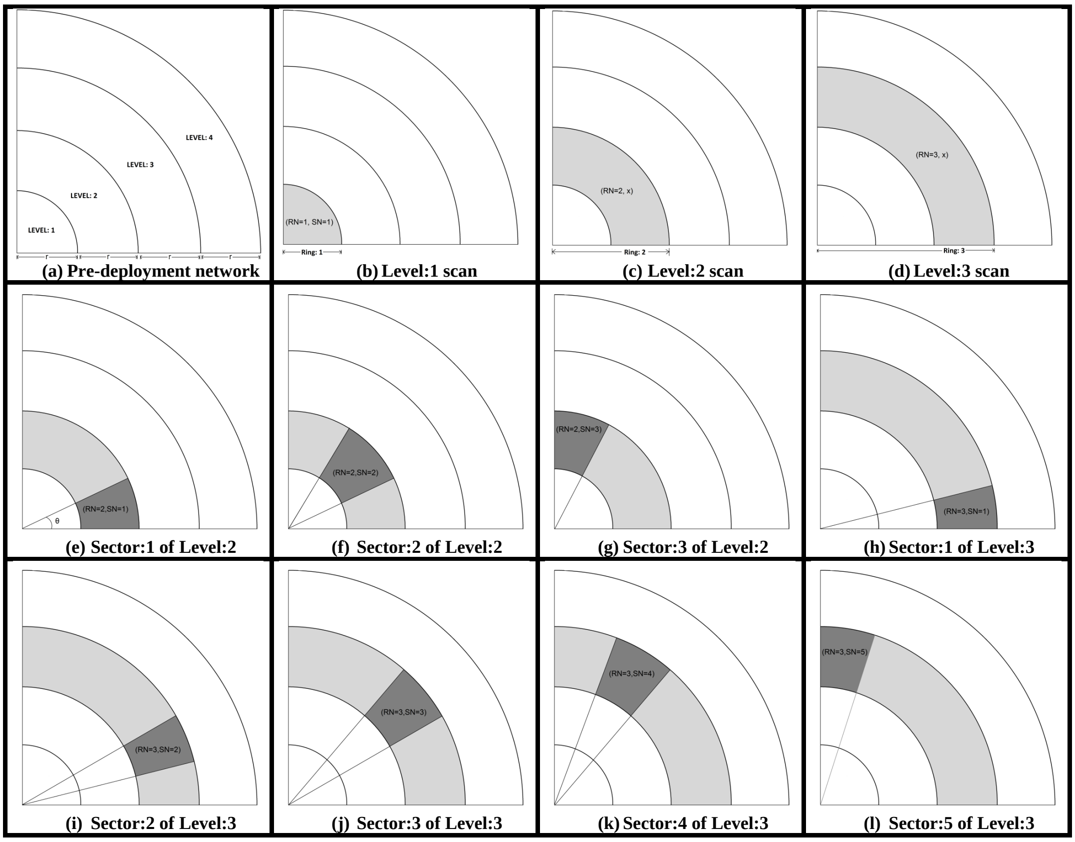
(c) Sector-wise processing

(d) Network Model with zone Ids

Figure 3.2 Proposed Network Design Space Step-by-step Process

3.2.1 Cluster Formation

Sensor nodes with same (L_n, S_n) value are grouped together to form clusters. In other words, each zone acts as a cluster. Since all sensor nodes are homogeneous with same capabilities, in the first data transmission round, cluster heads are selected randomly from each cluster. Like in Cluster-based BeamStar (Li and Yang, 2009), from second data trans-



(a) Pre-deployment network **(b) Level:1 scan** **(c) Level:2 scan** **(d) Level:3 scan**

(e) Sector:1 of Level:2 **(f) Sector:2 of Level:2** **(g) Sector:3 of Level:2** **(h) Sector:1 of Level:3**

(i) Sector:2 of Level:3 **(j) Sector:3 of Level:3** **(k) Sector:4 of Level:3** **(l) Sector:5 of Level:3**

Figure 3.3 Network design space scanning mechanism

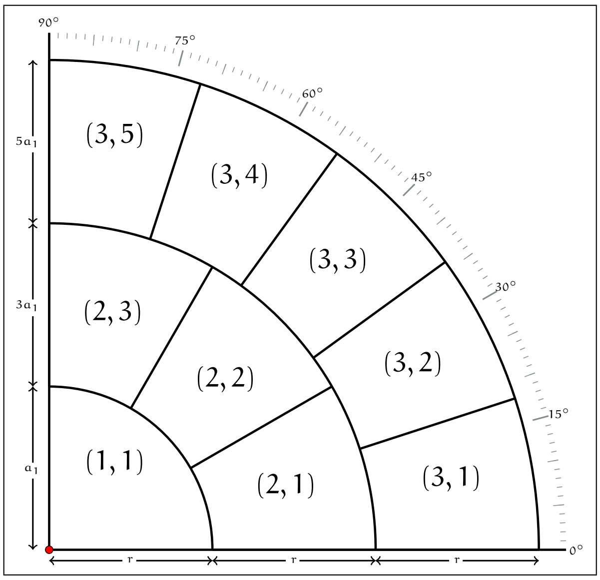


Figure 3.4 A 3-level network design space

mission round onwards, sensor nodes with greatest residual energy are selected as cluster heads for each zone in BANDS.

3.2.2 Data Forwarding Technique

Each cluster head assigns Time Division Multiple Access (TDMA) slots to its cluster members to receive information. Sensor nodes send sensed data to their respective cluster heads in the given time slots. Cluster heads process and aggregate the received information into single fixed-length packet and forward towards base station. Cluster head to cluster head multi-hop data forwarding mechanism delivers data to destination. Cluster head chooses a relay cluster head from its downstream level which has minimum distance to data forwarding cluster head and the base station.

3.3 SIMULATION RESULTS

Performance of the proposed network design space is investigated through simulations using Castalia simulator (Boulis, 2013) in this section.

In the first level of simulation, a wireless sensor network consisting of 100 nodes deployed randomly within 120 meters radius is considered. Each sensor node is equipped with an initial energy of 18720 joules and are deployed in three levels in the network field. The base station is located at the origin and simulation is carried out for 500 seconds with 50 seconds data transmission round length. The proposed network design space, BANDS is compared with LEACH (Heinzelman et al., 2002) and Cluster-based BeamStar (CBS) (Li and Yang, 2009) routing protocols. The results are given by the average value of 10 simulation runs.

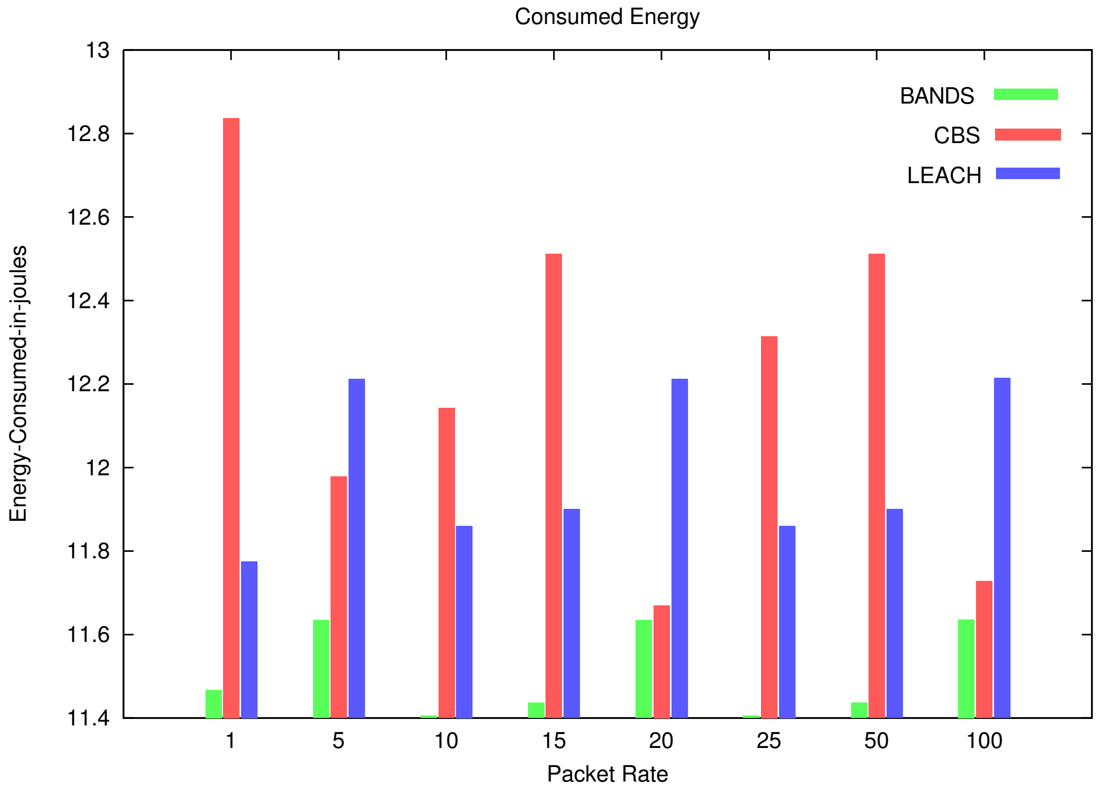


Figure 3.5 Energy Consumption

Total energy consumed for different data packet rates is shown in Fig. 3.5 for BANDS, Cluster-based Beamstar and LEACH routing protocols. In the figure, X-axis represents data packet rates and Y-axis represents energy consumed in joules. It is realized from the figure that the proposed work, BANDS, consumes less power compared to LEACH and Cluster-based Beamstar. Overhead free cluster formation and cluster head rotation mechanism conserves valuable network resources. BANDS data transmission technique uses only local information to find relay cluster heads to forward data towards base station.

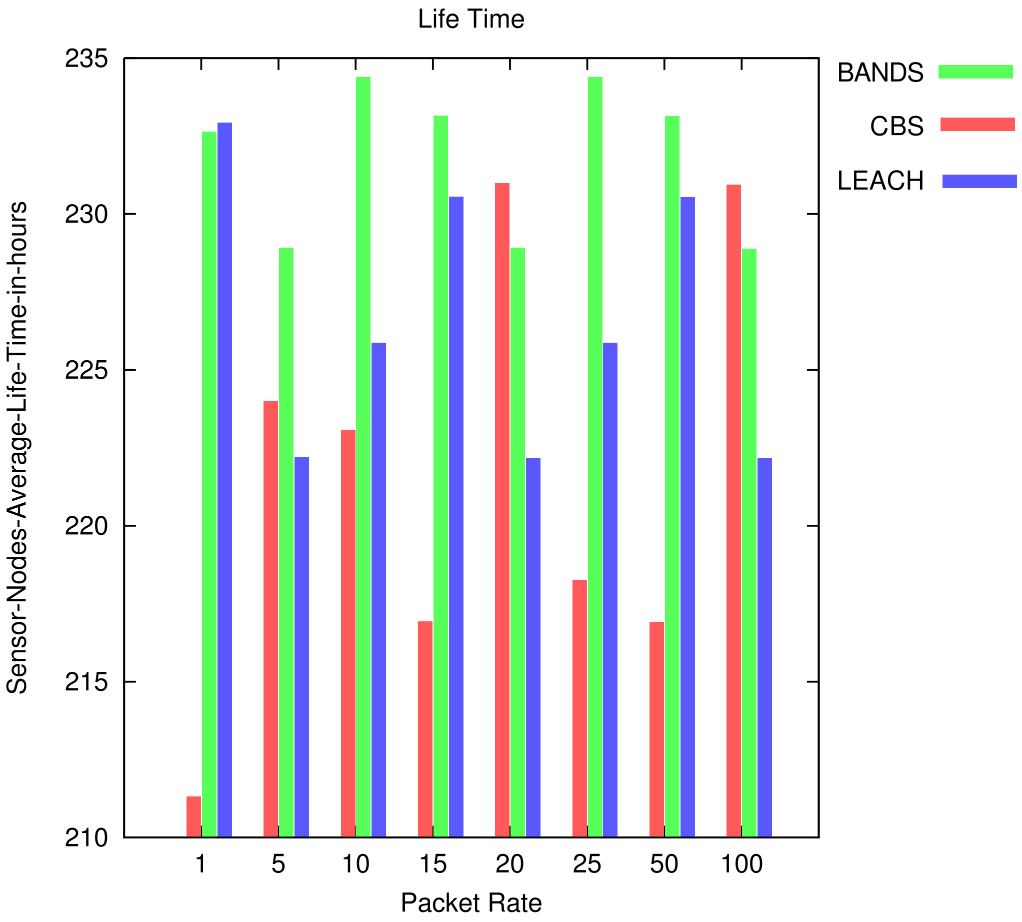


Figure 3.6 Network Lifetime

Simple network operations consume little amount of energy resources and help sensor nodes to extend their availability. The average lifetime of sensor nodes for different data packet rates in the sensing field is presented in Fig. 3.6. In the figure, X-axis represents data packet rate and Y-axis represents average lifetime of sensor nodes in hours. From the result, it is interpreted that, the proposed work enhances sensor node's average lifetime on the whole. With effective clustering and routing algorithms the lifetime of each sensor node can be improved further.

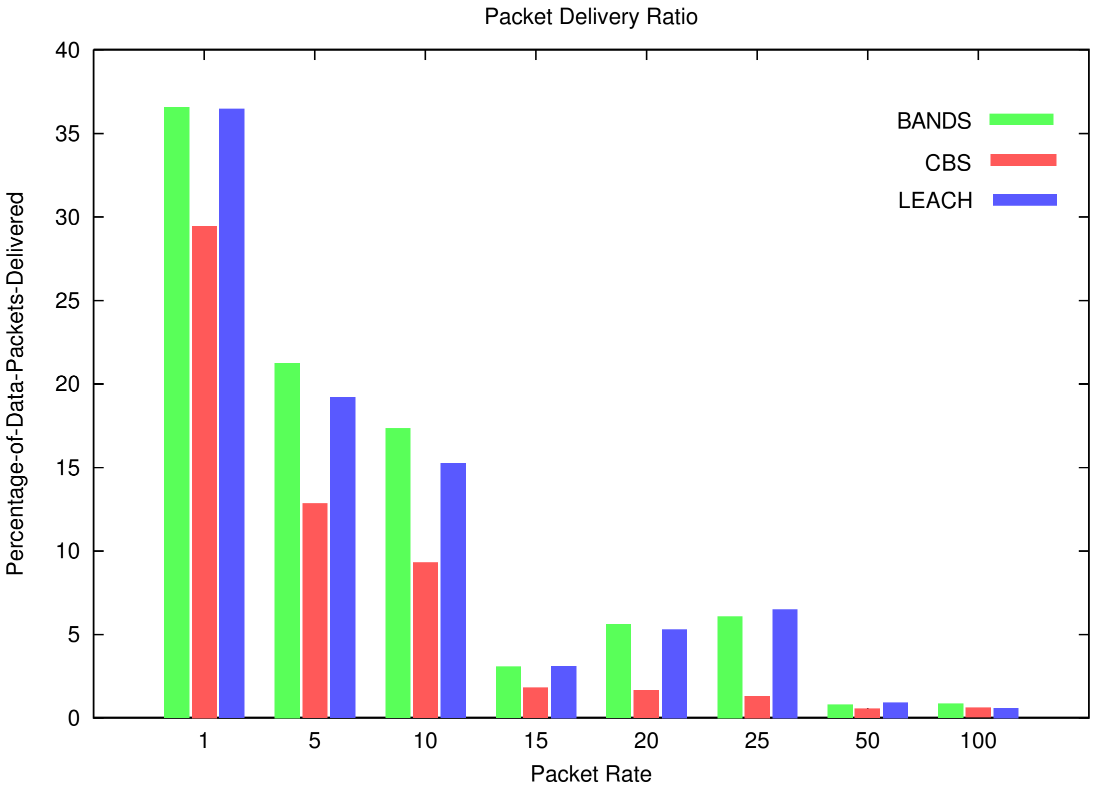


Figure 3.7 Packet Delivery Ratio

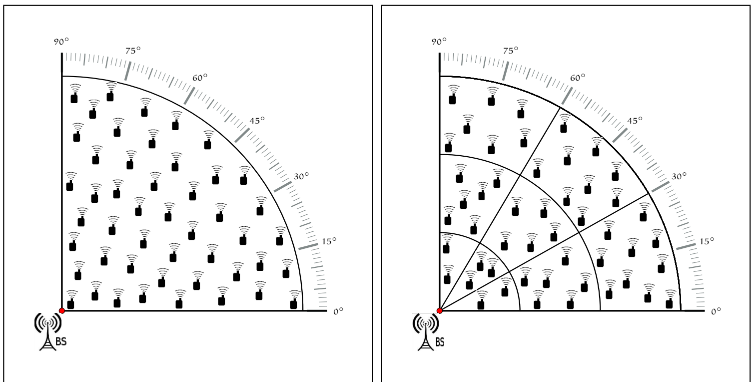
Even though sensor nodes send data periodically, it is very much required to deliver sensed information without any loses or delay. Fig. 3.7 represents packet delivery ratio on Y-axis for different data packet rates on X-axis. It is observed from the figure that, the packet delivery fraction is high in the proposed network model compared to Cluster-based Beamstar and LEACH. The layered architecture guides the network to transmit data with little control burden on data relaying nodes and rises data delivery ratio.

Extended simulation results are illustrated in the following section with enhanced network parameters to analyze BANDS's influence on network's energy consumption and lifetime.

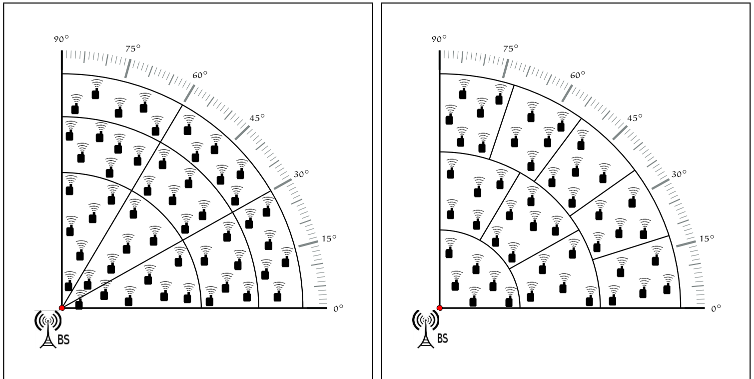
3.3.1 Network Scenarios

Four network design spaces, Plain Network, BANDS, BeamStar and Cluster-based BeamStar are considered here for experimental evaluation. Figures 3.8(a), 3.8(b), 3.8(c) and

3.8(d) represent plain network, BeamStar (Mao and Hou, 2007), Cluster-based BeamStar (Li and Yang, 2009) and the proposed network design space, BANDS respectively.



(a) Plain Network (b) BeamStar Network Model

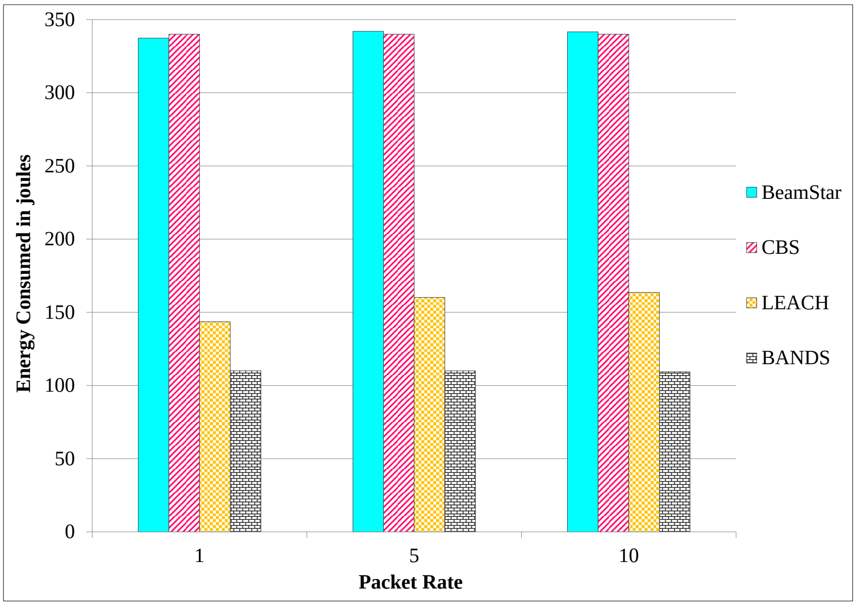


(c) CBS Network Architecture (d) BANDS

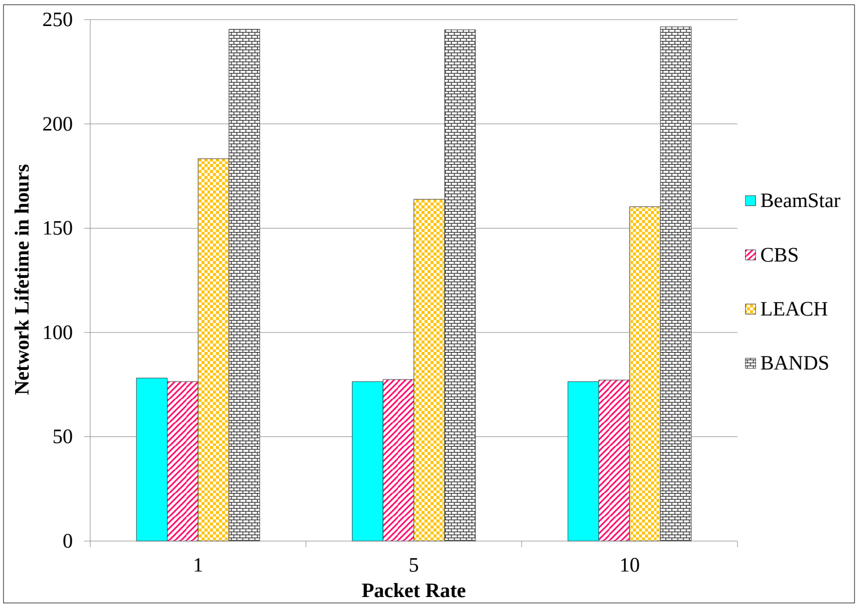
Figure 3.8 Different Network Organization Mechanisms

Each scenario is simulated for 5000 seconds, with 100 and 200 nodes deployed randomly within 200 meters radius from the base station for 50, 100 and 250 seconds data forwarding round lengths. The results are given by the average of 10 simulation runs interms of the following figures.

The following figures illustrate total energy consumed and average network lifetime for different data packet rates over 100 and 200 node network with 50, 100 and 200 seconds data transmission rounds. In the figures, X-axis represents packet rate and Y-axis represent energy consumption in joules and average network lifetime in hours accordingly.



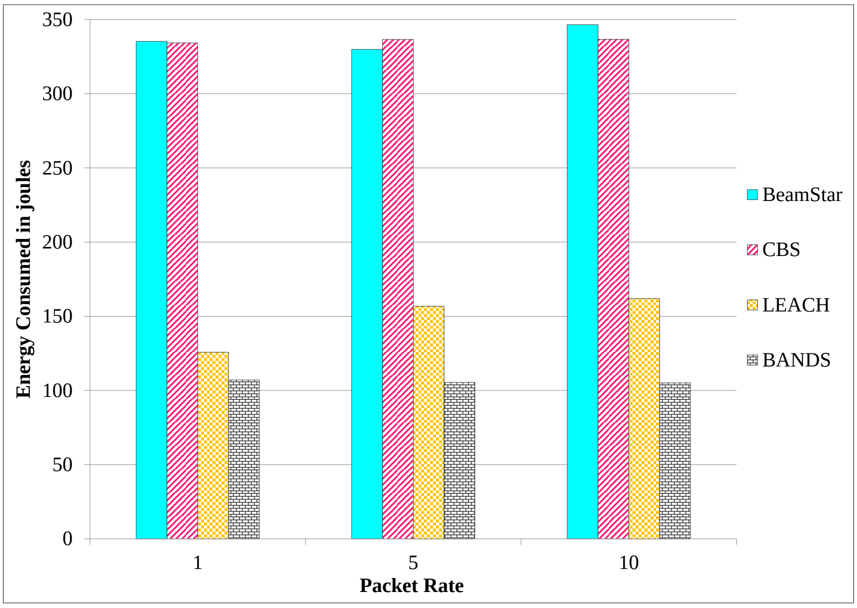
(a) Total energy consumed



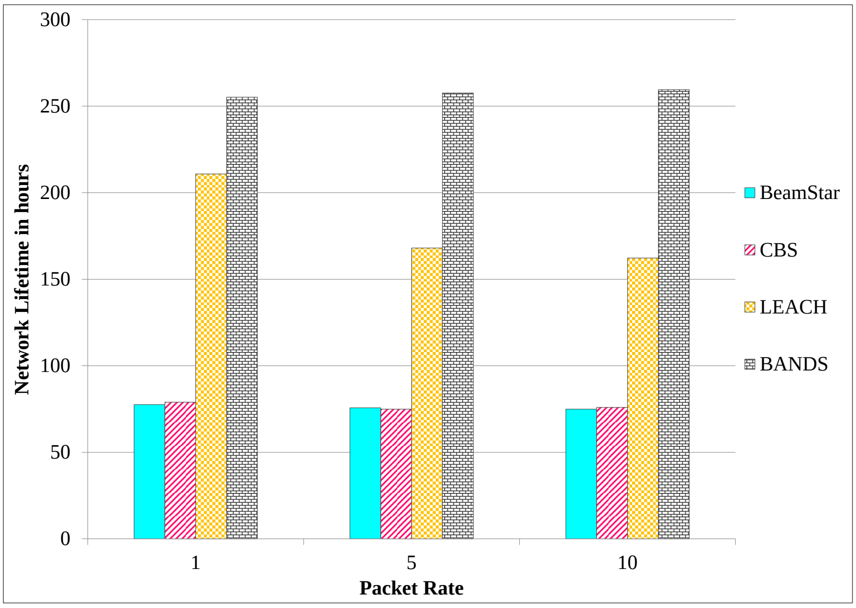
(b) Average network lifetime

Figure 3.9 100 node network with 50sec round length

Fig. 3.9(a) and Fig. 3.9(b) represent total amount of energy consumed and average network lifetime of BANDS, BeamStar, Cluster-based BeamStar and LEACH respectively in a 100 node sensor network for 50 seconds round length.



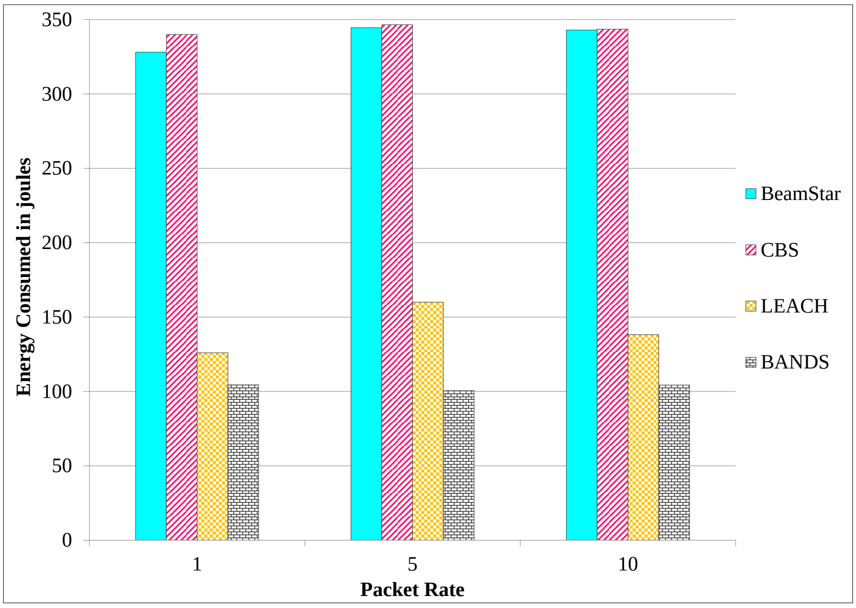
(a) Total energy consumed



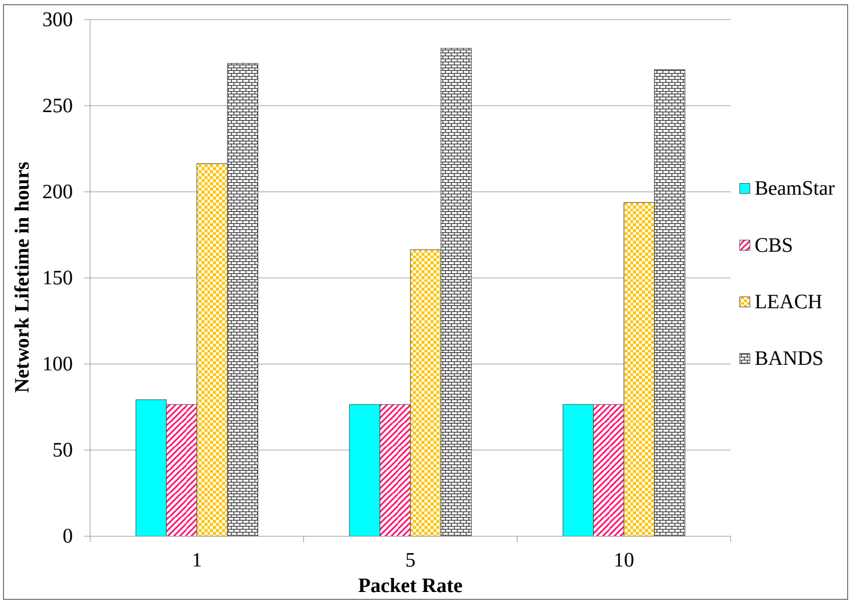
(b) Average network lifetime

Figure 3.10 100 node network with 100sec round length

The amount of energy consumed and average network lifetime for a 100 node network with 100 seconds data forwarding round length is shown in Fig. 3.10 for BANDS, BeamStar, Cluster-based BeamStar and LEACH routing protocols.



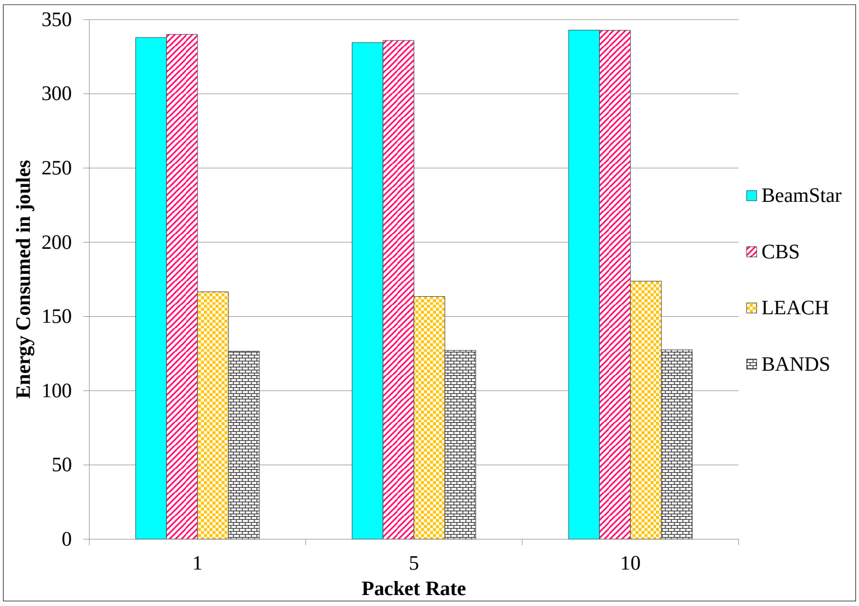
(a) Total energy consumed



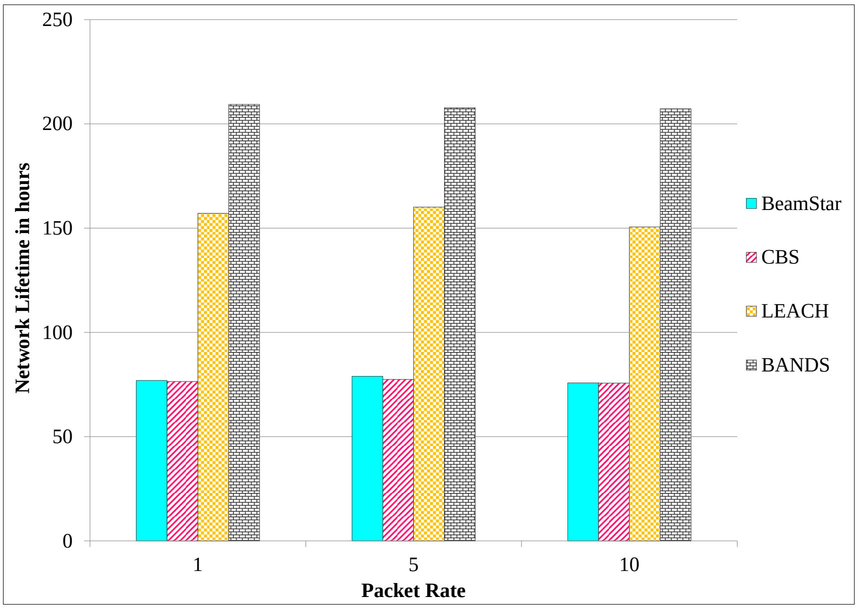
(b) Average network lifetime

Figure 3.11 100 node network with 250sec round length

Fig. 3.11(a) and Fig. 3.11(b) present total amount of energy consumed and average network lifetime of BANDS, BeamStar, Cluster-based BeamStar and LEACH respectively in a 100 node sensor network with 250 seconds round length.



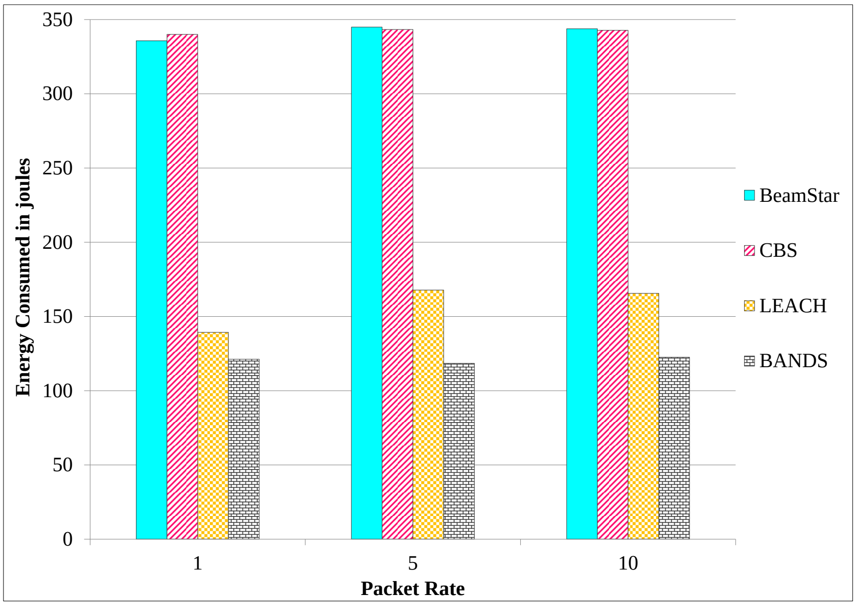
(a) Total energy consumed



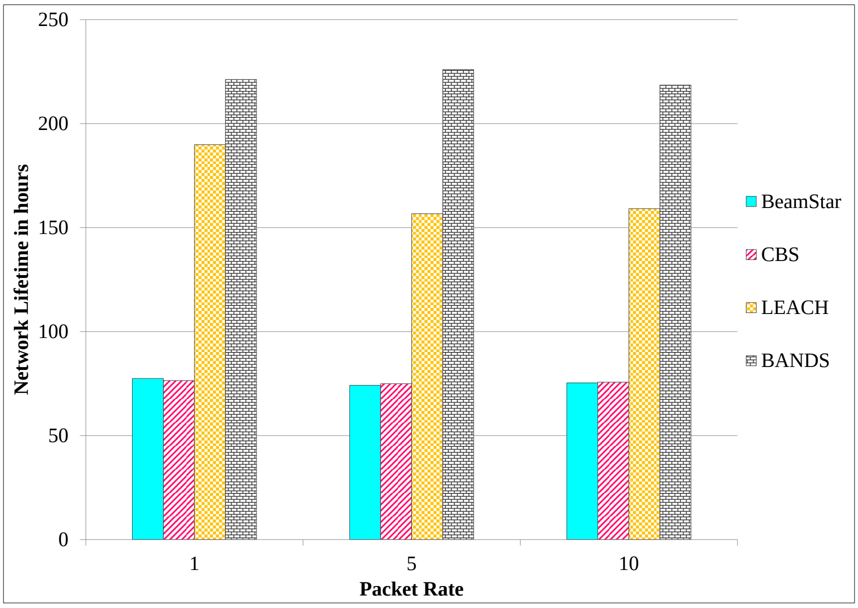
(b) Average network lifetime

Figure 3.12 200 node network with 50sec round length

Fig. 3.12 illustrates total amount of energy consumed and average network lifetime of a 200 node network with 50 seconds data transmission round length for BANDS, BeamStar, Cluster-based BeamStar and LEACH respectively.



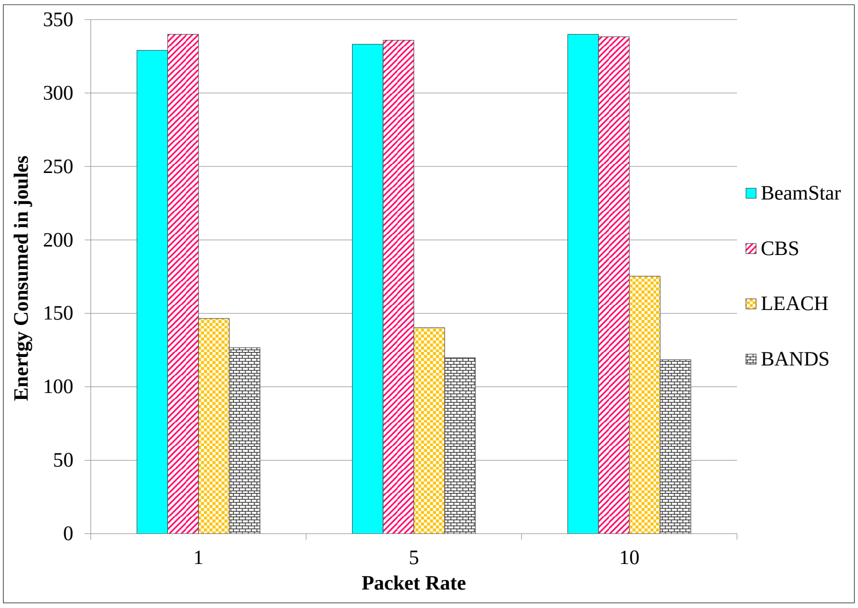
(a) Total energy consumed



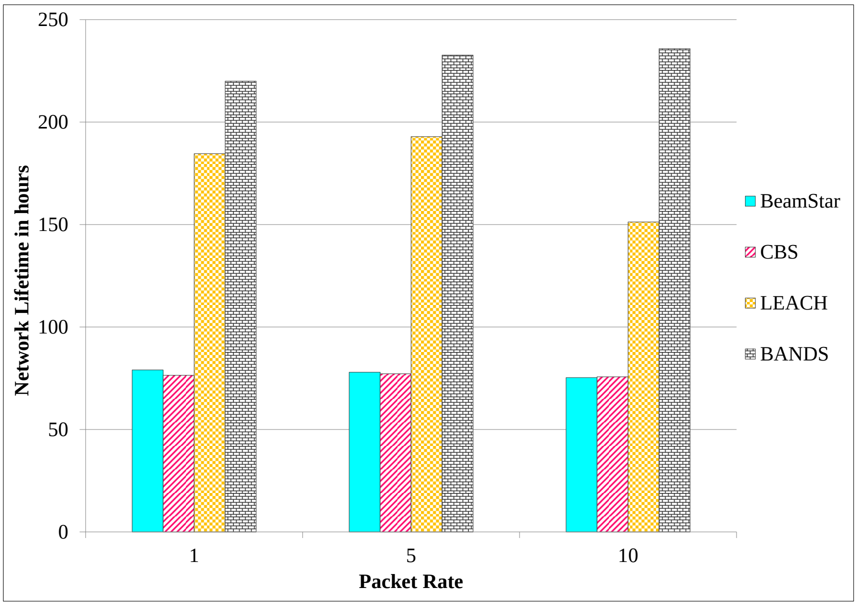
(b) Average network lifetime

Figure 3.13 200 node network with 100sec round length

Total amount of energy spent and average network lifetime of BANDS, BeamStar, Cluster-based BeamStar and LEACH in a 200 node network with 100 seconds data forwarding round length is shown in Fig. 3.13(a) and Fig. 3.13(b) respectively.



(a) Total energy consumed



(b) Average network lifetime

Figure 3.14 200 node network with 250sec round length

Fig. 3.14(a) and Fig. 3.14(b) represent total amount of energy consumed and average network lifetime of BANDS, BeamStar, Cluster-based BeamStar and LEACH respectively in a 200 node sensor network with 250 seconds round length.

Table 3.1 is presented with reference to the Fig. 3.9. From the simulation results it is inferred that, the proposed network design space conserves approximately an average of 67.72%, 67.70% and 29.24% of energy and increases network lifetime approximately by an average of 68.65%, 68.64% and 31.14% when compared to BeamStar, Cluster-based BeamStar and LEACH respectively.

Table 3.1 BANDS Performance in 100 node network with 50 sec round length

Number of Nodes = 100 & Round Length = 50 seconds	**Algorithm**	**Packet Rate**		
		1	*5*	*10*
% of Energy Saved by BANDS	*BeamStar*	67.37	67.83	67.98
	CBS	67.62	67.64	67.83
	LEACH	23.31	31.30	33.12
% of Lifetime Improved by BANDS	*BeamStar*	68.15	68.80	68.99
	CBS	68.84	68.40	68.69
	LEACH	25.30	33.14	34.99

With reference to the Fig. 3.10, the Table 3.2 is shown. It is observed from the table that, in 100 node network with 100 sec round length, BANDS saves approximately an average of 68.58%, 68.47% and 27.56% of energy and raises network lifetime by an average of 70.45%, 70.23% and 29.87% approximately over BeamStar, Cluster-based BeamStar and LEACH respectively.

Table 3.2 BANDS Performance in 100 node network with 100 sec round length

Number of Nodes = 100 & Round Length = 100 seconds	**Algorithm**	**Packet Rate**		
		1	*5*	*10*
% of Energy Saved by BANDS	*BeamStar*	68.06	68.02	69.66
	CBS	67.96	68.66	68.78
	LEACH	14.86	32.70	35.11
% of Lifetime Improved by BANDS	*BeamStar*	69.61	70.61	71.12
	CBS	69.05	70.90	70.73
	LEACH	17.39	34.76	37.47

The simulation results of BANDS in a 100 node network with 250 sec round length is illustrated in Table 3.3 with reference to the Fig. 3.11. From the results it is realized that, the proposed network design space, BANDS, approximately conserves 69.52%, 69.96% and 26.24% of energy on average and prolongs network lifetime on an average of 71.98%, 72.32% and 30.32% against BeamStar, Cluster-based BeamStar and LEACH respectively.

Table 3.3 BANDS Performance in 100 node network with 250 sec round length

Number of Nodes = 100 & Round Length = 250 seconds	**Algorithm**	**Packet Rate**		
		1	*5*	*10*
% of Energy Saved by BANDS	*BeamStar*	68.16	70.81	69.58
	CBS	69.27	70.98	69.63
	LEACH	17.09	37.15	34.48
% of Lifetime Improved by BANDS	*BeamStar*	71.14	73.01	71.78
	CBS	72.15	73.01	71.78
	LEACH	21.20	41.28	28.48

Table 3.4 is given with reference to the Fig. 3.12. From the simulation results it is inferred that, the proposed network design space approximately conserves an average of 62.44%, 62.57% and 24.28% of energy and increases network lifetime approximately by an average of 62.89%, 63.22% and 25.07% when compared to BeamStar, Cluster-based BeamStar and LEACH respectively.

Table 3.4 BANDS Performance in 200 node network with 50 sec round length

Number of Nodes = 200 & Round Length = 50 seconds	**Algorithm**	**Packet Rate**		
		1	*5*	*10*
% of Energy Saved by BANDS	*BeamStar*	62.53	61.99	62.81
	CBS	62.76	62.15	62.80
	LEACH	24.03	22.21	26.61
% of Lifetime Improved by BANDS	*BeamStar*	63.25	62.00	63.42
	CBS	63.48	62.71	63.47
	LEACH	24.97	22.92	27.33

With reference to the Fig. 3.13, Table 3.5 is shown. It is observed from the table that, BANDS approximately saves an average of 64.64%, 64.70% and 22.80% energy and raises network lifetime by an average of 65.90%, 65.88% and 24.01% over BeamStar, Cluster-based BeamStar and LEACH respectively.

Table 3.5 BANDS Performance in 200 node network with 100 sec round length

Number of Nodes = 200 & Round Length = 100 seconds	**Algorithm**	**Packet Rate**		
		1	*5*	*10*
% of Energy Saved by BANDS	*BeamStar*	63.89	65.67	64.35
	CBS	64.35	65.51	64.25
	LEACH	12.98	29.43	25.97
% of Lifetime Improved by BANDS	*BeamStar*	64.99	67.17	65.53
	CBS	65.43	66.84	65.36
	LEACH	14.17	30.66	27.20

The simulation results of BANDS in a 200 node network with 250 sec round length is illustrated in Table 3.6 with reference to the Fig. 3.14. From the results it is realized that, the proposed network design space, BANDS, approximately conserves 63.58%, 64.03% and 20.21% of energy on average and prolongs network lifetime on an average of 66.21%, 66.66%, and 23.02% approximately against BeamStar, CLuster-based BeamStar and LEACH respectively.

Table 3.6 BANDS Performance in 200 node network with 250 sec round length

Number of Nodes = 200 & Round Length = 250 seconds	**Algorithm**	**Packet Rate**		
		1	*5*	*10*
% of Energy Saved by BANDS	*BeamStar*	61.52	64.07	65.15
	CBS	62.76	64.35	64.98
	LEACH	13.58	14.61	32.43
% of Lifetime Improved by BANDS	*BeamStar*	64.07	66.50	68.06
	CBS	65.24	66.83	67.90
	LEACH	16.09	17.10	35.87

From the above computed simulation results, it is inferred that the proposed novel network design space is highly energy efficient when compared to BeamStar, Cluster based BeamStar and LEACH. Also, It is realized from the results that, BANDS prolongs network lifetime with consistent energy consumption among sensor nodes irrespective of data transmission rates.

3.4 DISCUSSION

Though sensor nodes are densely deployed, network holes are still possible with faulty sensor nodes. This leads to poor connectivity and coverage issues in the network field. To find communication holes, network health needs to be checked in regular intervals of time. Blind spots need to be spotted immediately to avoid communication holes and coverage issues in the network. Most of the existing routing protocols flood control packets to monitor network health (Intanagonwiwat et al., 2003; Mao and Hou, 2007), which consumes valuable network resources and incurs significant control overhead on sensor nodes.

To overcome this issue, BANDS proposes a novel network health monitoring technique to find exact location of communication hole with little control burden on sensor nodes resources. In a timely fashion, first zone in each level sends a network monitoring packet called, *Token*. To avoid token collision and congestion, the time frame to receive the token increases with zone number in each level and is application dependent. If the token reaches last zone of a level, this will conclude that the level is fully functional. Suppose, if a zone doesn't receive the health check-up packet in a given time frame, then it will ask for the token from its immediate lower zone. If lower zone replies with token, then the zone forwards it to other higher zones. Otherwise, the zone will report the base station with its zone number (let say, x). Base station queries two consecutive lower zones(let say, $x-1=y$ and $x-2=z$) which are adjacent to the reported zone. If base station receives reply (from y *and* z), then it assumes that the level is operational. If base station receives reply from z, then zone y will be identified as a communication hole. Otherwise, base station queries center zone of first and $z-1$ zones and the process repeats until if finds the blind spot.

Similarly, after some network operational time, few sensor nodes die emptying their energy resources. These dead nodes create network holes and, causes network coverage and connectivity problems. To avoid network being partitioned due to this network holes, dead nodes need to be distributed uniformly across the phenomenon in regular intervals of time to guarantee good coverage and well connected network. The distribution can be done in two different ways: Either by re-deploying sensor nodes physically or by re-configuring the sensor network. Physical re-deployment of sensor nodes is not an easy task especially when the sensor nodes are deployed at hazardous areas like, forest, mountains, terrains etc., whereas network reconfiguration needs global knowledge of sensor network like, physical locations of sensor nodes, dead node count, etc. Moreover, process to obtain this information from the network incurs extra burden on sensor node resources.

To reconfigure the sensor network without any extra overhead on sensor nodes, this chapter explores the advantages of resource abundant edge-base-station. As aforementioned, the base station is equipped with power controlled capability directional antenna and, by varying its beam-width and transmission power level, base station can reach any part of the network. Using this advantage, network can be partitioned into several equally spaced zones without redeploying sensor nodes physically. Change in directional antenna properties promote distribution of dead nodes into several zones in the network to avoid network holes and there by network coverage and connectivity issues. Using such a base station, network can be re-configured with little control overhead on sensor nodes. Fig. 3.15 represents a reconfigured sensor network.

3.5 SUMMARY

BANDS conserves valuable energy resources of sensor nodes by reducing number of control messages exchanged in the sensor network. By exploiting edge-base-station potentials, new possibilities are opened-up to simplify existing and upcoming algorithms in sensor network research. A Base-station assisted novel network design space for edge-based wireless sensor networks is proposed in this chapter. The proposed work explores advantages of resource rich, constraint-free base station available in the network. The proposed mechanism minimizes control burden on sensor nodes during control and managerial func-

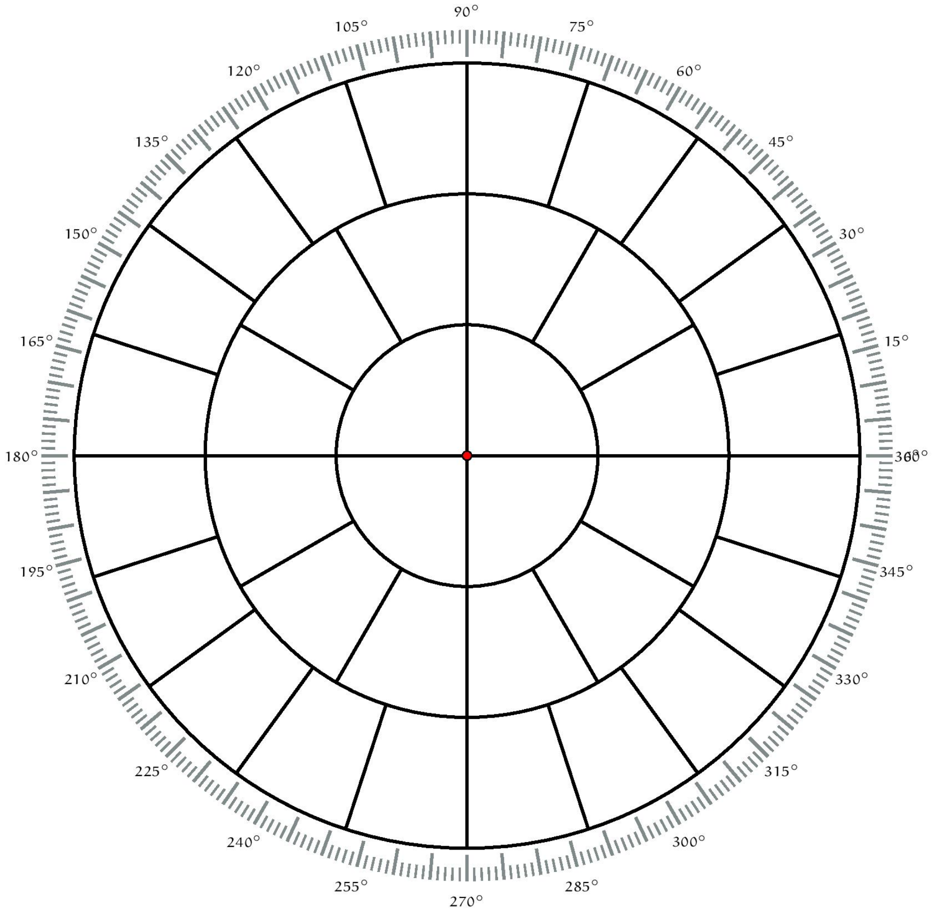


Figure 3.15 Network Reconfiguration Scheme

tions using edge-base-station characteristics. With intelligent network partitioning scheme, sensor nodes are distributed uniformly across different levels in the network. Location discovery process gives location information and helps network to create clusters with little burden on sensor nodes' resources. The layered network model promotes uniform energy dissipation among cluster heads and enhances sensor network lifetime. Experimental results prove that the proposed network architecture conserves network resources by overhead-free control operations during cluster formation and data transmission.

Chapter 4

ZONE-BASED ROUTING PROTOCOL

Many cluster-based routing algorithms have been developed for different network design spaces proposed in the literature (Mao and Hou, 2007; Kuong Ho et al., 2009; Li and Yang, 2009; Soro and Heinzelman, 2005; Bai et al., 2009; Liu et al., 2012). However, these algorithms are tightly bound to their network architectures, change in network models require change in routing or clustering algorithms too, which will incur significant additional network cost on sensor nodes. Based on application requirements, each one of them focuses on either one or more design aspects of wireless sensor network. In this chapter, a *Zone-Based Routing Protocol (ZBRP)* is proposed for edge-based wireless sensor networks based on the introduced network design space, BANDS. The main goal of the proposed routing algorithm is to improve sensor network lifetime with little control overhead on network resources.

4.1 NETWORK DESIGN SPACE

To provide identities and organize sensor nodes into clusters, ZBRP uses the Base station assisted novel network design space proposed earlier. The power controlled capability directional antenna equipped with base station provides location information to sensor nodes by varying its transmission power level in different directions. BANDS compartmentalizes the given network into several equally spaced subdivisions called, *Zones*. Sensor nodes with same location information are grouped together to form clusters.

4.2 ZONE-BASED ROUTING PROTOCOL

The proposed zone-based routing protocol uses random back-off timers having communication cost as one of the primary parameters to select cluster heads for each data forwarding round.

4.2.1 Cluster Formation Phase

With uniform node deployment, the proposed routing protocol generates even size clusters with no extra burden on network resources using BANDS. Every zone in the network design space acts as a cluster except the first one. To avoid heavy relay data traffic, nodes from fist zone communicate base station directly. Fig. 4.1 represents considered network design space with zone information, where (i, j) represents j^{th} partition in i^{th} level.

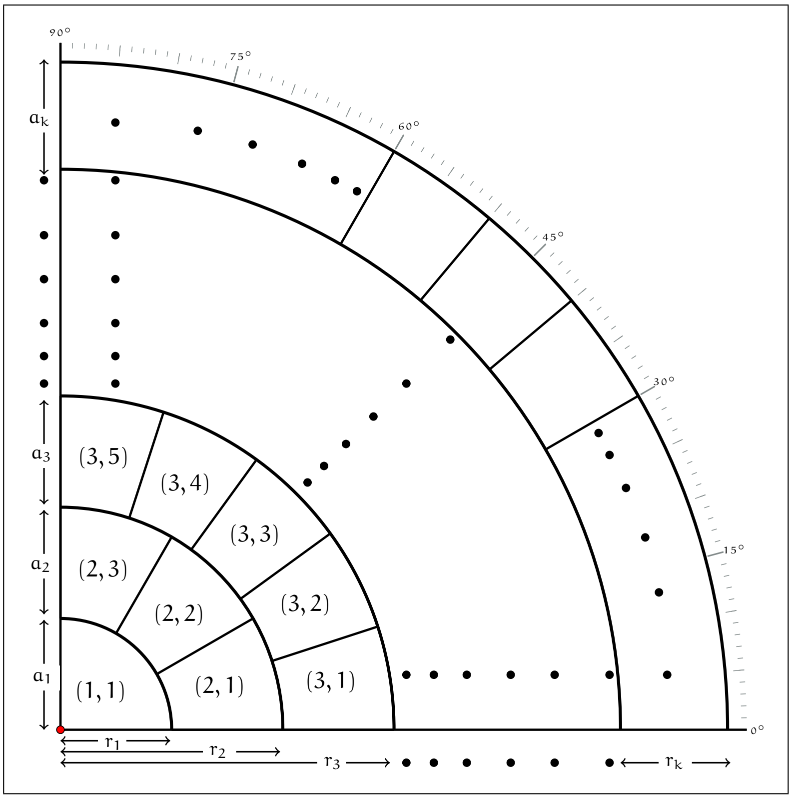


Figure 4.1 Novel network organization mechanism

4.2.2 Cluster Head Selection Phase

During network initialization phase, base station broadcasts an advertisement across the network. Based on received signal strength, each node calculates its distance with the base station. At the beginning, every sensor node advertises its Zone-Id with in the transmission radius r to find its neighboring nodes. Number of signals that a node receives from its zone members represent neighborhood count. During first data transmission round, each node starts a timer (T), which is given below.

$$\beta = \frac{d(S,BS)}{NH_{count}} \tag{4.1}$$

$$T = \frac{1-\alpha}{\beta} \tag{4.2}$$

where α is a random value between (0,1), $d(S,BS)$ is distance between source node S and base station BS, and NH_{count} is number of neighborhood nodes.

Parameter β guides each zone in finding a sensor node which has more number of neighborhood nodes and less distance from base station. Node which clears the timer T will announce itself as a cluster head and the remaining nodes join the cluster head by sending a join message. After cluster formation, each cluster member receives a Time Division Multiple Access (TDMA) slot to send sensed information to its cluster head, whereas the sensor nodes from first ring get TDMA slots form base station during network deployment phase because they communicate base station directly. Cluster head aggregates the data received from its cluster members and forward it as a single fixed length data packet to downstream cluster head towards base station. From second round onwards, each node initiates random back-off timer T as given in equation (4.5) to compete for the position of cluster head.

$$p = \frac{E_{init} - E_{re}}{R_{num} - 1} \tag{4.3}$$

$$q = \frac{E_{se}}{E_{re}} * (1 - \frac{p}{NH_{count}}) \tag{4.4}$$

$$T = \frac{1}{1-q} \tag{4.5}$$

where E_{re} = Residual Energy, E_{init} = Initial Energy, R_{num} = Round Number and E_{se} = node spent energy.

Each sensor node starts its timer using its local information to compete for cluster head position. For cluster head competition, sensor nodes use *communication cost* and *neighborhood count* as primary parameters. The second parameter, neighborhood count, assists ZBRP to choose a sensor node with maximum neighbors as a cluster head in each zone to guarantee good network coverage, which makes ZBRP cluster head selection process distributive. Sensor node with less communication cost and greater neighborhood count clears the timer T and announces itself as cluster head for that zone. Other sensor nodes in the zone stop timers and join the cluster head. The proposed algorithm uses only local information to form clusters and select cluster heads in each data forwarding round. By this, ZBRP minimizes control information exchange among sensor nodes, which conserves valuable energy reserves of the network. Fig. 4.2 and 4.3 explain the pseudo code and flow-chart of the proposed zone-based clustering mechanism respectively.

4.2.3 Multi-hop Data Transmission Phase

Each cluster head aggregates the data received locally and forwards it to base station via multi-hop data forwarding model. Cluster head to cluster head inter cluster communication mechanism delivers data to base station. Relay cluster head in multi-hop data transmission model is primarily selected based on its location information. Every cluster head maintains history of the number of messages it relayed in previous data forwarding rounds. Prior to data transmission, cluster heads announce their location Id, residual energy, distance with base station and number of messages it relayed. This information will be used to select relay nodes by data forwarding cluster heads during data transmission process, further avoiding the selection of respective relaying cluster heads often. This promotes uniform load distribution among cluster heads in each level while data is being forwarded. Cluster head from downstream close to base station with greatest residual energy and less number of messages relayed will be selected as a relay node. Data forwarding cluster head always broadcasts its forwarding message with its data relaying cluster head information. This

```
Start
if $R_{num} = 1$
    $\alpha \leftarrow$ rand (0, 1)
    $\beta \leftarrow \frac{d(S,BS)}{NH_{count}}$
    $T \leftarrow \alpha * \frac{1}{\beta}$
else
    $p \leftarrow \frac{E_{init}-E_{re}}{R_{num}-1}$
    $q \leftarrow (E_{se}/E_{re}) * (1 - p/NH_{count})$
    $T \leftarrow \frac{1}{1-q}$
End if

Start timers T for node S
If $T = 0$
    Call CANCEL_TIMERS_MSG ($Z_n$) from S
    Call CH_ADV_MSG ($Z_n$) from S
End if

On call CANCEL_TIMERS_MSG ($Z_n$) from S
If $S.Z_n = N.Z_n$
    $T \leftarrow -1$
End if

On Receive CH_ADV_MSG ($Z_n$) from S
If $S.Z_n = N.Z_n$ AND $T = -1$
    Send JOIN_MSG() from X
End if

On Receive JOIN_MSG() from X
    Push X to S.Cluster_Members
    Increment Cluster_Member_Count
End Function
```

Figure 4.2 ZBRP Pseudo Code

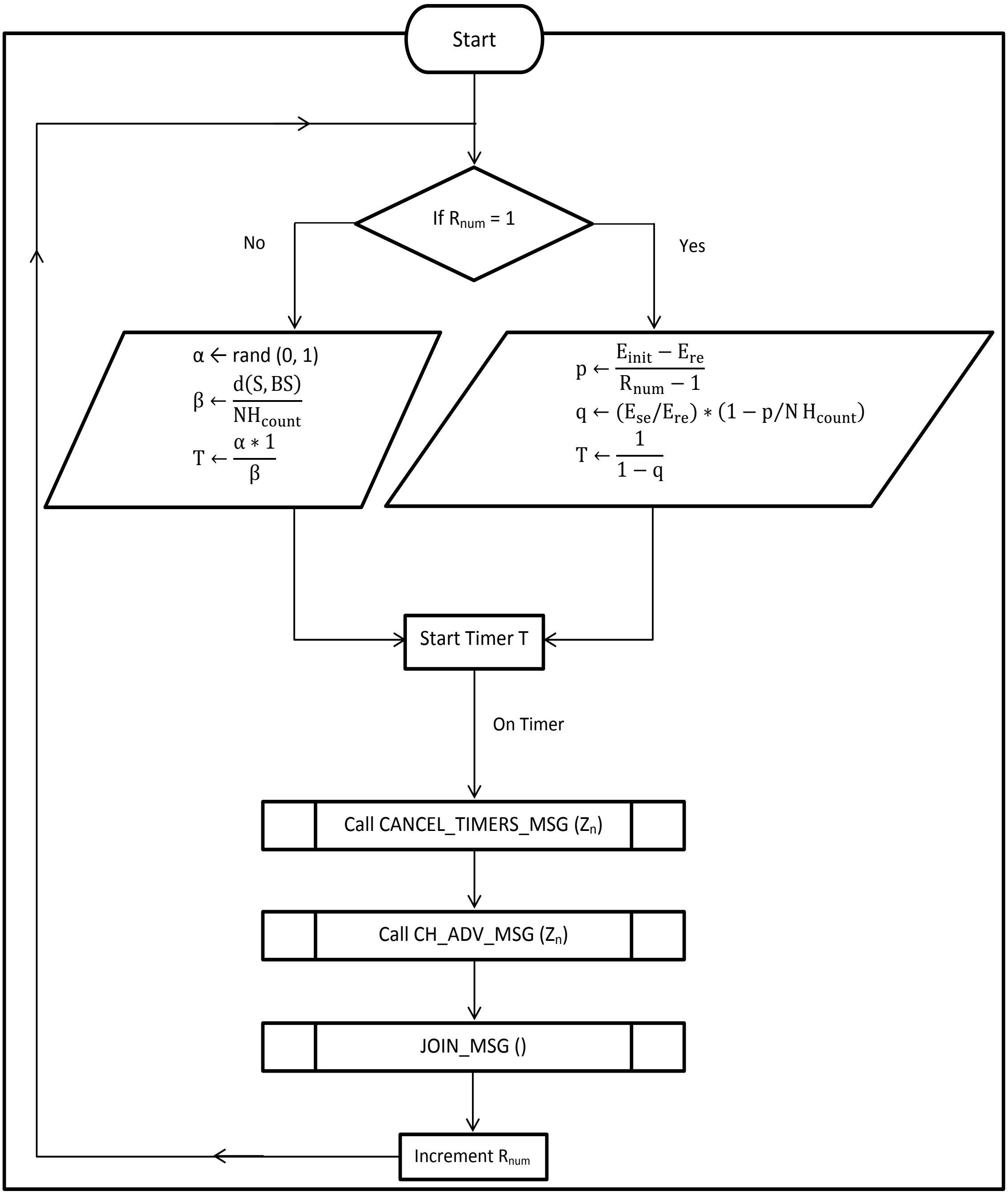


Figure 4.3 ZBRP Flow Chart

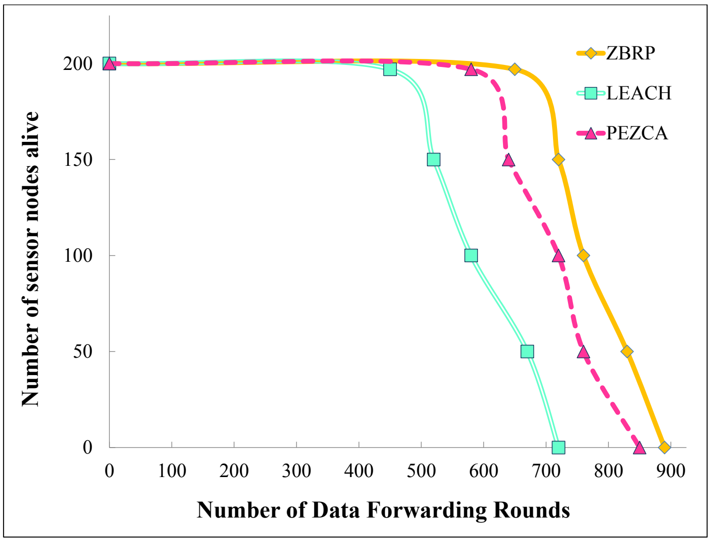
indicates the other cluster heads in that level that message counters of relaying cluster head needs to be updated for future relay node selection process. Cluster heads communicate information directly to base station when data reaches second level.

4.3 EXPERIMENTAL RESULTS

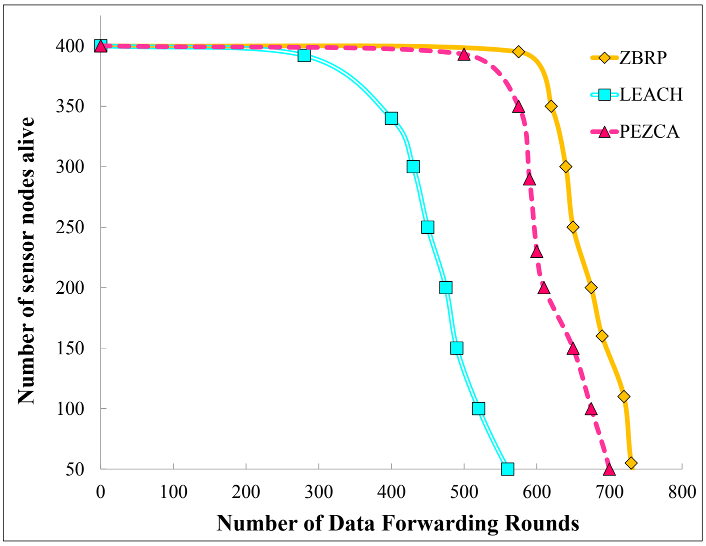
In this section, characteristics of the proposed zone-based routing protocol are studied via simulations using Castalia Simulator (Boulis, 2013). ZBRP performance is analyzed interms of energy consumption and network lifetime. The simulation results are compared with two well-known cluster-based routing protocols, LEACH (Heinzelman et al., 2002) and unequal cluster-based routing protocol Power-Efficient Zoning Clustering Algorithm (PEZCA) (Bai et al., 2009). The radio hardware energy dissipation model shown in (Heinzelman et al., 2002) is used here. The simulation parameters are given in the Table 4.1.

Table 4.1 Simulation Parameters

Parameter	**Value**
Simulation Area	100mX100m & 200mX200m
Base station Location	(0,0)
Number of Nodes	200 & 400
Node Deployment Type	Uniform
Initial energy	200 joules
Energy Consumed to Transmit/Receive (E_{elec})	50 nJ/bit
Transmit Amplifier (E_{amp})	100 pJ/bit/m^2
Data Packet Size	2000 bits
Packet Rate	1 per second
Number of Runs	10
Simulation Time	1500 seconds
Round Time	50 seconds
Radius	100m & 200m



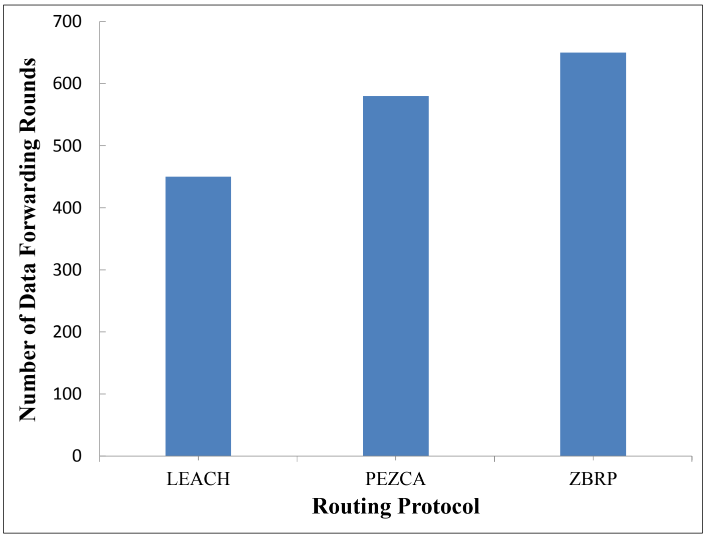
(a) 200 Nodes



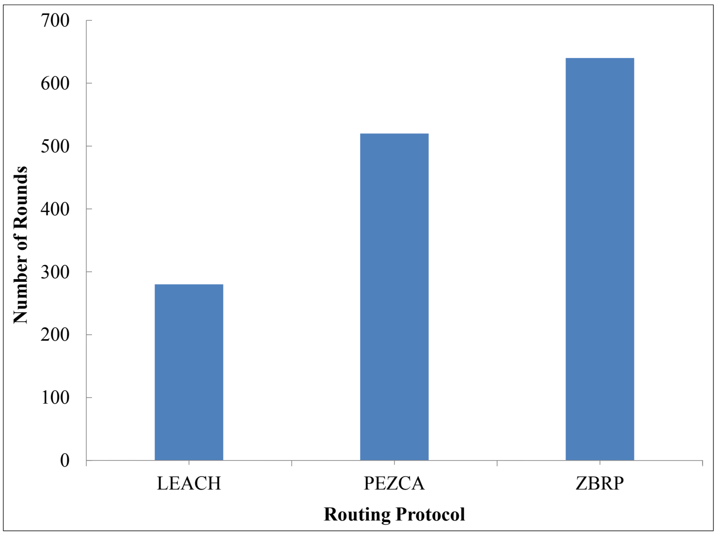
(b) 400 Nodes

Figure 4.4 Number of Sensor Nodes Alive in the network

Number of sensor nodes alive in a network versus number of data forwarding rounds is depicted in Fig. 4.4 for LEACH, PEZCA, and ZBRP. Fig. 4.4(a) represents number of live nodes in a 200 node network and Fig. 4.4(b) represents number of live nodes in a 400 node network. It is inferred from the figures that the proposed routing protocol, ZBRP enhances sensor nodes lifetime using its distributed cluster head selection mechanism. Also, It is observed from the figures that the number of nodes die is gradual with ZBRP.



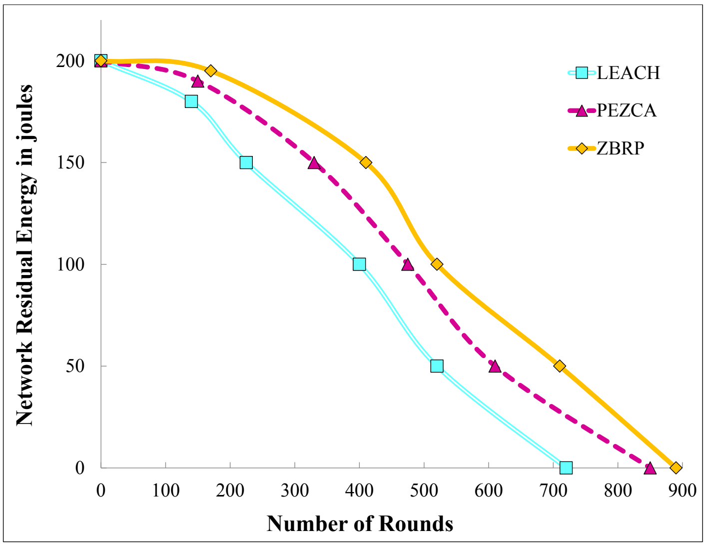
(a) 200 Nodes



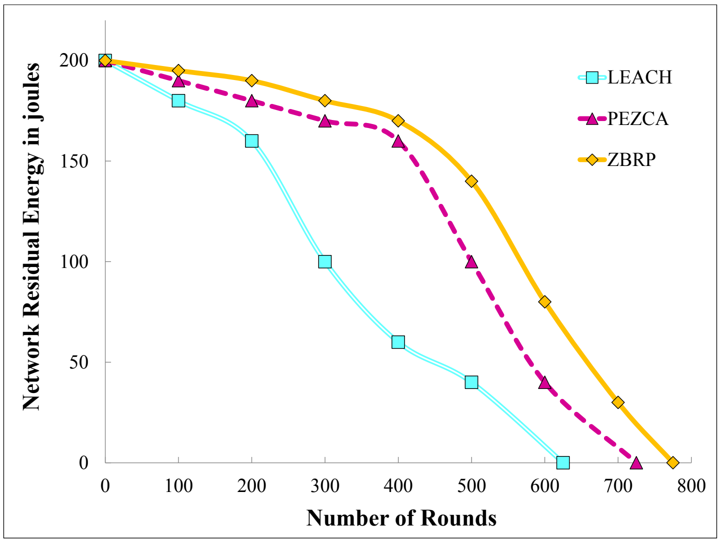
(b) 400 Nodes

Figure 4.5 Network Lifetime

Fig. 4.5 presents network lifetime of LEACH, PEZCA and ZBRP algorithms when 1% of nodes dead in 200 and 400 node network. It is realized from the figure that the proposed routing protocol elevates sensor network lifetime compared with LEACH and PEZCA. ZBRP's distributed cluster head selection mechanism rotates cluster head role uniformly among cluster members, which enables uniform energy consumption among sensor nodes in each cluster. The proposed multi-hop communication mechanism balances energy dissipation among cluster heads and extends their lifetime.



(a) 200 Nodes



(b) 400 Nodes

Figure 4.6 Residual Energy in the network

ZBRP's distributed cluster head selection mechanism rotates cluster head role among sensor nodes and promotes uniform energy consumption among cluster heads in each and every level of the sensor network field. Fig. 4.6 illustrates residual energies of three routing protocols: LEACH, PEZCA and ZBRP for different data forwarding rounds. From the figure it is interpreted that, ZBRP consumes less energy compared with the other two routing algorithms.

4.4 SUMMARY

In this chapter, a zone-based routing protocol is proposed for edge-based wireless sensor networks using base-station assisted novel network design space. The primary goal of ZBRP is to prolong sensor network lifetime with uniform energy consumption among clusters in the network. Uniform node deployment produces even size clusters with little control overhead on network reserves. The proposed multi-hop data forwarding mechanism distributes network load uniformly among cluster heads with its intelligent relay node selection process. From the simulation results, it is interpreted that, the proposed routing protocol enables uniform energy dissipation among the clusters and extends sensor network lifetime.

Chapter 5

ENERGY-EFFICIENT UNEQUAL CLUSTERING ALGORITHM

Wireless sensor networks are a distributed collection of small embedded devices, each with sensing, computational and communicational capabilities. Sensor nodes are constrained in terms of processing power, communication bandwidth, and storage space. Energy has been an important issue when designing any wireless sensor network application. Sensor nodes are often grouped to create individual disjoint sets called, *Clusters*. Clustering techniques actively support network scalability, resource sharing and efficient use of constrained network resources. Cluster formation is generally based on energy reserves of sensors and sensor's proximity to the Cluster Head. Clustering is one of the prominent techniques to save energy consumption in wireless sensor networks. Clustering schemes offer reduced communication overheads, efficient resource allocation with low interference among sensor nodes (Kumar et al., 2011).

Wireless sensor networks are very large scale networks where clustering can simplify the multi-hop route discovery process compared to flat, location based and other non-clustering methods. Although formation and maintenance of clusters introduces additional cost of control messages, clustering structure of network limits number of transmissions in multi-hop data transmission environment. As every sensor node is connected to cluster head, the route discovery process among cluster heads is sufficient to establish a feasible route in the network (Veyseh, 2005).

The main aim of hierarchical routing or cluster-based routing is to efficiently utilize energy reserves of sensor nodes by involving them in multi-hop data communication model, because, only the given cluster head is required to perform routing task and the other sensor nodes just forward their data to cluster head. Clustering has important applications in high-density sensor networks, because it is much easier to manage a set of cluster representatives (cluster heads) from each cluster than managing the whole set of sensor nodes in the network. Sensor nodes in a cluster transmit the sensed information to their cluster head. Each cluster head aggregates the collected data and forwards it to the sink node either directly or via multi-hop path using other cluster heads. In a clustered network, network traffic is composed of intra-cluster and inter-cluster traffic, which are either single or multi-hop. Previous research has shown that multi-hop communication between source and destination is more energy efficient than direct or single-hop communication (Liu et al., 2012). However, the hierarchical (clustering) paradigm causes uneven energy consumption among clusters.

5.1 PROBLEMS WITH UNEVEN ENERGY CONSUMPTION: HOT-SPOT PROBLEM

Energy consumption happens at two levels in clustering (Liu et al., 2012). They are: Inter-cluster and Intra-cluster. The first category represents the energy consumed for communicating with other cluster heads as well as with the sink node. The later corresponds to energy consumption within the cluster for data transmission and data aggregation. Inter-cluster communication consumes more energy than intra-cluster communication as the cluster heads process their own information and also act as relays to forward upstream data. This causes uneven energy consumption among clusters. Cluster heads located near sink node are burdened with heavy relay traffic and will drain their energy and die faster leaving the network partitioned. This is known as, *Hot-spot problem* and is shown in Fig. 5.1. To solve this problem, unequal clustering technique (Li et al., 2005; Lee et al., 2008; Soro and Heinzelman, 2005; Bai et al., 2009; Liu et al., 2012) has been proposed in the recent literature. This mechanism creates clusters in different sizes and the size of a cluster increases in correspondence with the base station distance. The idea behind creating smaller clusters near base station is to preserve some energy for inter-cluster communication.

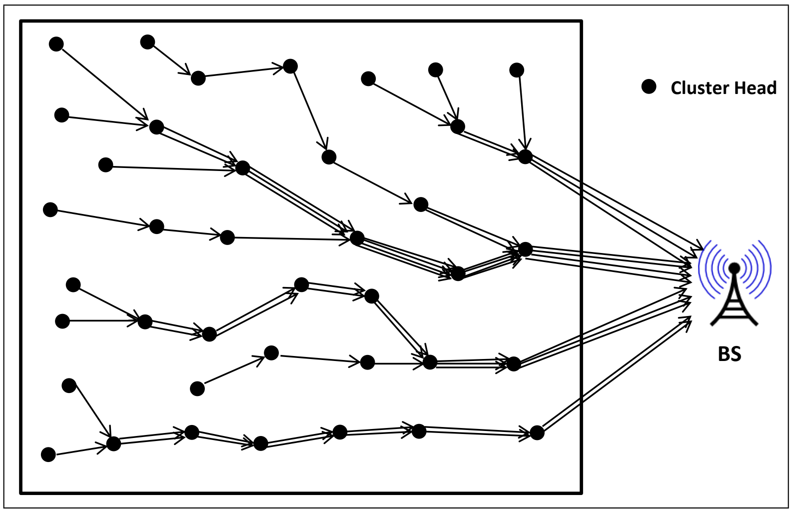


Figure 5.1 Hot-spot problem in multi-hop clustering environment

5.1.1 Problems with Unequal Clustering Mechanism

Even though unequal clustering mechanism avoids hot spot problem, it introduces additional problems into the network. Unequal clustering mechanism achieves uniform energy dissipation among cluster heads, but not between cluster members and cluster heads. Problems with unequal clustering are listed below:

1. As the network size grows, the network connectivity degrades with the increase in cluster size.
2. Since it has no control on percentage of cluster heads it creates (like in LEACH), number of cluster heads selected may vary rapidly from round to round.
3. Irregular and random cluster formation leads to uneven energy consumption among sensor nodes.
4. Control overhead involved in cluster head selection and cluster formation is very high.
5. Further more, as cluster formation depends on base station distance in unequal clustering technique, it doesn't guarantee fully connected network.

An *Energy-efficient UnEqual Clustering Mechanism* (EUEC) is proposed in this chapter to address the problems of unequal clustering mechanism.

5.1.2 Goals of the Proposed Work

Following are the goals set to be achieved with the proposed unequal clustering mechanism.

1. To balance energy consumption in inter cluster-heads communication.
2. To avoid hot-spot problem completely.
3. To create limited number of cluster heads in each data forwarding round.
4. To elevate sensor network's lifetime with uniform load distribution among cluster heads.

5.2 ENERGY-EFFICIENT UNEQUAL CLUSTERING ALGORITHM

Clustering means, partitioning the network into sub-parts called, *Clusters*. Each cluster will have a cluster head and some ordinary nodes as its members. This section details the proposed energy-efficient unequal clustering algorithm.

5.2.1 Cluster Radius Computation

Maximizing network lifetime under given energy constraints is the primary challenge for all sensor network researchers. The fundamental idea is to conserve energy in any wireless sensor network by applying, *Clustering techniques* and to distribute energy consumption load uniformly, rotate the role of cluster head periodically among sensor nodes in the network. Even though, cluster head rotation balances energy consumption between cluster heads and the corresponding cluster members (i.e., intra-cluster communications), and gives better results in single-hop data routing scenarios, it hardly balances the energy consumed by cluster heads in inter-cluster communication. Many clustering algorithms have been proposed in the literature with residual energy as the only or primary criterion in cluster head selection. But, it is not sufficient to balance energy consumption among sensor nodes in the network Li et al. (2005).

The main aim of the the proposed research work is to overcome hot-spot problem completely with limited number of cluster heads. Intelligent cluster formation and cluster head selection process distributes energy consumption uniformly among cluster heads and raises wireless sensor network lifetime. Also, a multi-hop routing scheme is proposed to route data between source and destination with little burden on network resources.

BANDS is used to generate initial level clusters in the sensor network. Since each zone acts as a cluster, $(2i-1)$ number of cluster heads are elected for each level i. But, according to pigeon hole principal, there will be clusters in lower levels which will have to relay more than one cluster information. This leads to variable energy dissipation among cluster heads and causes hot-spot problem in the network. To overcome this problem, the proposed work constructs maximum of M number of cluster heads at each level except the first one, as the nodes from first level communicate base station directly to send their information. M is calculated as follows,

$$M = 2L_{total} - 1, \qquad \forall l > 1 \tag{5.1}$$

where L_{total} = total number of levels in the network.

Using the above equation, we determine number of clusters C to be created for each zone in the level i as follows,

$$C = \left\lceil \frac{M}{2i-1} \right\rceil \qquad \forall i > 1 \tag{5.2}$$

To avoid hot-spot problem, the proposed mechanism creates distinct data flow paths between source and the sink, which enables disjoint multi-hop routing in the network. Since the proposed algorithm creates more than one cluster head in a zone, it computes radius for each cluster as follows.

$$c_z \times \pi \times {r_{ch}}^2 = z_a \tag{5.3}$$

where z_a = area of a zone, c_z = number of cluster heads required and r_{ch} = radius of a cluster head.

Then,

$$r_{ch} = \sqrt{\frac{z_a}{\pi c_z}} \tag{5.4}$$

5.2.2 Cluster Head Selection Phase

Cluster heads are primarily selected based on their communication cost in each data forwarding round. Initially, several tentative cluster heads are selected for each zone with some probability P, where P is varies dynamically from level to level as the percentage of cluster heads differ from level to level. Equation (5.5) gives the probability value P_i for a given level i. The tentative cluster heads compete with each other to become final cluster heads, whereas the non-competing nodes go into sleep mode, until final cluster heads are selected.

$$P_i = \frac{L_n - \alpha}{Z_t + \beta} \qquad \forall i > 1 \tag{5.5}$$

Here, L_n represents level number, Z_t indicates number of zones in the given level and α, β are random values between $(0,1)$.

Cluster head radius r_{ch} for each tentative cluster head is computed from equation(5.4) as cluster head's competition radius. Each tentative cluster head broadcasts *COMPETE_CLUSTER_HEAD_MSG* message, which contains node details *(Node_ ID)*, zone information (Z_n) and Spent energy (E_{se}). Also, every tentative cluster head maintains a *Neighbor_Tentative_CH* set to store its neighborhood tentative cluster heads information. Tentative cluster head s is said to be a neighbor of another tentative cluster head t if s belongs to the same zone as t belongs and is in t's competition diameter or t is in s's competition diameter. Final cluster head selection is made based on neighboring nodes set *Neighbor_Tentative_CH*. Each tentative cluster head takes the decision whether it can act as a final cluster head or not based on its neighborhood set. If the set is $NULL$ for a given tentative cluster head t, then t becomes final cluster head as it does not have any competition. Otherwise, t checks its *Neighbor_Tentative_CH* set to find a node with least communication cost and minimum hop count to reach base station. If t finds itself has least communication cost, then it will win the competition and becomes final cluster head. Tentative cluster head which wins the competition announces itself as a final cluster head by broadcasting *FINAL_CLUSTER_HEAD_MSG* message with incremented cluster head counter to inform all its *Neighbor_Tentative_CH* set. Tentative cluster head which receives *FINAL_CLUSTER_HEAD_MSG* from one of its neighbor, will give-up the competition and inform all its neighbors by broadcasting *QUIT_CLUSTER_HEAD_COMPITITION_MSG*. If a tentative cluster head t receives *QUIT_CLUSTER_HEAD_COMPITITION_MSG* from its neighbor s, it will remove tentative cluster head s from its *Neighbor_Tentative_CH* set. After all this, when a tentative cluster head becomes final cluster head, then it is guaranteed that there is no other cluster head within its cluster radius r_{ch}. This completes cluster head selection process and the same is explained in detail for an arbitrary sensor node s in the pseudo code given in Fig. 5.2. Flow chart for the described cluster head selection process is given in Fig. 5.3.

```
ComputeRand ($L_n$, $Z_t$)
$\alpha \leftarrow$ Rand(0,1)
$\beta \leftarrow$ Rand(0,1)
return ($L_n - \alpha$) / ($Z_t + \beta$)

$\lambda \leftarrow$ ComputeRand ($L_n$, $Z_t$)
if $\lambda < T$, then
    s.Status ← Tentative_Cluster_Head
    Call COMPETE_CLUSTER_HEAD_MSG (Node_ID, $Z_n$, $E_{se}$)
else
    s.Status ← Sleep
    EXIT
end if

On call COMPETE_CLUSTER_HEAD_MSG (Node_ID, $Z_n$, $E_{se}$) from node t
if $s.Z_n = t.Z_n$ AND $d(s,t) < s.r_{ch}$ then
    Push t to s. Neighbor_Tentative_CH
end if
while s.Status = Tentative_Cluster_Head do
    if s. Neighbor_Tentative_CH = NULL AND ++Counter <= C then
        s.Status ← FINAL_CLUSTER_HEAD_MSG
        Call FINAL_CLUSTER_HEAD_MSG (Node_ID)
        EXIT
    else if s.CommunicationCost < t.CommunicationCost $\forall t \in$ s. Neighbor_Tentative_CH
                                        AND ++ Counter <= C AND d(s, BS) < d(t, BS) then
        s.Status ← FINAL_CLUSTER_HEAD_MSG
        Call FINAL_CLUSTER_HEAD_MSG (Node_ID)
        EXIT
    end if
end while

On call FINAL_CLUSTER_HEAD_MSG (Node_ID) from node t
 if $t \in$ s. Neighbor_Tentative_CH then
    s.Status ← NonCH
    Call QUIT_CLUSTER_HEAD_COMPITITION_MSG (Node_Id)
    EXIT
end if

QUIT_CLUSTER_HEAD_COMPITITION_MSG (Node_Id) from node t
if $t \in$ s. Neighbor_Tentative_CH then
    Delete t from s. Neighbor_Tentative_CH
end if
```

Figure 5.2 Cluster head selection pseudo code

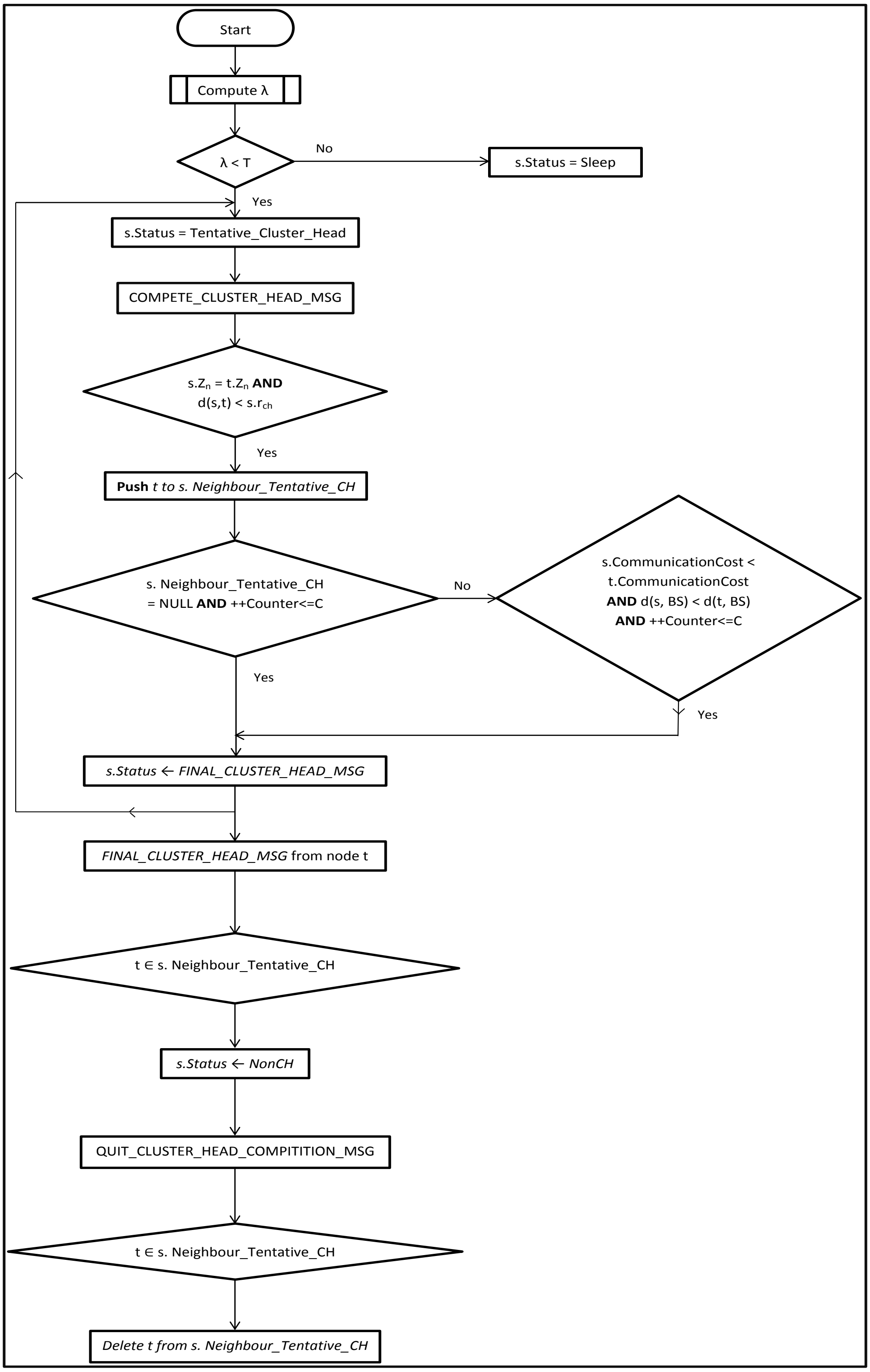


Figure 5.3 Flow chart for cluster head selection process

5.2.3 Cluster Formation Phase

On completion of final cluster head selection, each cluster head broadcasts a *CH_ADV_MSG* message across the network. All sleeping nodes wake-up and join their nearest cluster head which has largest received signal strength by sending a *JOIN_CH_MSG* message.

5.2.4 Multi-hop Routing Mechanism

Cluster heads use multi-hop data routing scheme explained in this section to deliver data between source and destination. Once clusters are formed, cluster members send data to their cluster heads. Cluster heads aggregate the received information and forward it to downstream cluster heads in the direction of base station. To select data relay nodes for each data transmission round, cluster heads broadcast *RELAY_CLUSTER_HEAD_MSG* message with its cluster head Id (*Node_Id*), level number (L_n), residual energy (E_{re}) and distance from base station. Cluster heads in upstream use this information to find their data relay node. Cluster heads from downstream with greater R_{ch} are selected as relay cluster heads for upstream data forwarding cluster heads. In-case of a tie, the node with lower *Node_Id* is selected as a relay node. R_{ch} is calculated as given below,

$$R_{ch} = \frac{(F_{re} - D_{re})^2}{d(F_{ch}, D_{ch})^2 + d(D_{ch}, BS)} \tag{5.6}$$

where F_{re} = Data forwarding cluster head residual energy, D_{re} = Downstream relay cluster head residual energy, $d(F_{ch}, D_{ch})$ = Distance between the forwarding and downstream cluster head, and $d(D_{ch}, BS)$ = Distance between downstream cluster head and the base station.

With M number of cluster heads in each level, EUEC promises disjoint multi-hop routing paths between source and the sink node, which guarantees immutable relay traffic burden among cluster heads across the network.

5.3 PROTOCOL ANALYSIS

This section explains the algorithmic complexity of the proposed work, EUEC.

Lemma 5.3.1. *The big Oh complexity of the proposed work is $O(N)$, where N is total number of nodes in the network.*

Proof. Let n_{tch} be the number of tentative cluster heads. According to *COMPETE_CLUSTER_HEAD_MSG* method, all the n_{tch} tentative cluster heads will start sending the signal. So, there will be n_{tch} signals at this point of time in the network. Now, it is fair enough to assume that, some of these n_{tch} nodes will become final cluster heads and the rest will return to their original state. Let, k be the number of such nodes. At this point of time, there will be $(n_{tch} - k)$ number of *FINAL_CLUSTER_HEAD_MSG* signals and k - *QUIT_CLUSTER_HEAD_COMPITITION_MSG* signals in the network.

Also, all these $(n_{tch} - k)$ final cluster head nodes, will send *CH_ADV_MSG* signals. After receiving advertisement, remaining k nodes reply with *JOIN_CH_MSG* message to highest RSSI cluster head.

So, summing up all these signals in this cluster formation phase, we have a total of, $n_{tch} + (n_{tch} - k) + k + (n_{tch} - k) + k$ number of signals per round i.e., $O(N)$.

□

Lemma 5.3.2. *There won't be two cluster heads if one is in other's cluster head competition radius r_{ch}.*

Proof. Suppose s and t are two tentative cluster heads. s is located in the cluster head competition radius of t.

According to EUEC, s belongs to $t.Neighbor\_Tentative\_CH$ set. If t becomes cluster head first, then s will be notified about its state, so s quits the competition and becomes an ordinary node; vice-versa. □

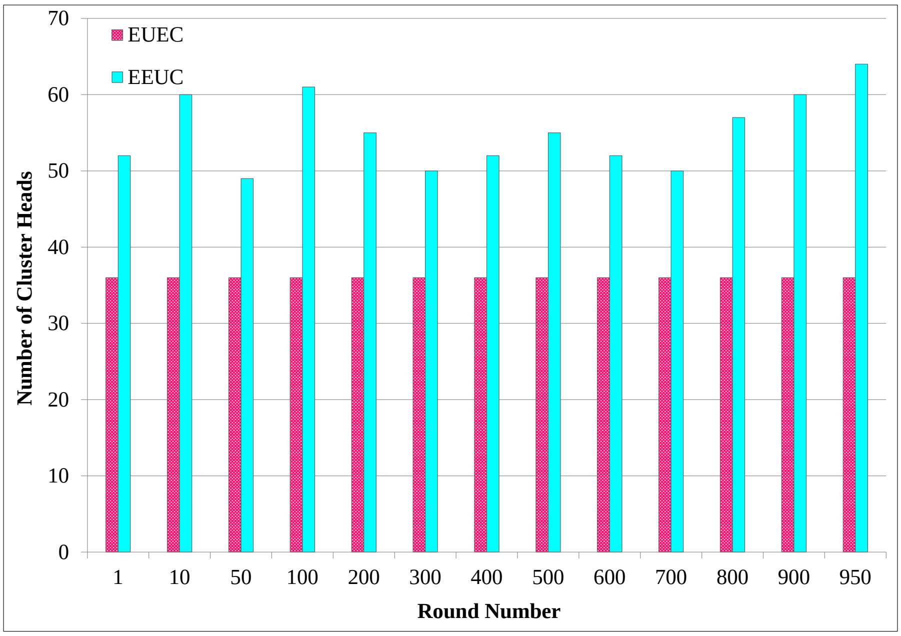
5.4 SIMULATION RESULTS

In this section the proposed work, Energy Efficient UnEqual Clustering Algorithm (EUEC) performance is evaluated through simulations using CASTALIA network simulator (Boulis, 2013). An ideal MAC layer and error-free communication links are assumed for experimental work. EUEC characteristics are analyzed in comparison with widely accepted well known multi-hop unequal clustering algorithm, Energy-Efficient Unequal Clustering Mechanism (EEUC) (Li et al., 2005). Since LEACH (Heinzelman et al., 2002) is one-hop routing protocol, it is not compared with the proposed work. Simulation parameters used for EUEC performance evaluation are given in Table 5.1. Radio hardware energy dissipation model shown in (Li et al., 2005) is used here.

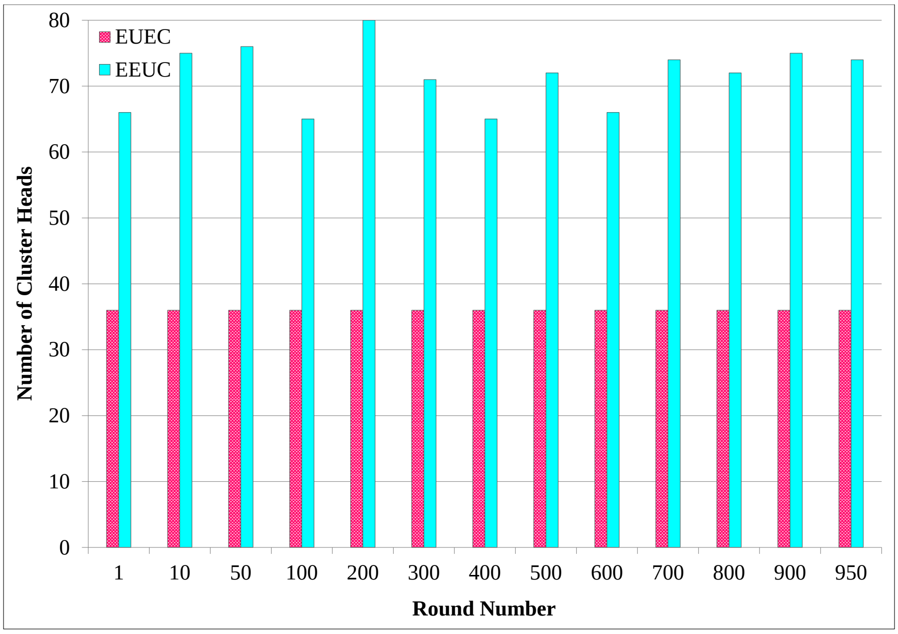
Table 5.1 Simulation Parameters

Parameter	**Value**
Simulation Area	(0,0)∼(1000,1000)m
Base Station Location	(0,0)
Number of nodes	200 & 400
Initial energy	18720 joules
E_{elec}	50 nJ/bit
E_{amp}	10 pJ/bit/m^2
E_{DA}	5 nJ/bit/signal
Data Packet Size	2000 bits
Packet Rate	1 per second
Radius R	200 meters
Simulation Time	25000 seconds
Number of Runs	10
Round Time	25 seconds

The number of cluster heads selected for each data forwarding round by EUEC and EEUC is shown in Fig. 5.4. From the figure it is interpreted that, EEUC choose huge and varied number of clusters whereas EUEC constructs consistent number of cluster heads for each data forwarding round. Constraint on number of cluster heads to be selected for each level assists the network to pick equivalent number of cluster heads and guides network to distribute them uniformly across the network.



(a) 200 Node Network



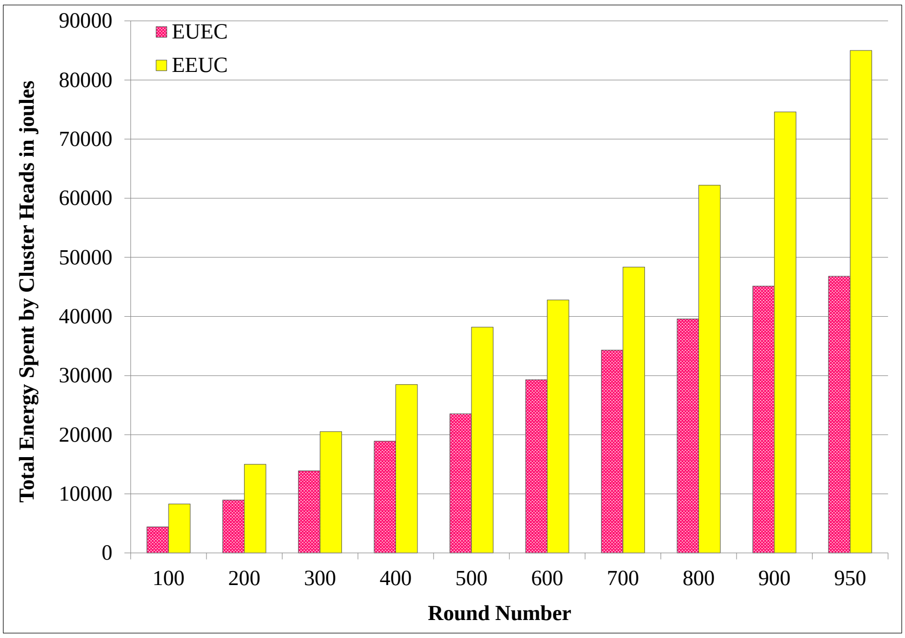
(b) 400 Node Network

Figure 5.4 Number of cluster heads selected in each round

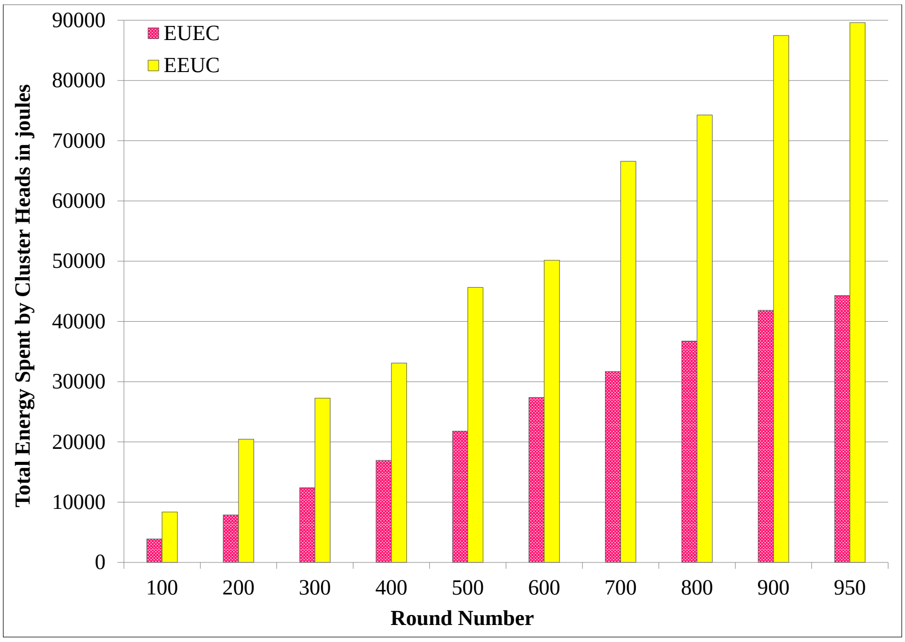
5.4.1 Energy Consumption

This section investigates EUEC's energy expenditure routine in sensor nodes and cluster heads in the network.

Total amount of energy spent by EUEC and EEUC cluster heads in 200 and 400 node



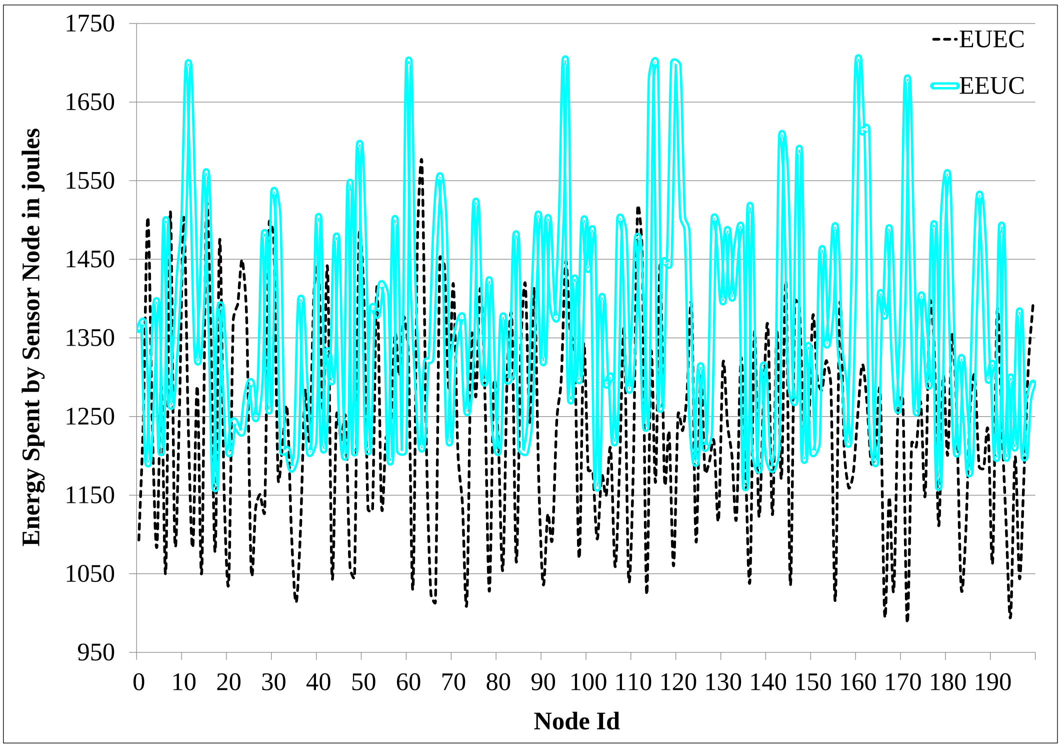
(a) 200 Node Network



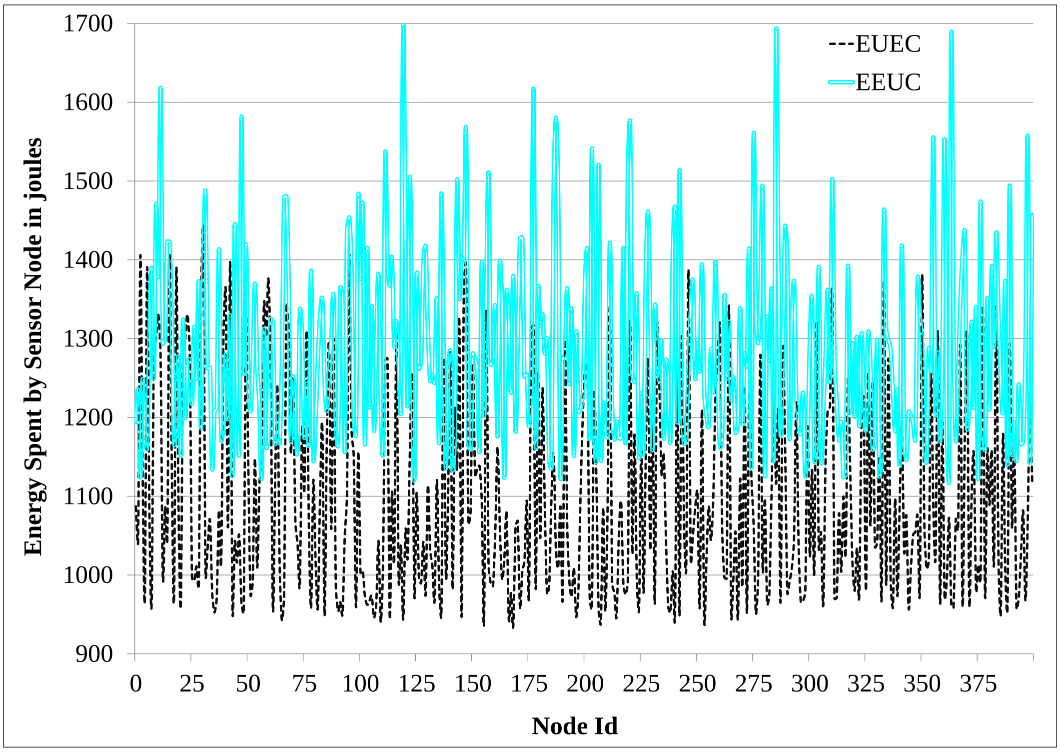
(b) 400 Node Network

Figure 5.5 Total amount of energy consumed by cluster heads

network for different data forwarding rounds is illustrated in Fig. 5.5. It is inferred from the figure that, EUEC consumes less energy and the rise in energy dissipation is consistent cum gradual compared to EEUC, due to the fact that the number of CHs are consistent in each level. Due to the lack of control on number of clusters formed, the energy dissipation is very high and raises rapidly with EEUC.



(a) 200 Node Network



(b) 400 Node Network

Figure 5.6 Total amount of energy consumed by sensor nodes

Fig. 5.6 represents, total amount of energy spent by EUEC and EEUC sensor nodes in 200 and 400 node network. From the figure, it is realized that the amount of energy spent by EUEC sensor nodes is less when compared to EEUC sensor nodes. Excess number of cluster heads and irregular cluster sizes cause imbalance in energy dissipation among sensor nodes in EEUC network.

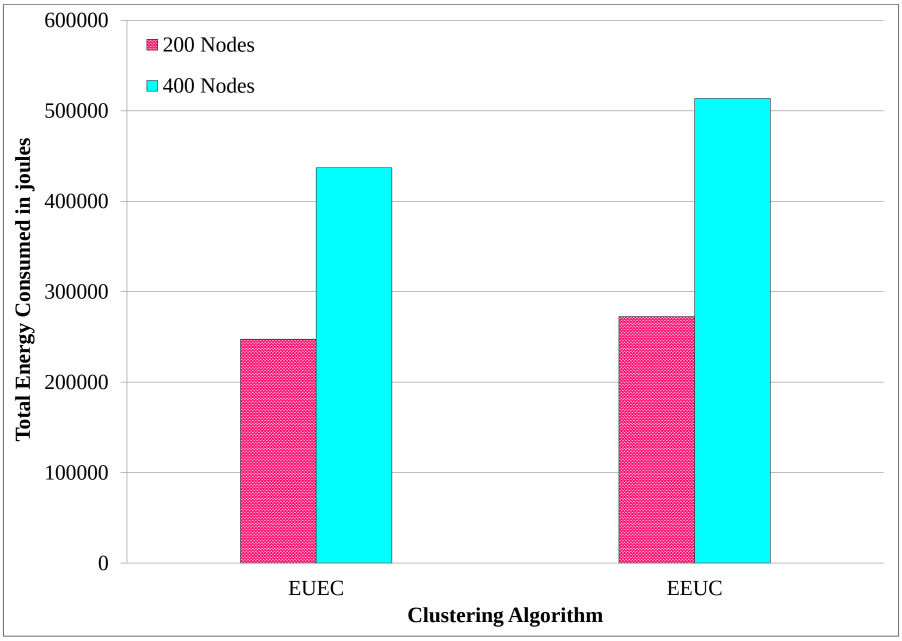
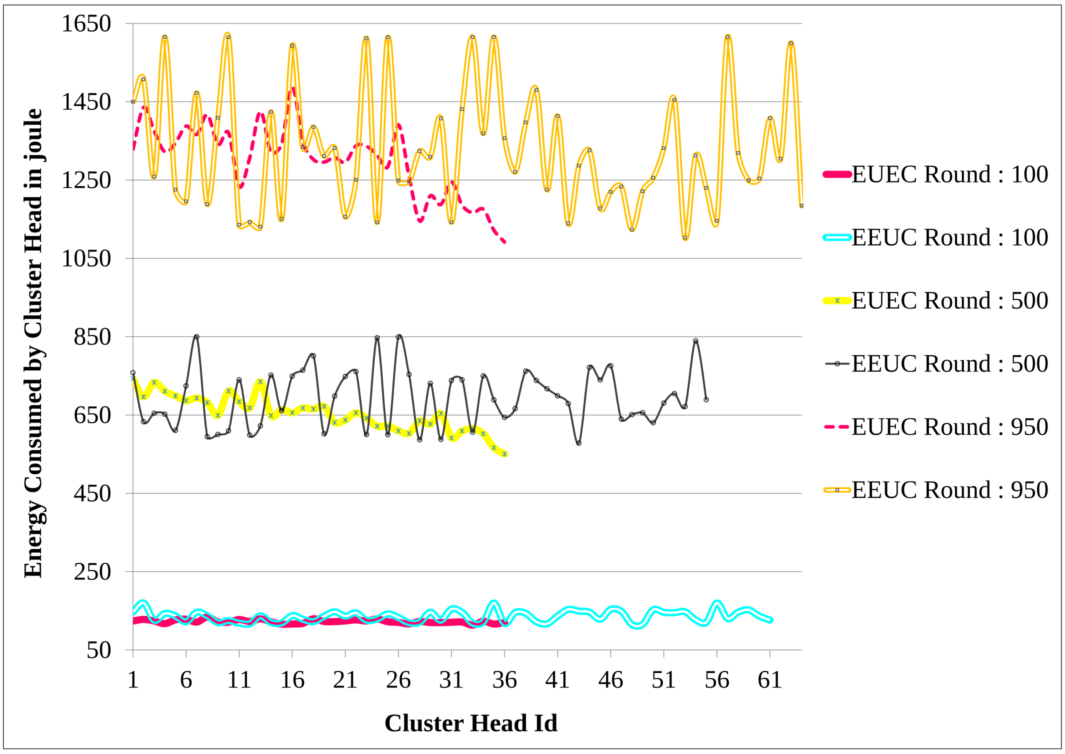


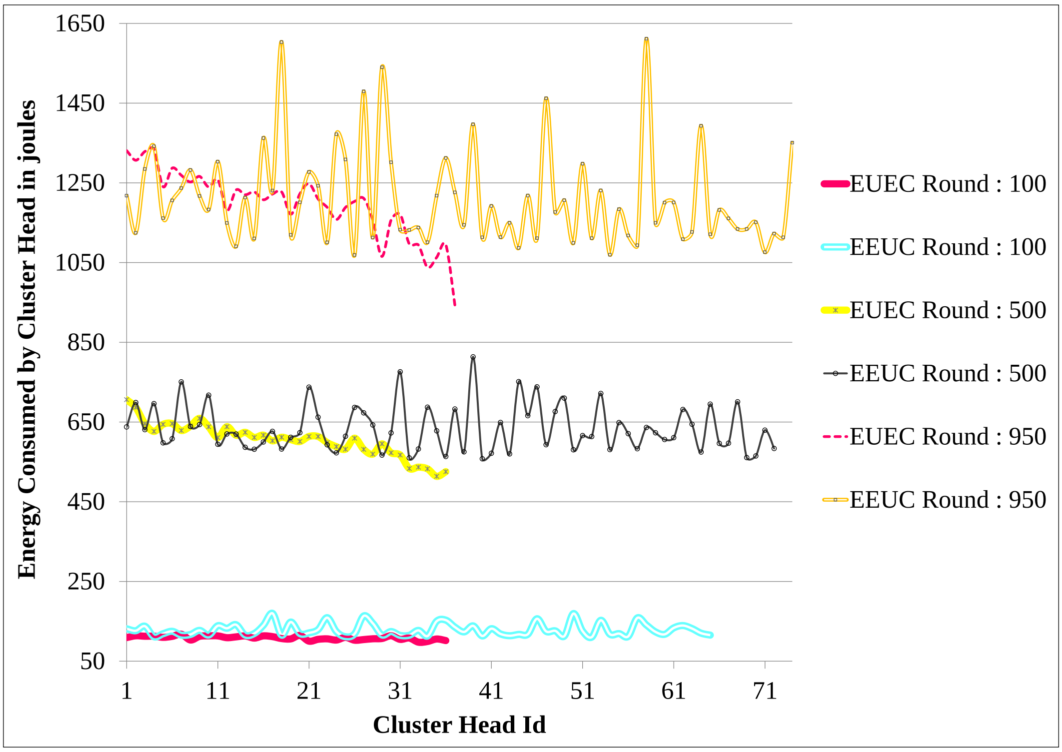
Figure 5.7 Total energy consumed by EEUC and EUEC networks

The total amount of energy consumed by EEUC and EUEC networks is presented in Fig. 5.7. Form the results, it is interpreted that, the limitation on the number of clusters enables optimal power utilization among sensor nodes at different levels in EUEC network.

The proposed cluster head rotation mechanism balances energy consumption among sensor nodes by rotating cluster head position uniformly among sensor nodes. Fig. 5.8 shows energy consumed by cluster heads at randomly selected data forwarding rounds for EUEC and EEUC networks. It is observed form the figure that the energy dissipation reduces for EUEC cluster heads as the number of data forwarding rounds increases compared with EEUC cluster heads.



(a) 200 Node Network



(b) 400 Node Network

Figure 5.8 Amount of energy consumed by cluster heads at random rounds

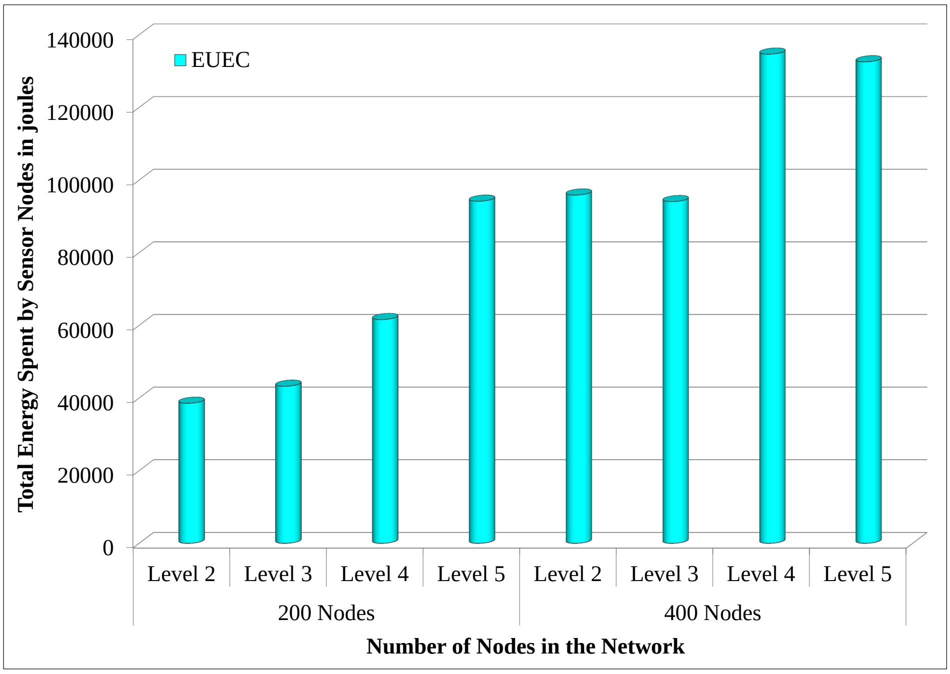
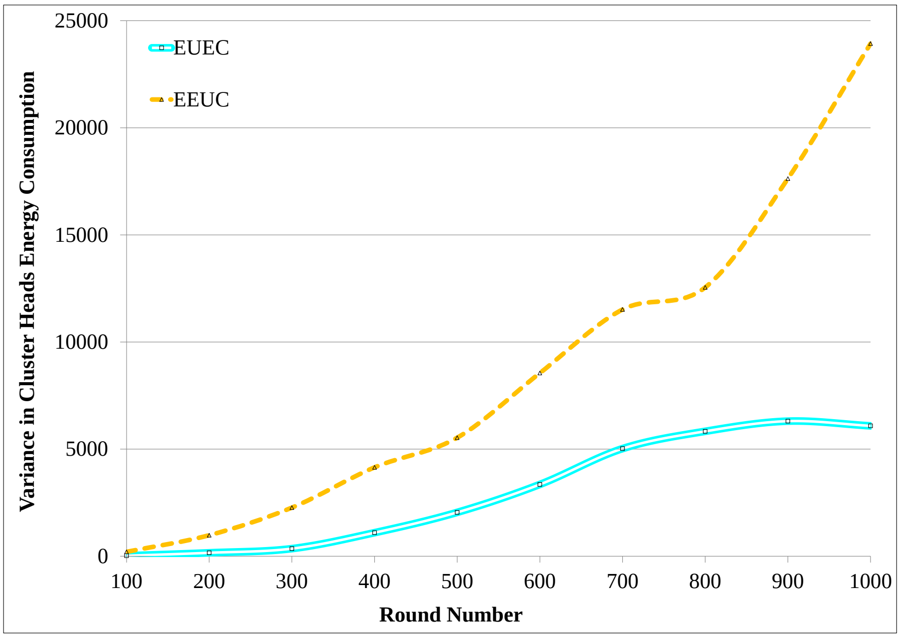


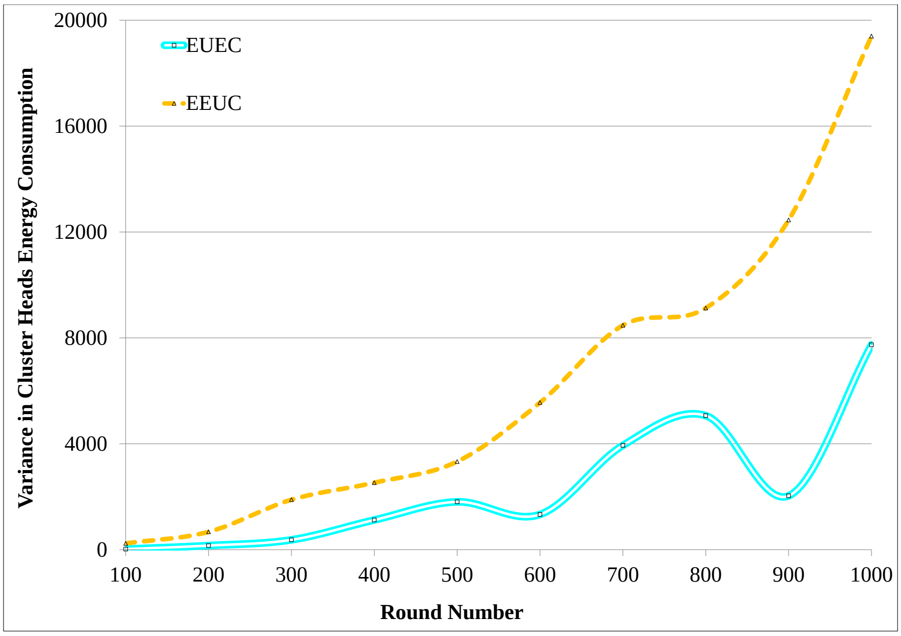
Figure 5.9 Total amount of energy spent at different levels

Fig. 5.9 shows, total amount of energy spent by EUEC sensor nodes at different levels in the network. From the figure, it is observed that the total amount of energy consumed by sensor nodes rises as the level number increases. This proves that the proposed unequal clustering algorithm balances the energy dissipation between intra and inter-cluster communications and promotes hot-spot free network.

Uniform cluster head distribution enables consistent power consumption among cluster heads in EUEC network. The variance in the amount of energy spent by cluster heads for EUEC and EEUC at various data forwarding rounds in 200 and 400 node network is shown in Fig. 5.10. From the figure it is inferred that the variance in energy dissipation is quite low for EUEC cluster heads, which highlights the significance of creating equivalent number of cluster heads at each level across the network.



(a) 200 Node Network



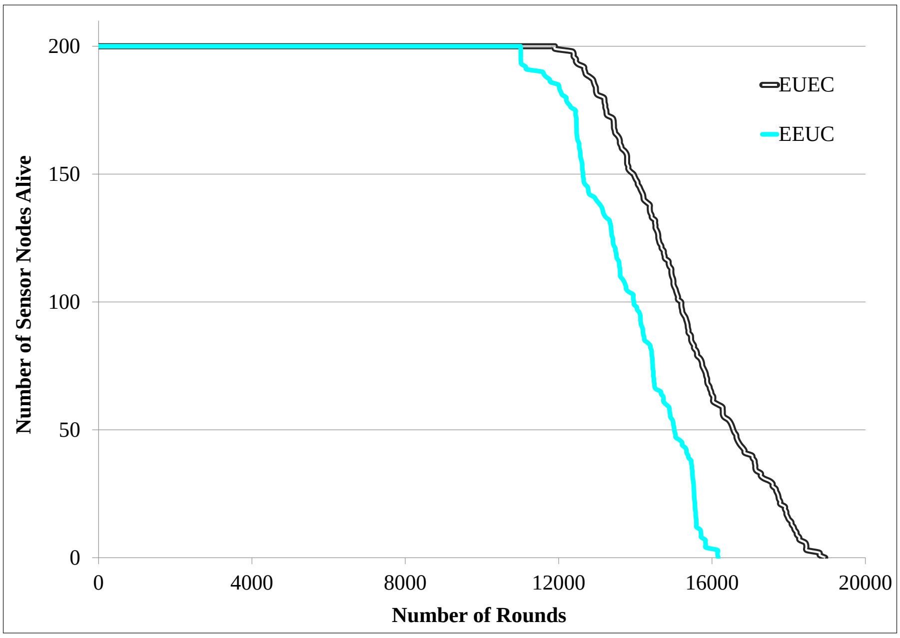
(b) 400 Node Network

Figure 5.10 Variance in amount of energy spent by CHs

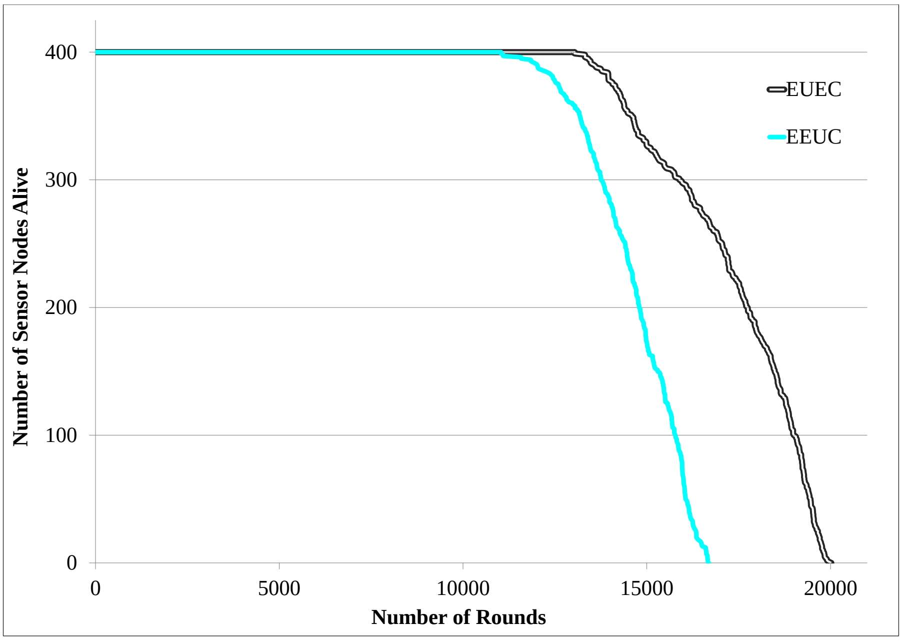
5.4.2 Lifetime Computation

Following section examines the characteristics of the introduced algorithm in-terms of sensor network lifetime.

Fig. 5.11 represents sensor network lifetime when 1% of nodes dead in 200 and 400



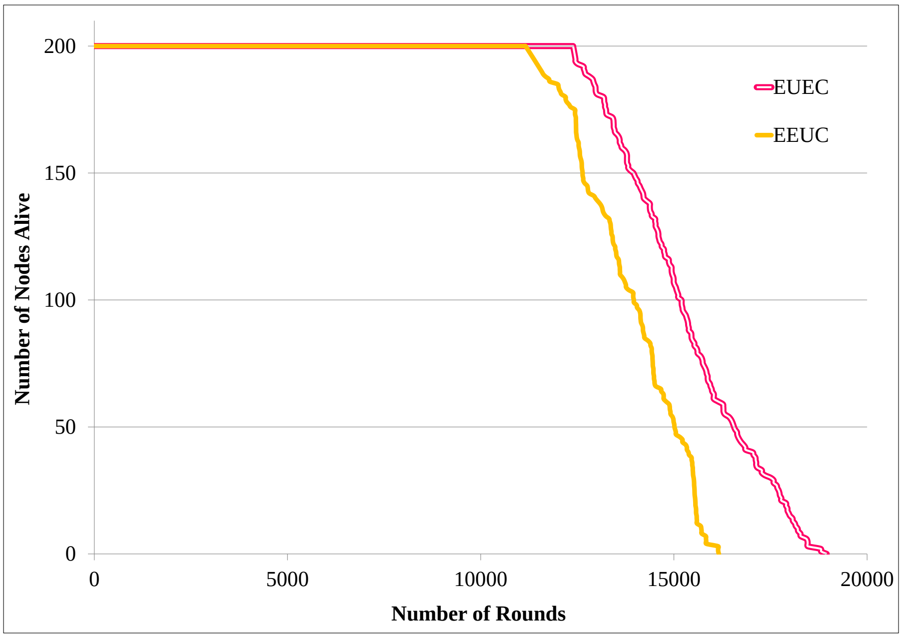
(a) 200 Node Network



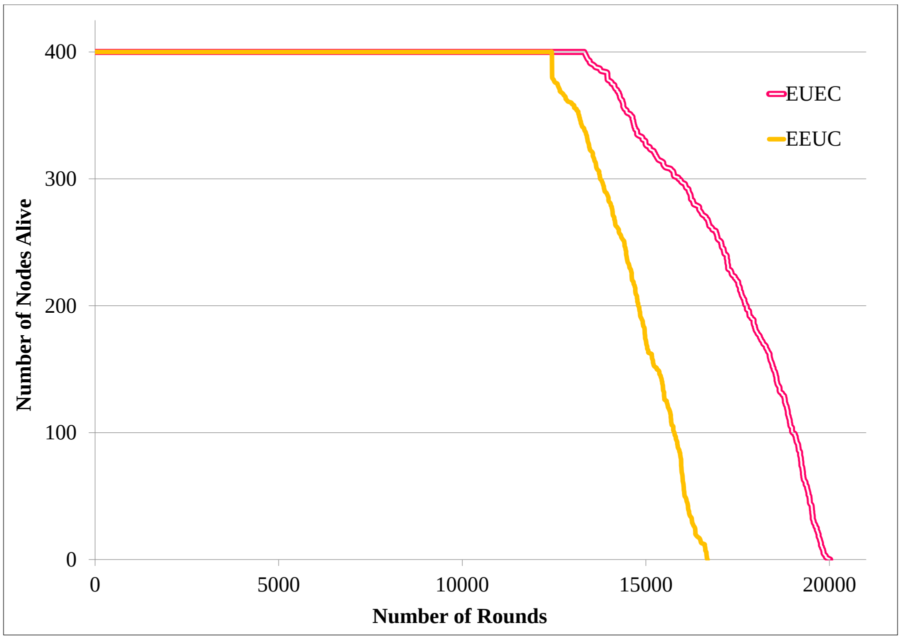
(b) 400 Node Network

Figure 5.11 Number of sensor nodes alive in the network

node networks for EUEC and EEUC. It is quantified from the results that the proposed unequal clustering mechanism prolongs network lifetime by 8% and 18% approximately in 200 and 400 node networks respectively over EEUC. The uniformity in power consumption among sensor nodes enhances every individual sensor node's lifetime, thereby network's.



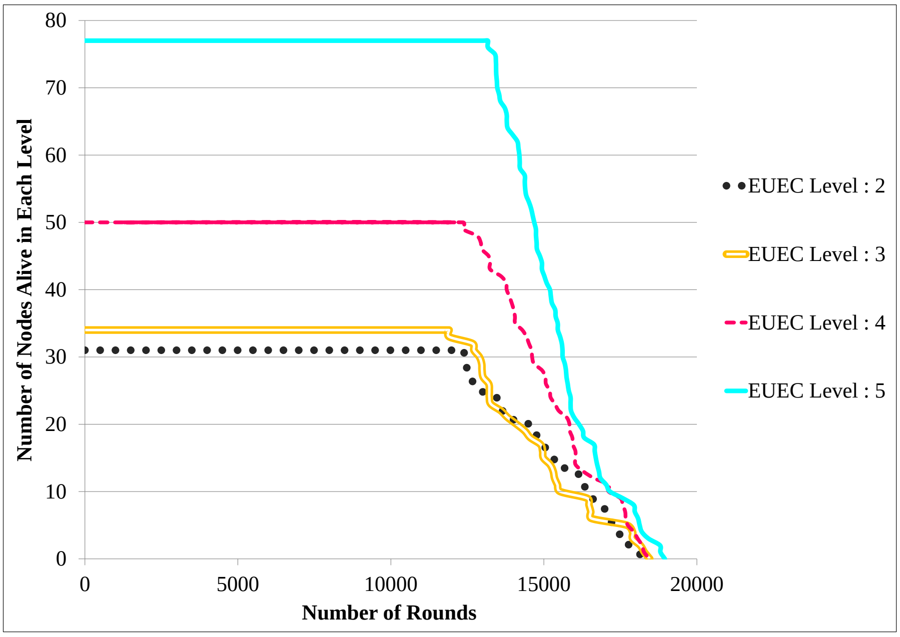
(a) 200 Node Network



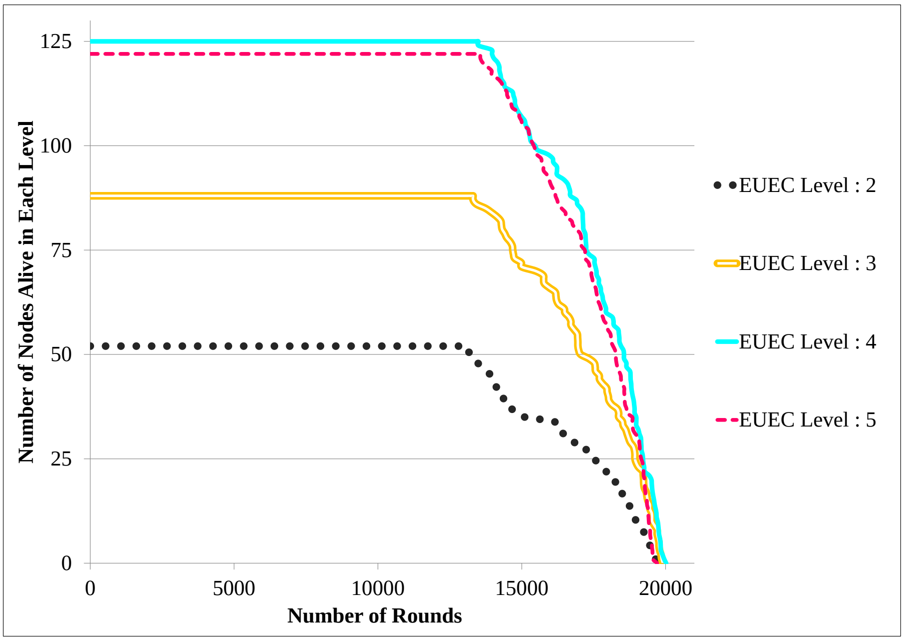
(b) 400 Node Network

Figure 5.12 Lifetime of sensor nodes in the network

The consistency in energy dissipation among sensor nodes in each cluster and uniform load distribution among cluster heads in each data flow path elevate network lifetime. Network lifetime when 5% of nodes die in 200 and 400 node network is shown in Fig. 5.12. It is observed from the figure that, EUEC performs consistently till the last node dies in the network. It is calculated from the simulation results that, EUEC extends network lifetime by 9% and 12% approximately compared with EEUC in 200 and 400 node network respectively.



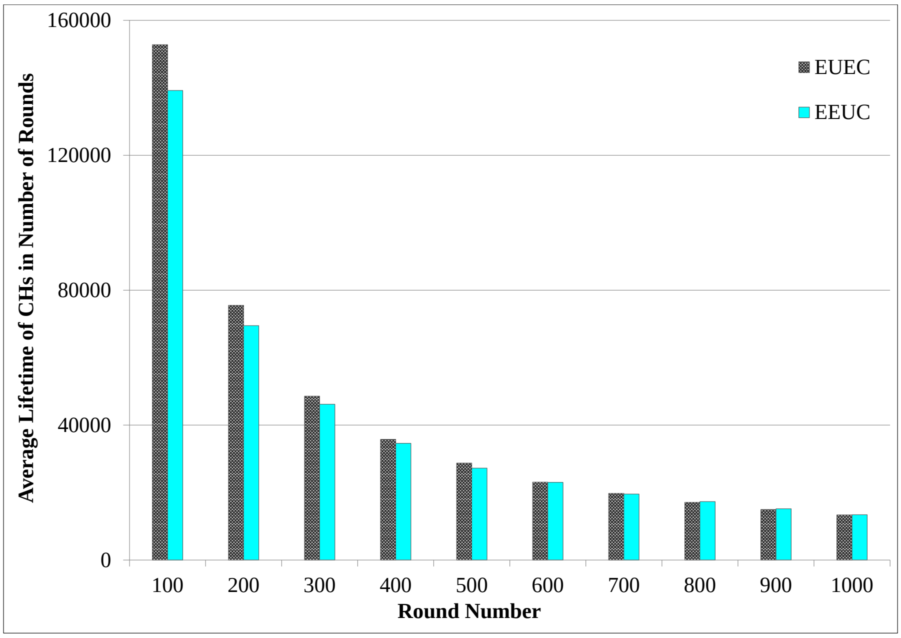
(a) 200 Node Network



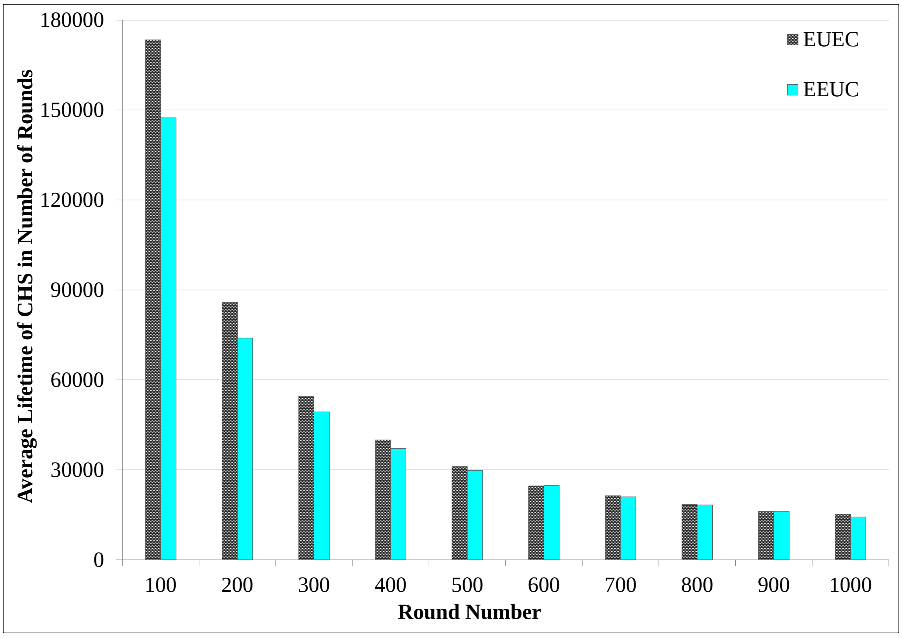
(b) 400 Node Network

Figure 5.13 Number of nodes alive in different levels of the network

Number of sensor nodes alive at each level in 200 and 400 node network of EUEC is presented in Fig. 5.13. It is observed from the figure that, sensor nodes in each level start dying almost at the same time. From the figure it is also interesting to note that, lifetime of each level when 100% of nodes die is same, which strengthens our statement that, the proposed unequal clustering algorithm enables uniform energy consumption efficiently among sensor nodes.



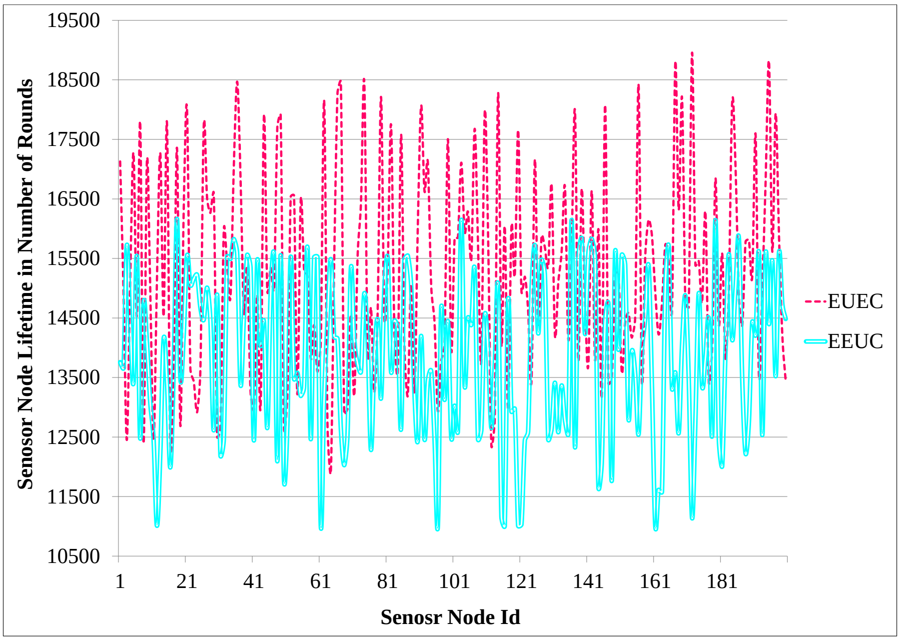
(a) 200 Node Network



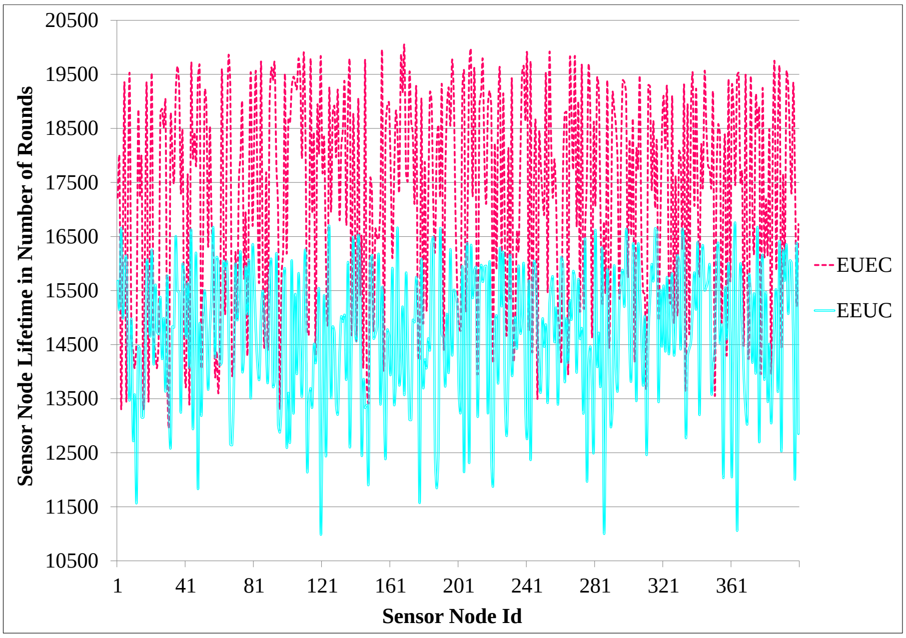
(b) 400 Node Network

Figure 5.14 Average lifetime of cluster heads in the network

Fig. 5.14 represents average lifetime of cluster heads versus data forwarding rounds. The proposed multi-hop data routing algorithm improves cluster heads' lifetime by distributing network load uniformly among cluster heads. From the simulation results it is computed that, EUEC extends cluster heads' lifetime by 0.5% to 9% and 1% to 17% depending on round number over EEUC in 200 and 400 node network respectively.



(a) 200 Node Network



(b) 400 Node Network

Figure 5.15 Lifetime of sensor nodes in the network

The proposed cluster head rotation scheme helps sensor nodes to share energy load uniformly among clusters and the multi-hop data transmission technique distributes routing load evenly among all data forwarding routes, which increases sensor nodes' lifetime. Fig. 5.15 shows lifetime of every individual sensor node of EUEC and EEUC in 200 and 400 node network.

5.5 SUMMARY

In multi-hop data routing model, hot-spot problem arises when employing clustering mechanism. Unequal clustering methodology has been proposed to overcome hot-spot problem in the literature. But, it generates huge number of clusters in various sizes at different levels to achieve it. Though unequal clustering avoids hot-spot problem, it increases hop-count between source and destination, which leads to energy wastage. Also, irregular size clusters causes imbalance in energy dissipation among sensor nodes and degrades network lifetime. To overcome these issues a novel Energy-efficient unequal clustering algorithm is proposed for edge-based wireless sensor networks in this chapter. It creates limited and equivalent number of unequal clusters at each level, where cluster size rises as the distance with base station increases. This constructs small size clusters near base station to preserve some energy for inter-cluster communication, which balances energy consumption among cluster heads and avoids hot-spot problem. Also, the proposed disjoint multi-hop routing protocol distributes network load uniformly among all data forwarding routes. Limited and equivalent number of clusters in each level helps to employ disjoint multi-path routing for data transmission. The intelligent relay node selection process assists cluster heads to further choose a relay node to forward data towards base station. Simulation results prove that the proposed unequal clustering technique enables hot-spot free network by balancing energy consumption among uniformly distributed cluster heads. The proposed multi-hop routing scheme shares network load uniformly among all data forwarding routes and prolongs network lifetime.

Chapter 6

ENERGY-EFFICIENT HYBRID CLUSTERING MECHANISM

The cluster size is one of the important factors that influences network operations directly, because large number of clusters will congest the network field with small size clusters and a very small number of clusters will exhaust the cluster heads with large amount of messages transmitted from cluster members. Therefore, the number of clusters to be formed should be decided carefully to minimize the trade-off between intra and inter cluster communication. The unequal clustering mechanism proposed earlier (EUEC) constructs constant number of clusters at each level to overcome hot-spot problem. But, the number of clusters EUEC builds increase either with number of levels as the network size grows or with poor network radius selection. This results network congestion with several clusters formed and introduces scalability issues.

To overcome hot-spot problem without scalability issues, a novel unequal clustering technique called, *Energy-efficient Hybrid Clustering Mechanism (EHCM)* is proposed for edge-based wireless sensor networks. The main aim of the proposed mechanism is to lift network lifetime by balancing energy consumption between intra and inter-cluster communications. EHCM combines features of equal and unequal clustering techniques to promote hot-spot free network with optimum number of clusters. Like EUEC, EHCM also uses the previously proposed network design space, BANDS to create initial level clusters in the network.

6.1 ENERGY-EFFICIENT HYBRID CLUSTERING MECHANISM

The proposed hybrid clustering algorithm is detailed in this section. A multi-hop data routing scheme is also introduced here to distribute routing load evenly among various data flow paths.

6.1.1 Number of Cluster Heads Computation

The network design space, BANDS divides sensor network into several levels and each level i is again subdivided into $2i-1$ number of equally spaced zones, where each zone acts as a cluster. As it is widely known that having one cluster head for each zone causes hot-spot problem, the proposed algorithm produces variable number of cluster heads for each zone depending upon sensor node level number. As the level number decreases the number of cluster heads selected increases to ensure concentrated clusters near base station to share network relay load uniformly among cluster heads. Equation (6.1) computes the number of cluster heads (N_{CHs}) that EHCM selects for each zone. The intention behind creating dynamic number of cluster heads for each zone is to render a platform that handles upstream relay traffic and equally shares among cluster heads across different levels of the network.

$$N_{CHs} = x^{'} \tag{6.1}$$

where,

$$x = [1 + \frac{\gamma}{2L_n - 1}] \qquad \forall L_n > 1 \tag{6.2}$$

γ is a random variable in the interval $[2, L_{total} - 1]$ and L_{total} represents total number of levels in the network and L_n is sensor node's level number.

Here, the number of cluster heads will be

$$x^{'} = \begin{cases} n & if \quad n \le x \le n/2 \\ n+1 & if \quad n/2 < x \le n+1 \end{cases} \tag{6.3}$$

Based on Equation (6.1), each zone chooses either one or maximum of two cluster heads. Level number plays an important role in identifying number of cluster heads that each zone selects. Maximum number of cluster heads for each zone is decided from the fact that the difference in number of zones for any two subsequent levels is two.

6.1.2 Cluster Head Selection Phase

Initially, several temporary cluster heads called, tentative cluster heads are selected for each zone with some probability T. The percentage of tentative cluster heads decreases as the level number increases. The probability value T is calculated for each sensor node using the following Equation (6.4) (Heinzelman et al., 2002) and it varies from level to level as the percentage of cluster heads vary in each level. Selected tentative cluster heads compete with each other to become final cluster head and the non-competing sensor nodes go to sleep mode, until final cluster heads are selected.

$$T = \frac{P}{1 - P * (R_{num} \quad mod \quad (1/P))} \tag{6.4}$$

where $P =$ the desired percentage of tentative cluster heads, $R_{num} =$ current round number.

$$P = 1/L_n \tag{6.5}$$

where L_n is sensor node's level number.

Each tentative cluster head broadcasts *COMPETE_CLUSTER_HEAD_MSG* with its Node Id *(Node_ID)*, Zone Id (Z_n) and Residual energy (E_{re}). Every tentative cluster head maintains a *Neighbor_Tentative_CH* set to store its neighboring tentative cluster heads information. Final cluster heads are selected based on saved information from *Neighbor_Tentative_CH*. After constructing *Neighbor_Tentative_CH* set, each tentative cluster head evaluates itself with other nodes in the set to take decision whether it can act as a final cluster head or not, which makes the proposed algorithm distributed.

If *Neighbor_Tentative_CH* set is *NULL* for a given tentative cluster head s, then s becomes final cluster head since it has no competition. Otherwise, tentative cluster head s checks its *Neighbor_Tentative_CH* set to find a neighboring node which has more residual energy and less distance with base station. If s finds itself having highest residual energy and minimum distance from base station, then s wins the competition and becomes final cluster head. Suppose, if s has same residual energy as one or more neighboring tentative cluster heads, then s becomes final cluster head only if, it is not a cluster head in previous data transmission rounds and has minimum distance to base station. To manage number of cluster heads, every iteration is verified for maximum number of cluster heads that a zone can have i.e., N_{CHs}. If a zone reaches its maximum cluster heads limit, then it aborts cluster head competition.

The tentative cluster head which wins the competition announces itself as a final cluster head by broadcasting *FINAL_CLUSTER_HEAD_MSG* message to inform all its neighbors, *Neighbor_Tentative_CH*. Tentative cluster head which receives

FINAL_CLUSTER_ HEAD_MSG from one of its *Neighbor_Tentative_CH* set will give-up the competition and inform all its neighbors by broadcasting quit message, *QUIT_CLUSTER_HEAD_COMP ITITION_MSG*. If a tentative cluster head s receives *QUIT_CLUSTER_HEAD_COMPITITION_MSG* from its neighbor t, then s removes tentative cluster head t from its *Neighbor_Tentative_CH* set. This process selects distributed cluster heads from each zone across all the levels in the network. Pseudo code of cluster head selection mechanism for an arbitrary sensor node s is given in Fig. 6.1.

6.1.3 Cluster Formation Phase

Once final cluster heads are selected for each zone, then each cluster head broadcasts a *CH_ADV_MSG* message across the network. All sleeping nodes wake-up and join their nearest cluster head which has greatest received signal strength by sending a *JOIN_CH_MSG* message.

6.1.4 Multi-hop Routing Mechanism

On completing cluster formation, cluster members start sending their sensing information to their cluster heads. Cluster heads aggregate received information into a single length-fixed data packets and forward them to downstream relay cluster heads in the direction towards base station. To select a relay node, each cluster head broadcasts *RELAY_CLUSTER_HEAD_MSG* message, which consists of Node Id (*Node_Id*), Zone Number (Z_n), Residual Energy (E_{re}) and its distance from base station. Neighboring cluster heads use this information to find relay node for data transmission. Cluster head close to base station with higher residual energy from lower level is selected as a relay node. Incase of a tie, node with smaller Z_n will be selected as a relay node.

Lemma 4.3.1: The big Oh complexity of the proposed work is $O(N)$, where N is total number of nodes in the network, given in the previous chapter holds good for the proposed hybrid clustering algorithm also.

```
Compute_Num_CHs ($L_n$)
x' = $1 + \frac{\gamma}{2L_n - 1} \quad \forall L_n > 1$
return x'

$N_{CHs}$ ← Compute_Num_CHs ($L_n$)
P ← $1/L_n$
T ← $P/(1-P*(R_{num} \bmod (1/P)))$
if $\lambda < T$, then
    s.Status ← Tentative_Cluster_Head
    Call COMPETE_CLUSTER_HEAD_MSG (Node_ID, $Z_n$, $E_{re}$)
else
    s.Status ← Sleep
    EXIT
end if

On call COMPETE_CLUSTER_HEAD_MSG (Node_ID, $Z_n$, $E_{re}$) from node s
if s. $Z_n$ = t. $Z_n$ then
    Push t to s.Neighbor_Tentative_CH
end if

while s.Status = Tentative_Cluster_Head AND Zone_CH_Counter <= $N_{CHs}$ do
    if s.Neighbor_Tentative_CH = NULL then
        s.Status ← FINAL_CLUSTER_HEAD_MSG
        Zone_CH_Counter ← Zone_CH_Counter + 1
        Call FINAL_CLUSTER_HEAD_MSG (Node_ID)
        EXIT
    else if s. $E_{re}$ > t. $E_{re}$ $\forall$ t ∈ s. Neighbor_Tentative_CH
        AND d(s, BS) <= d(t, BS) then
        s.Status ← FINAL_CLUSTER_HEAD_MSG
        Zone_CH_Counter ← Zone_CH_Counter + 1
        Call FINAL_CLUSTER_HEAD_MSG (Node_ID)
        EXIT
    else if s. $E_{re}$ = t. $E_{re}$ $\forall$ t ∈ s. Neighbor_Tentative_CH
        AND d(s, BS) < d(t, BS) AND !s.WasCH then
        s.Status ← FINAL_CLUSTER_HEAD_MSG
        Zone_CH_Counter ← Zone_CH_Counter + 1
        Call FINAL_CLUSTER_HEAD_MSG (Node_ID)
        EXIT
    end if
end while

On call FINAL_CLUSTER_HEAD_MSG (Node_ID) from node s
 if t ∈ s. Neighbor_Tentative_CH then
    t.Status ← NonCH
    Call QUIT_CLUSTER_HEAD_COMPITITION_MSG (Node_Id)
    EXIT
end if

On call QUIT_CLUSTER_HEAD_COMPITITION_MSG (Node_Id) from node s
if s ∈ t.Neighbor_Tentative_CH then
    Delete s from t.Neighbor_Tentative_CH
end if
```

Figure 6.1 Cluster head selection pseudo code

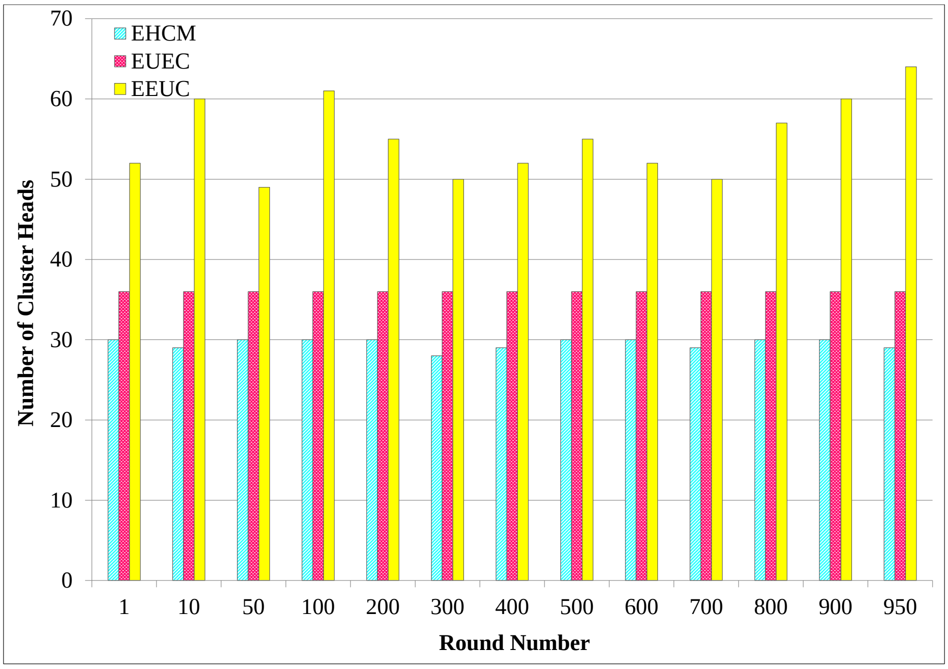
6.2 EXPERIMENTAL RESULTS

The characteristics of Energy Efficient Hybrid Clustering Mechanism (EHCM) are investigated via simulations using Castalia simulator Boulis (2013). At first, EHCM cluster head characteristics are studied then its energy consumption behavior in the network is investigated and later, its impact on sensor network lifetime is examined. For simplicity, an ideal MAC layer and error-free communication links are assumed. The proposed work, EHCM is compared with another well known unequal clustering algorithm Energy-Efficient Unequal Clustering Mechanism (EEUC) and previously proposed, Energy-Efficient Unequal Clustering Algorithm (EUEC). Detailed simulation parameters for experimental evaluation are given in Table 6.1. The radio hardware energy dissipation model shown in Li et al. (2005) is used here.

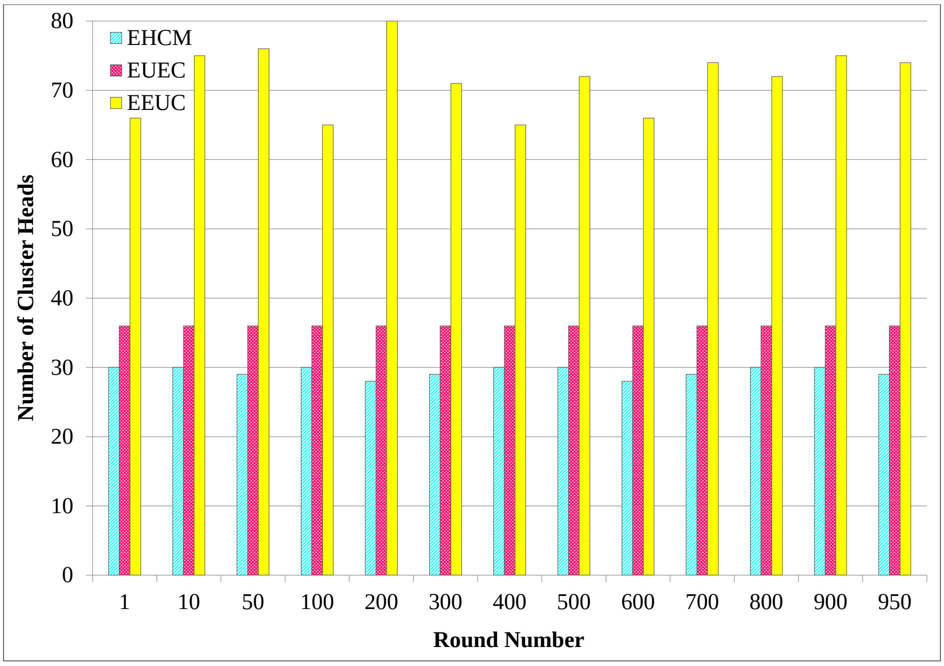
Table 6.1 Simulation Parameters

Parameter	**Value**
Simulation Area	(0,0)$\sim$(1000,1000)m
Base Station Location	(0,0)m
Number of nodes	200 & 400
Initial energy	18720 J
E_{elec}	50 nJ/bit
E_{amp}	10 pJ/bit/m^2
E_{DA}	5 nJ/bit/signal
Data Packet Size	2000 bits
Packet Rate	1/sec
Radius R	200m
Simulation Time	25000 seconds
Number of Runs	10
Round Time	25s

Cluster size influences network performance directly, because, large number of clusters congest the network and small number of clusters exhaust cluster heads' resources. Therefore, number of clusters to be generated should be decided carefully. The number of cluster heads selected by EHCM, EUEC and EEUC for each data forwarding round is shown in Fig. 6.2. From the figure it is observed that, EHCM selects limited and consistent number of cluster heads when compared with EUEC and EEUC, which have created more number of cluster heads for each data forwarding round. Also, it is noticed from the figure



(a) 200 Node Network



(b) 400 Node Network

Figure 6.2 Number of cluster heads selected for each round that EEUC has created huge number of clusters in varied numbers from round to round. Consistency in the number of cluster heads selected at each data transmission round enables uniform distribution of cluster heads across different levels in the EHCM network.

Table 6.2 Percentage of cluster heads selected in different data forwarding rounds

Clustering Algorithm	**EUEC**		**EHCM**		**Round Number**
# of nodes in the network	***200***	***400***	***200***	***400***	
% of Cluster Heads Selected w.r.t EEUC	69.23	54.55	57.69	45.45	*1*
	60.00	48.00	48.33	40.00	*10*
	73.47	47.37	61.22	38.16	*50*
	59.02	55.38	49.18	46.15	*100*
	65.45	45.00	54.55	35.00	*200*
	72.00	50.70	56.00	40.85	*300*
	69.23	55.38	55.77	46.15	*400*
	65.45	50.00	54.55	41.67	*500*
	69.23	54.55	57.69	42.42	*600*
	72.00	48.65	58.00	39.19	*700*
	63.16	50.00	52.63	41.67	*800*
	60.00	48.00	50.00	40.00	*900*
	56.25	48.65	45.31	39.19	*950*

Table 6.3 Change in cluster heads selection percentage between EUEC and EHCM

Clustering Algorithm	**EHCM**		**Round Number**
# of nodes in the network	***200***	***400***	
Difference in % of Cluster Heads Selected by EHCM w.r.t EUEC	16.67	16.67	*100*
	19.44	16.67	*200*
	16.67	19.44	*300*
	16.67	16.67	*400*
	16.67	22.22	*500*
	22.22	19.44	*600*
	19.44	16.67	*700*
	16.67	16.67	*800*
	16.67	22.22	*900*
	19.44	19.44	*1000*

Table 6.2 presents percentages of cluster heads selected by EUEC and EHCM with respect to EEUC in different data forwarding rounds. From the table and Fig. 6.2 it is clear that EHCM selects consistent and less percentage of cluster heads when compared to EEUC and EUEC. Also, from Table 6.3 it is noticed that EHCM has selected 16% to 22% percentage less number of cluster heads approximately when compared to EUEC.

6.2.1 Energy Consumption

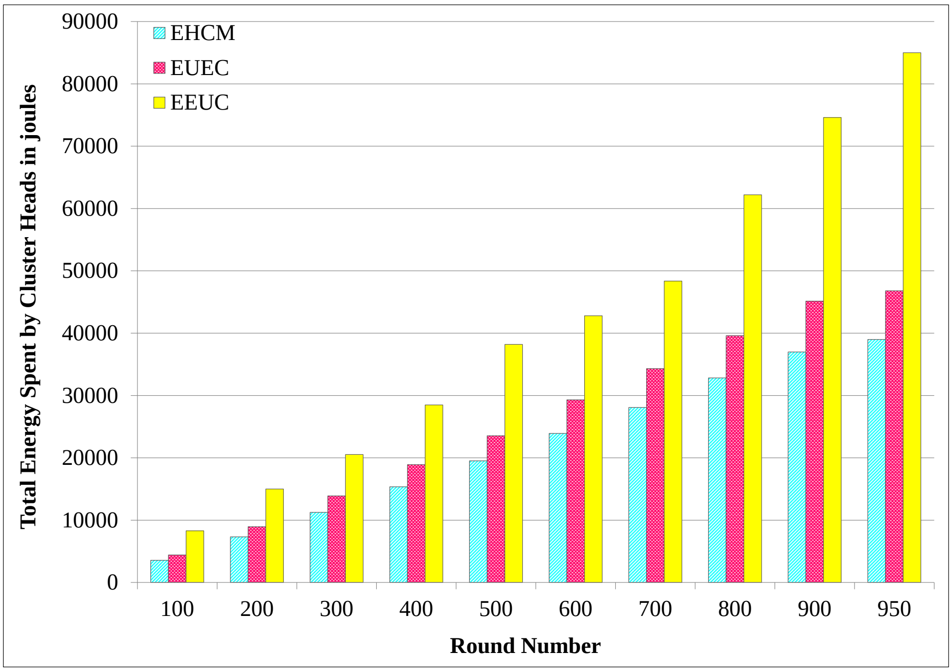
In this section, EHCMS's energy consumption behavior is examined for sensor nodes and cluster heads.

The total amount of energy consumed by cluster heads in various data forwarding rounds for 200 and 400 node network is presented in Fig. 6.3. From the experimental results it is interpreted that the proposed hybrid clustering mechanism consumes less amount of energy when compared to EUEC and EEUC irrespective of network size in any data forwarding round. Distributed cluster head selection process at each level promotes minimal energy consumption among cluster heads across the network.

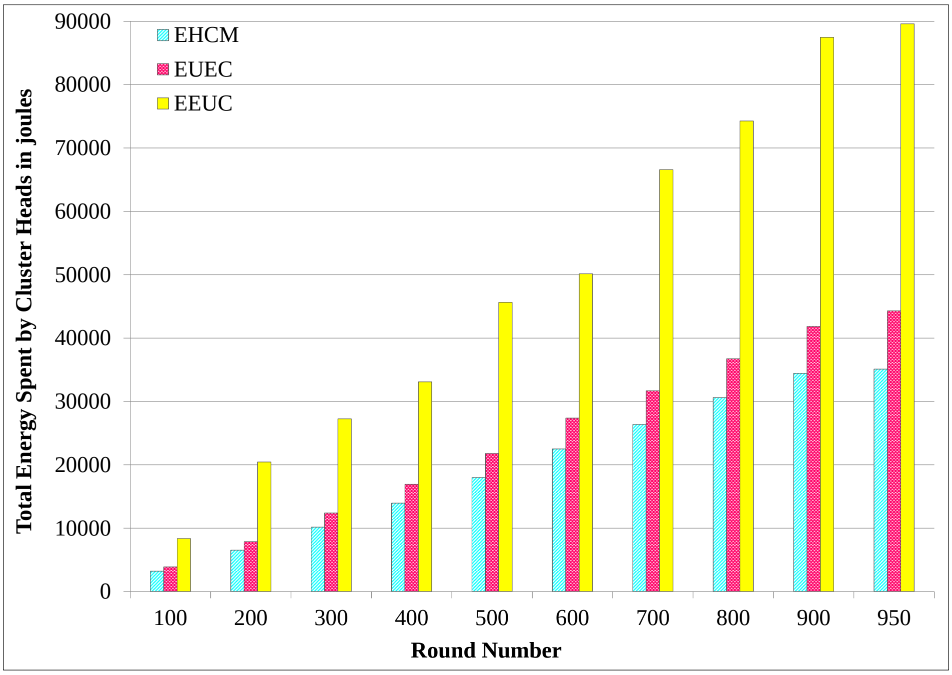
Table 6.4 Change in energy consumed percentage by cluster heads

Clustering Algorithm	**EUEC**		**EHCM**		**Round**
# of nodes in the network	***200***	***400***	***200***	***400***	**Number**
% of Energy Spent by Cluster Heads w.r.t EEUC	53.27	46.56	42.96	38.43	*100*
	59.64	38.52	48.78	31.97	*200*
	67.71	45.48	54.83	37.32	*300*
	66.38	51.20	53.90	42.19	*400*
	61.63	47.73	51.09	39.45	*500*
	68.47	54.60	55.90	44.88	*600*
	70.95	47.59	58.08	39.60	*700*
	63.65	49.47	52.76	41.22	*800*
	60.52	47.83	49.57	39.37	*900*
	55.07	49.45	45.87	39.18	*950*

As discussed in the above section if the number of cluster heads are chosen optimally, will improve the network performance. This statement has been supported by the results shown from Table 6.4. It is noted from the table that, with appropriate number of cluster heads, EHCM manged to spend minimum amount of energy when compared to EEUC and EUEC. Also, the results from Table 6.5 witnesses uniform energy dissipation by EHCM



(a) 200 Node Network



(b) 400 Node Network

Figure 6.3 Total amount of energy consumed by cluster heads

cluster heads irrespective to data forwarding round.

Table 6.5 Difference in energy consumption percentage

Clustering Algorithm	**EHCM**		**Round**
# of nodes in the network	***200***	***400***	**Number**
Less % of Energy Spent by EHCM Cluster Heads w.r.t EUEC	19.36	17.48	*100*
	18.22	17.01	*200*
	19.02	17.93	*300*
	18.80	17.59	*400*
	17.09	17.36	*500*
	18.36	17.80	*600*
	18.15	16.80	*700*
	17.10	16.68	*800*
	18.10	17.68	*900*
	16.71	20.77	*1000*

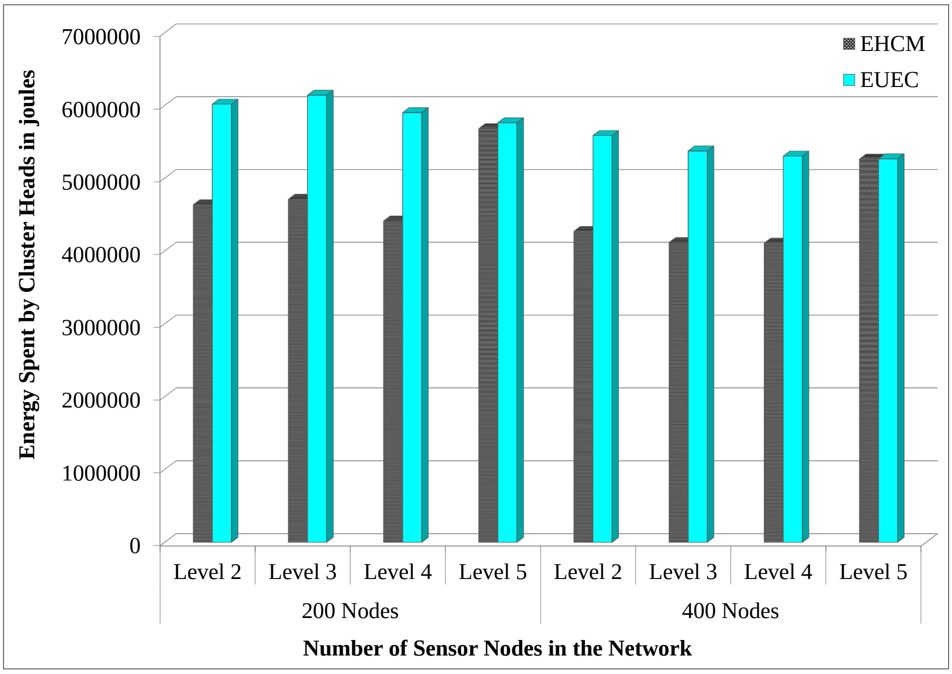


Figure 6.4 Total energy spent by cluster heads at different levels

To find out the difference in power consumption among different levels in the network, Fig. 6.4 is presented with total amount of energy spent by cluster heads at various levels by EUEC and EHCM in 200 and 400 node network. It is observed from the figure that, EHCM consumes consistent amount of energy by distributing network load uniformly among cluster heads at various levels in the network field. Also, the low and consistent energy dissipation at lower levels promotes a hot-spot free network with EHCM.

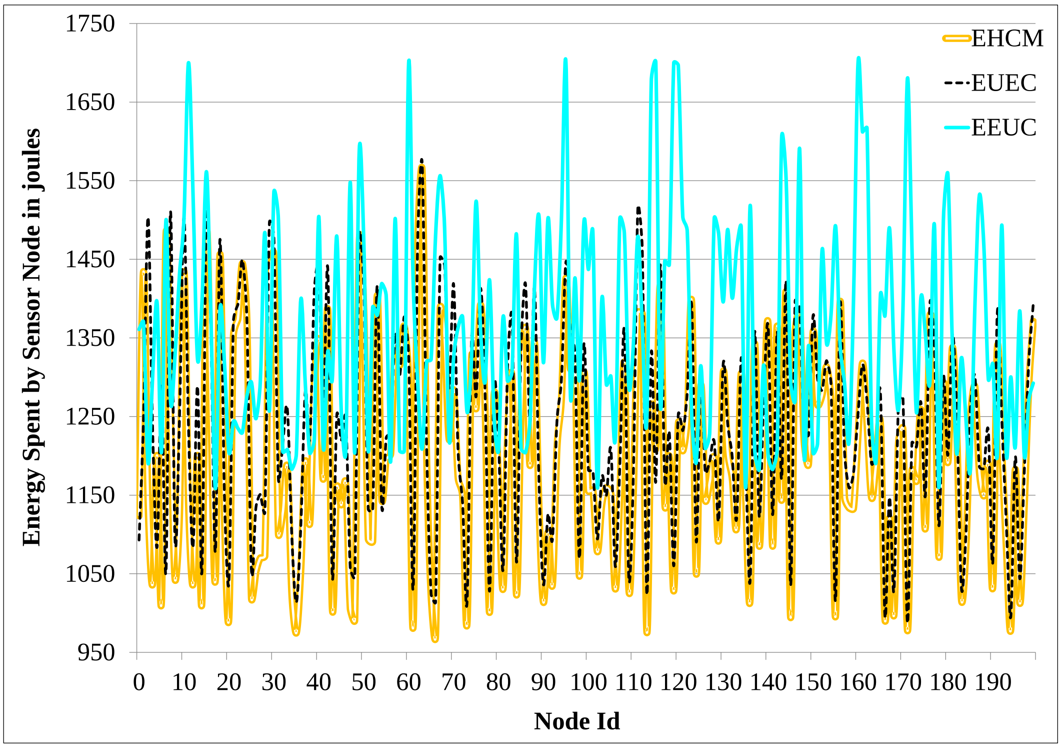
Table 6.6 Change in CHs energy consumption percentage at different levels

Clustering Algorithm	**EHCM**		**Level Number**
# of nodes in the network	***200***	***400***	
Difference in % of Energy Spent by CHs w.r.t EUEC	22.98	23.57	*2*
	23.28	23.41	*3*
	25.23	22.56	*4*
	1.42	0.07	*5*

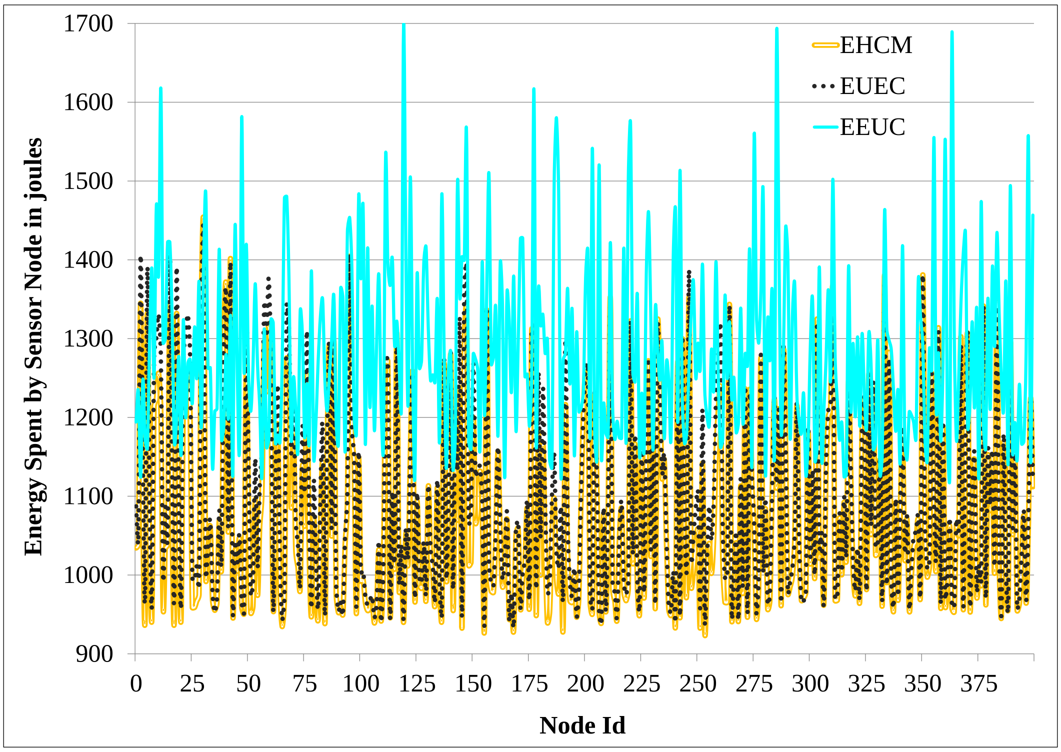
Identical results from Fig. 6.4 and Table 6.6 explain EHCM's uniform energy consumption behavior across different levels (except the last level in this case) in the network. Also, from the table it is observed atleast 20% saving in energy expenditure with EHCM compared to EUEC.

Dynamic number of clusters for each data forwarding round guide network to create distributed clusters. With unequal cluster formation, the network load is shared accordingly among different sized clusters. This promotes optimal energy dissipation among sensor nodes in the network. Fig. 6.5 represents total amount of energy utilized by EHCM, EUEC and EEUC sensor nodes in 200 and 400 node network. From the figure, it is realized that, sensor nodes energy consumption rate is high in EUEC and EEUC network compared with EHCM.

The amount of energy used by cluster heads in randomly picked data forwarding rounds is depicted in figure Fig. 6.6 for EHCM, EUEC and EEUC over 200 and 400 node network. From the figure it is proved that, EHCM rotates cluster heads in such a way that the energy consumption is distributed uniformly among sensor nodes.

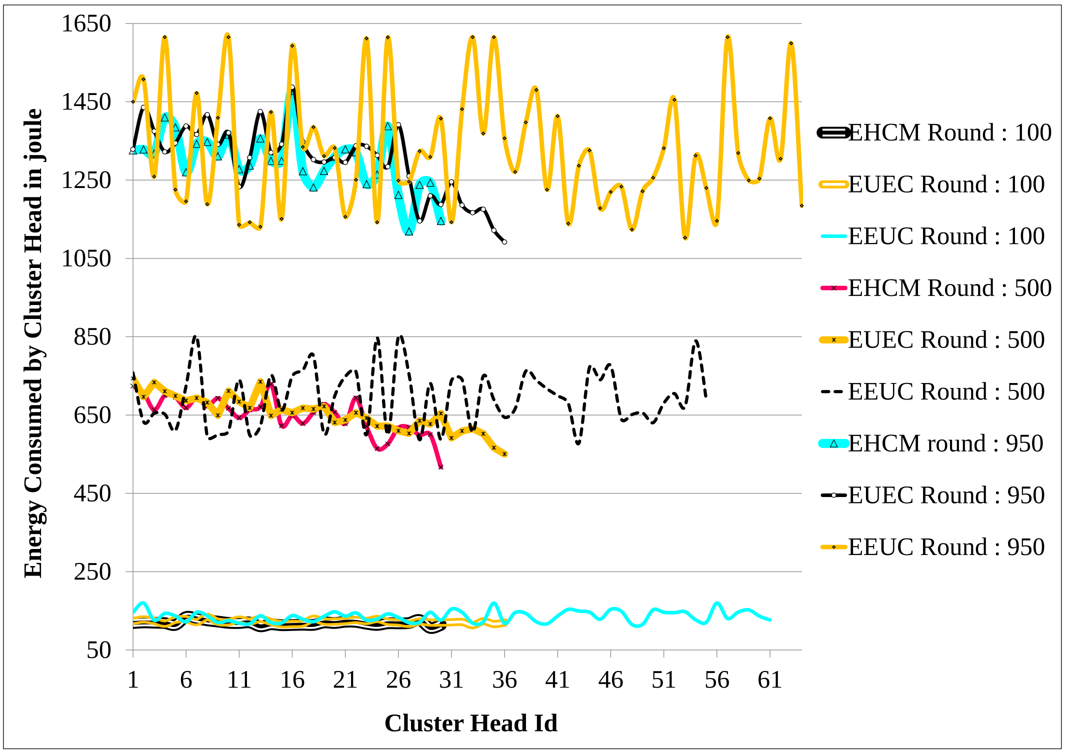


(a) 200 Node Network

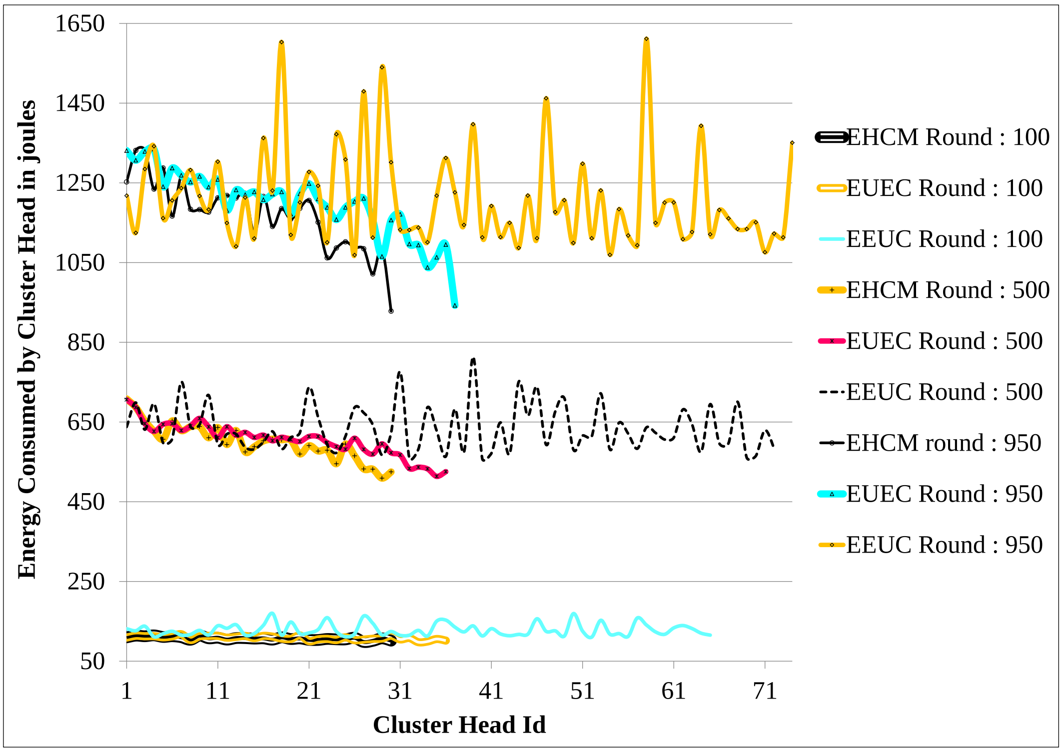


(b) 400 Node Network

Figure 6.5 Total amount of energy consumed by sensor nodes



(a) 200 Node Network



(b) 400 Node Network

Figure 6.6 Amount of energy consumed by cluster heads at random rounds

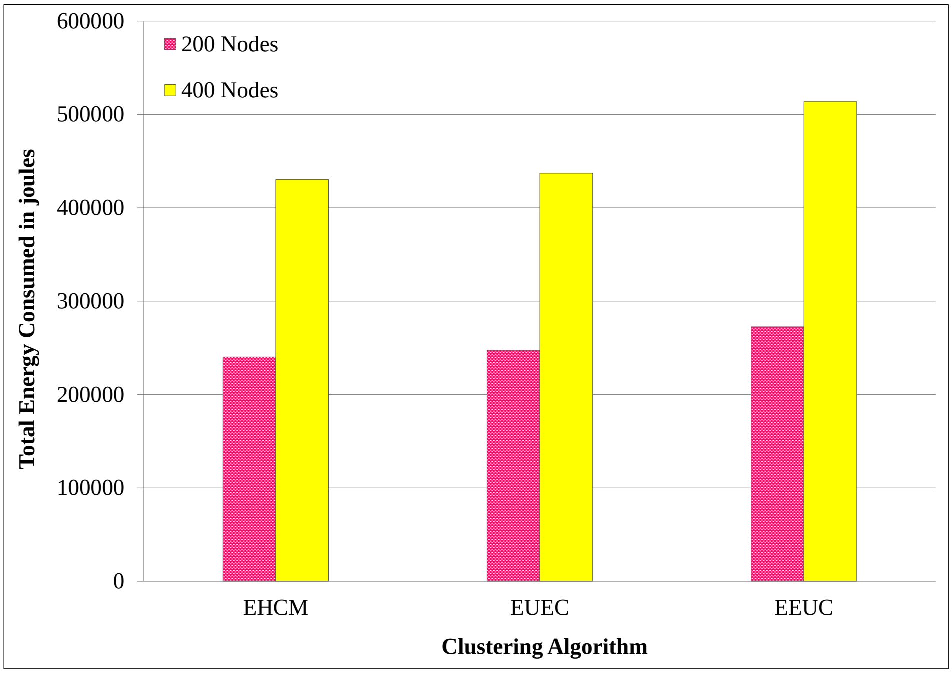


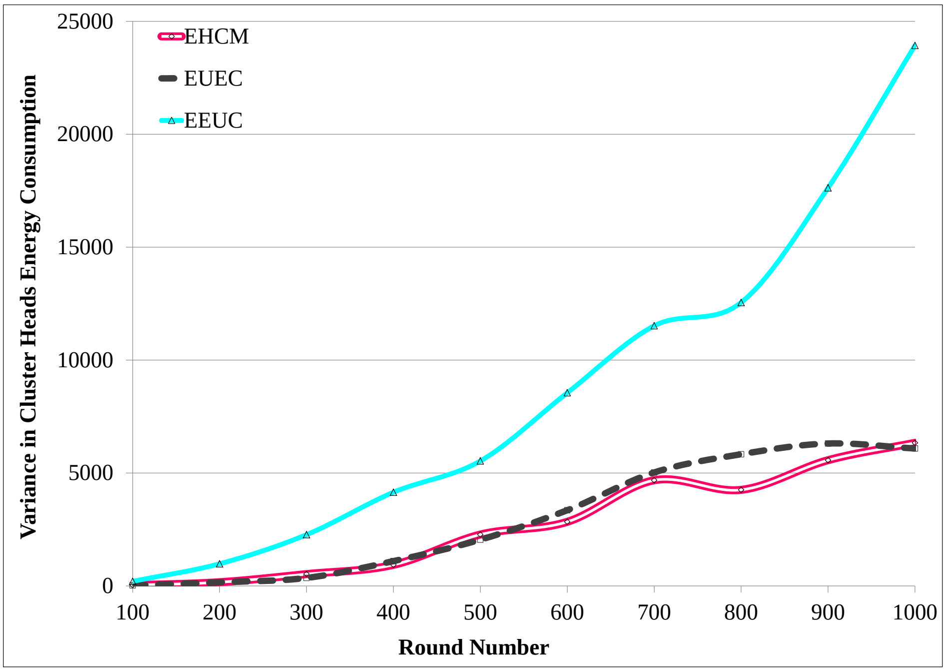
Figure 6.7 Total energy consumed by EEUC, EUEC and EHCM networks

Fig. 6.7 shows the total amount of energy dissipated by EEUC, EUEC and EHCM algorithms. It is inferred form the simulation results that, EEUC, EUEC networks spend more energy compared to EHCM network, which witness that the number of clusters directly influence network performance. The dynamic selection and limitation on number of cluster heads that EHCM selects promotes uniform power consumption in the network.

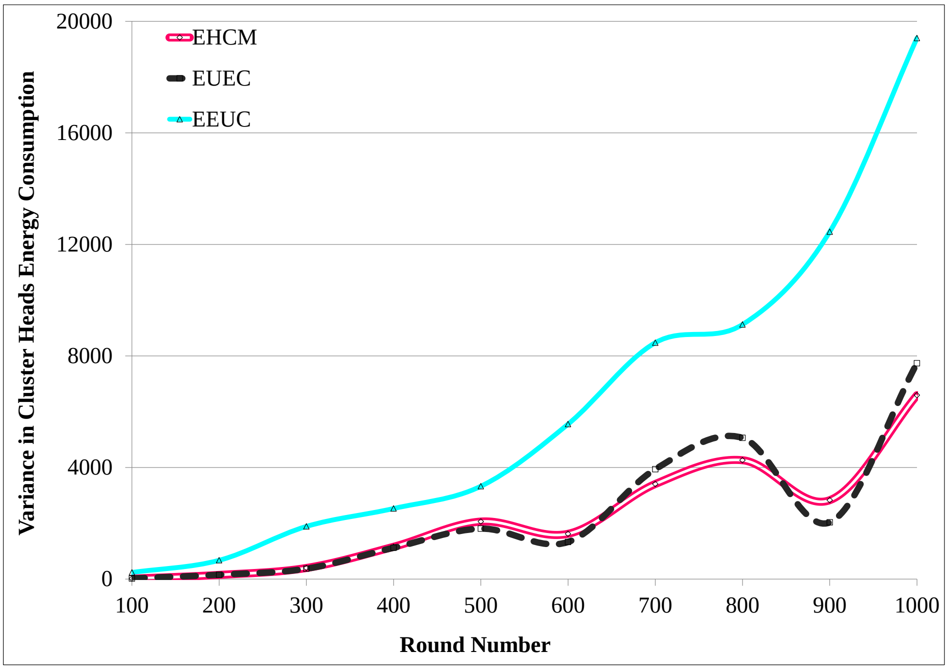
Table 6.7 Change in energy expenditure percentage

Clustering Algorithm		**EUEC**		**EHCM**	
# of nodes in the network		***200***	***400***	***200***	***400***
Change in Energy Dissipation	**EEUC**	9.18	14.91	11.84	16.24
% by the Network w.r.t	**EUEC**			2.93	1.57

Form the Table 6.7, it is noted that EHCM consumes less energy compared to EEUC and EUEC. The adaptive cluster head selection mechanism of EHCM enables even load distribution among sensor nodes in the network and conserves valuable network resources.



(a) 200 Node Network



(b) 400 Node Network

Figure 6.8 Variance in amount of energy spent by cluster heads

The variance in amount of energy dissipated by cluster heads in different data forwarding rounds for EHCM, EUEC and EEUC in 200 and 400 node network is illustrated in Fig. 6.8. From the figure it is interpreted that, EHCM stabilizes energy consumption among cluster heads at various levels in the network.

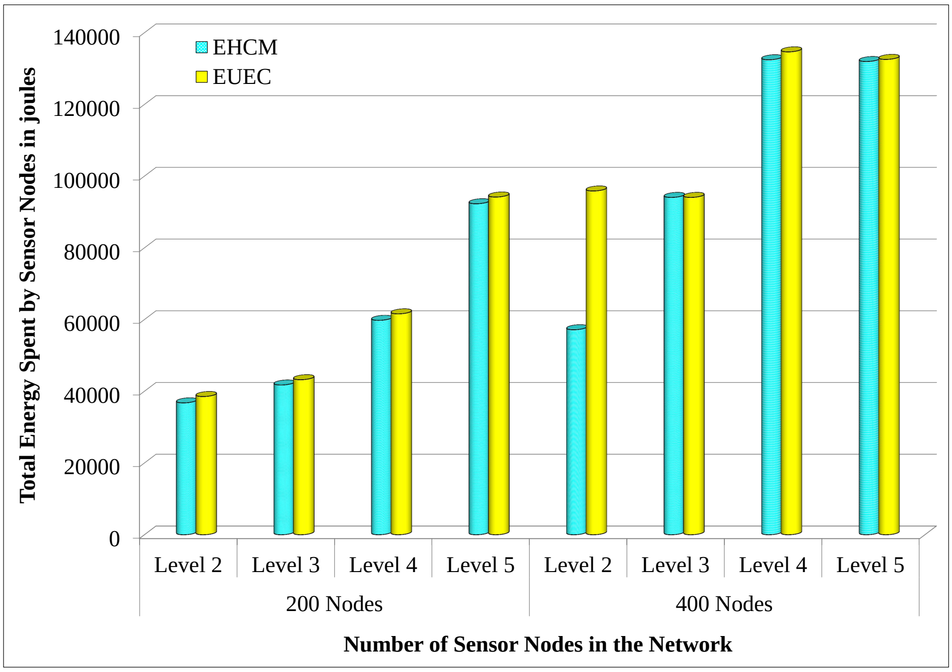


Figure 6.9 Total amount of energy dissipated at different levels

Fig. 6.9 shows total amount of energy spent by EHCM and EUEC networks at different levels in 200 and 400 node network. From the figure it is noticed that the total amount of power used raises as the level number increases in both EHCM and EUEC. But, it is to be noted that the results are given for individual levels and the number of nodes increases with level and thereby the consumption. Also, from the figure it is observed that there is a regular rise in energy usage between the levels with EHCM, which highlights the dynamic routine in cluster formation.

Table 6.8 Change in sensor nodes energy consumption percentage at different levels

Clustering Algorithm	**EHCM**		**Level**
# of nodes in the network	***200***	***400***	**Number**
Difference in % of Energy Spent by Sensor Nodes w.r.t EUEC	4.59	2.68	*2*
	3.42	1.88	*3*
	2.94	1.64	*4*
	1.99	0.45	*5*

To avoid hot-spot problem it is necessary to reduce energy dissipation on cluster heads as the level number decreases in the network. It is inferred from the Fig. 6.9 as well as from the Table 6.8 that, EHCM does this just by choosing optimal number of cluster heads at each level using its reactive cluster head selection mechanism and by rotating leaders in each cluster at regular basis.

6.2.2 Life Time Computation

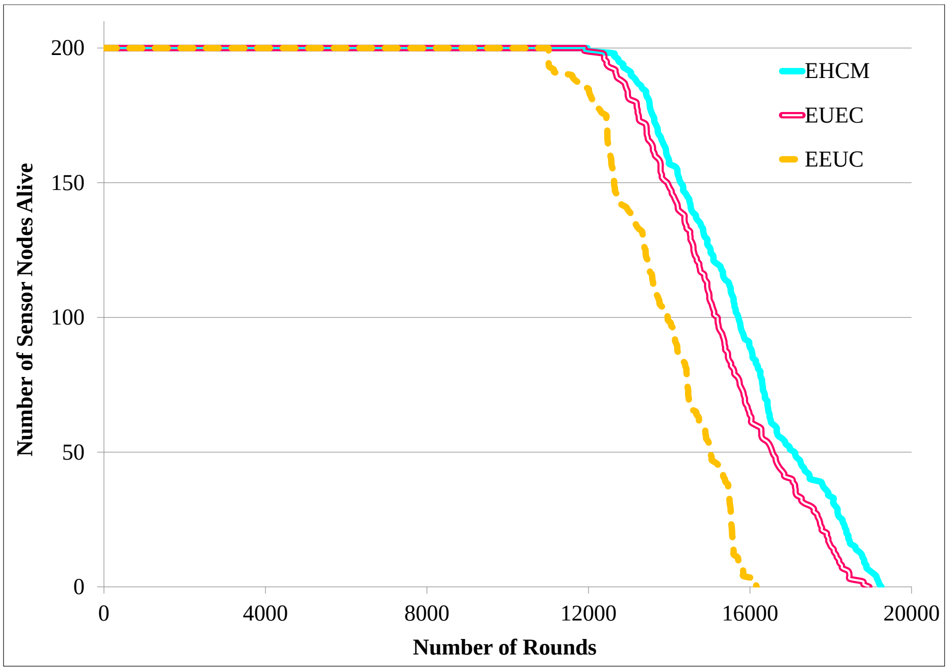
The following section presents the impact of the proposed hybrid clustering algorithm on sensor network life time.

The sensor network lifetime when 1% of nodes are dead in 200 and 400 node network of EHCM, EUEC and EEUC is shown in Fig. 6.10. EHCM's energy dissipation balancing mechanism extends sensor network lifetime by minimizing trade-off between intra and inter cluster communications. It is observed from the figure that the proposed scheme, EHCM, out-performs EUEC and EEUC by its uniform load dissipation technique. From the experimental results it is interpreted that the proposed clustering mechanism raises network lifetime by 1% and 2% against EUEC and 9% and 17% against EEUC approximately in a 200 and 400 node network respectively.

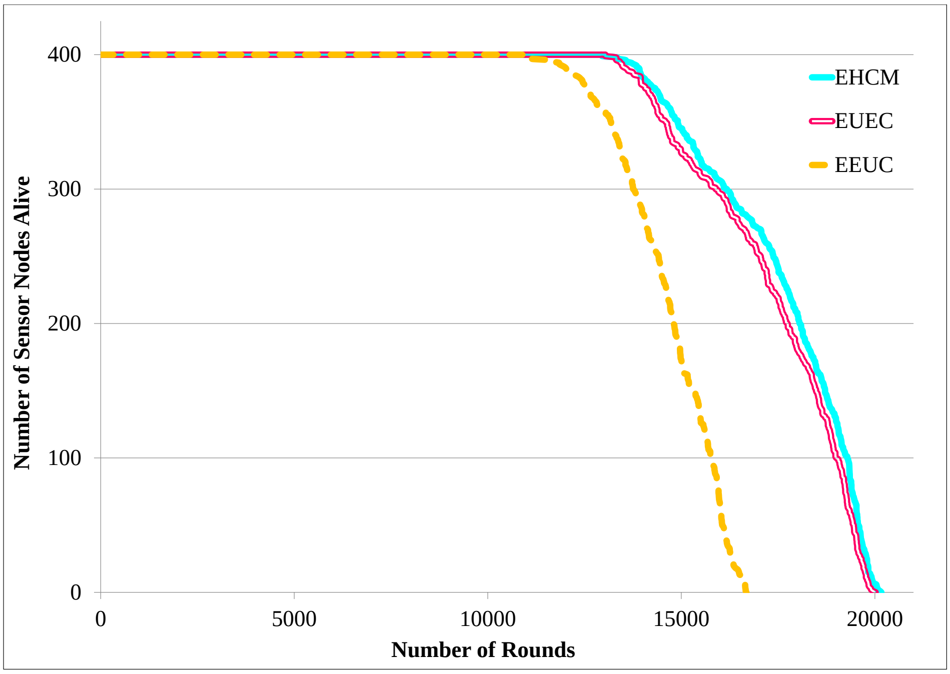
Table 6.9 Percentage rise in network lifetime when 1% nodes die

Clustering Algorithm		**EUEC**		**EHCM**	
# of nodes in the network		***200***	***400***	***200***	***400***
% rise in Network Lifetime (when 1%) w.r.t	**EEUC**	12.18	15.11	14.75	17.17
	EUEC			2.29	1.79

Table 6.9 presents change in EHCM's network lifetime percentage when 1% of nodes die in the network with respect to EEUC and EUEC algorithms. From the tabular values it is interpreted that, the dynamic behavior in cluster election mechanism, EHCM achieves uniform load distribution among the clusters and help the network live longer.



(a) 200 Node Network



(b) 400 Node Network

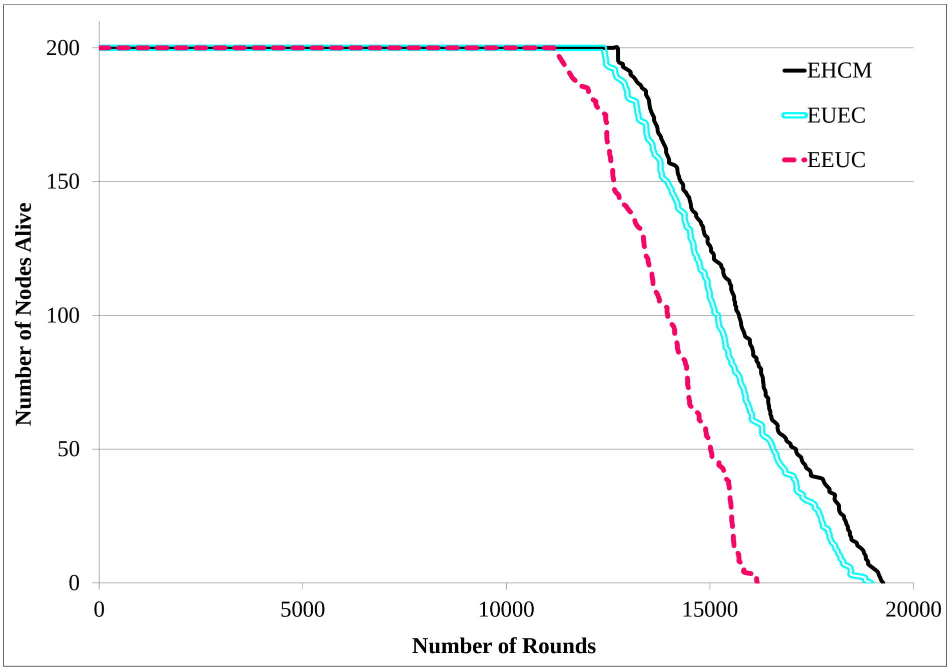
Figure 6.10 Number of sensor nodes alive in the network

Fig. 6.11 represents sensor network lifetime when 5% of nodes die in 200 and 400 node network for EHCM, EUEC and EEUC algorithms. It is observed from the figure that, EHCM produces consistent performance till the last node dies in the network irrespective of the network size. Despite its quick fall at the beginning, EHCM achieves consistent outcome from the network resources. It is computed from the simulation results that, EHCM elevates network lifetime by 3% and 1.5% over EUEC and 13% and 14% over EEUC approximately in 200 and 400 node network respectively.

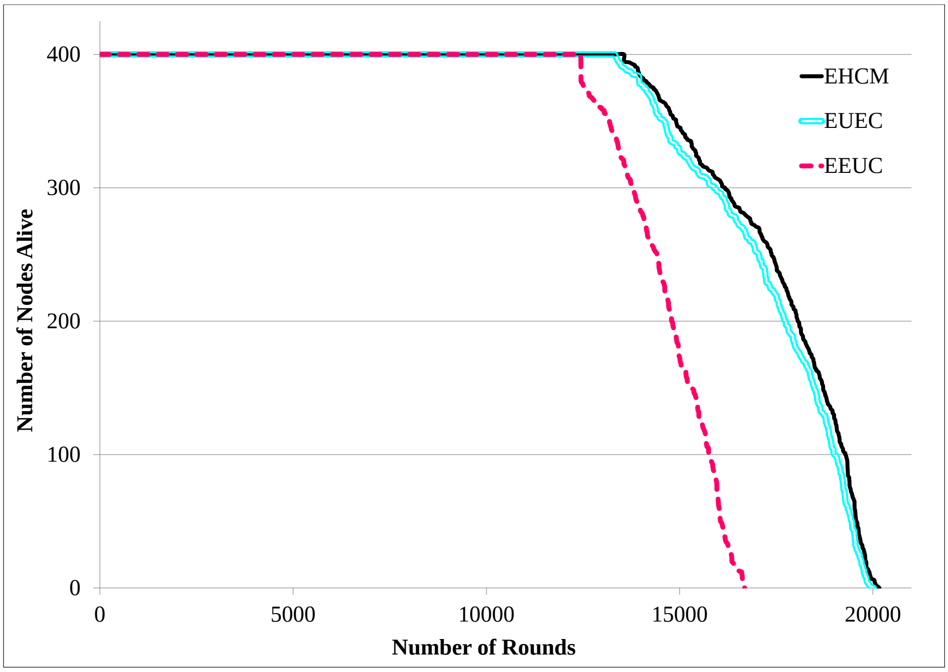
Table 6.10 Percentage change in network lifetime when 5% nodes die

Clustering Algorithm		**EUEC**		**EHCM**	
# of nodes in the network		***200***	***400***	***200***	***400***
% rise in Network Lifetime (when 5%) w.r.t	**EEUC**	9.62	12.11	12.73	13.50
	EUEC			2.83	1.24

Tabular values from the Table 6.10 give the percentage rise in EHCM's network lifetime when compared to EEUC and EUEC. It is observed from the numbers that the proposed algorithm's adaptive nature in cluster head selection is highly successful in distributing network load in even among cluster members by rotating cluster head role uniformly.

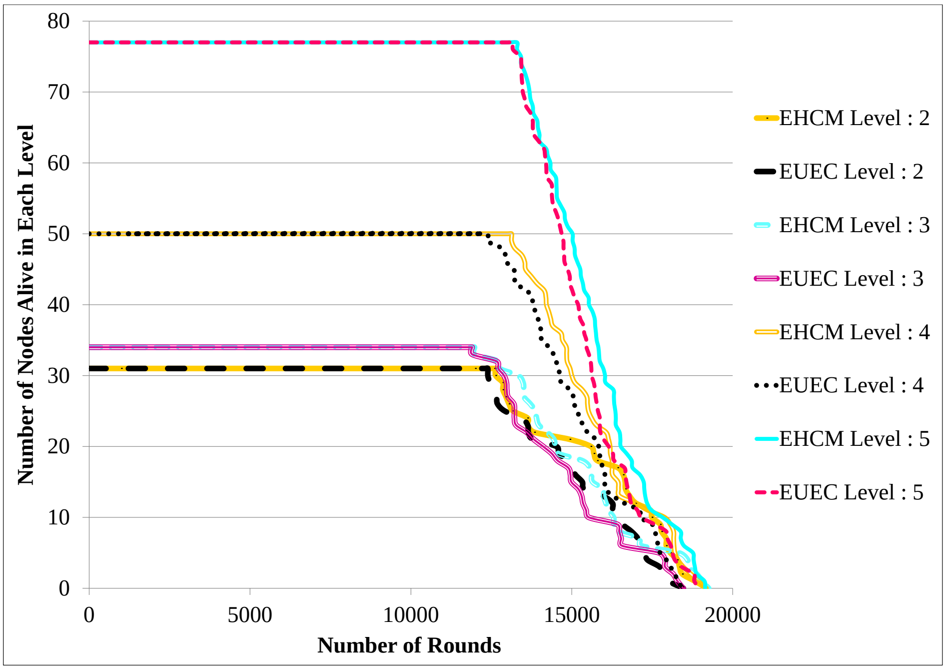


(a) 200 Node Network

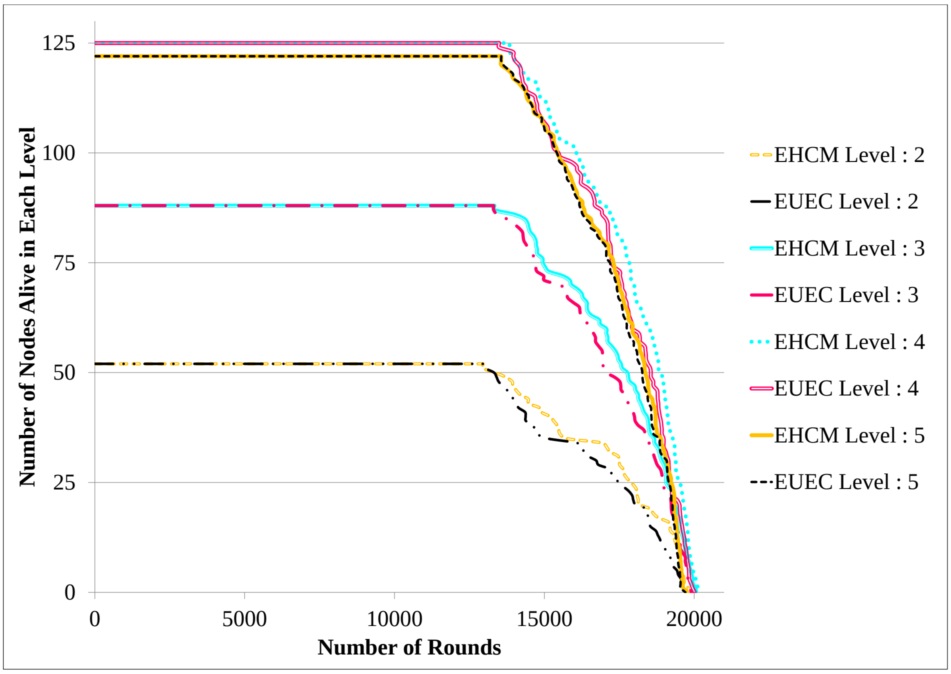


(b) 400 Node Network

Figure 6.11 Life time of sensor nodes in the network



(a) 200 Node Network



(b) 400 Node Network

Figure 6.12 Number of nodes alive in different levels of the network

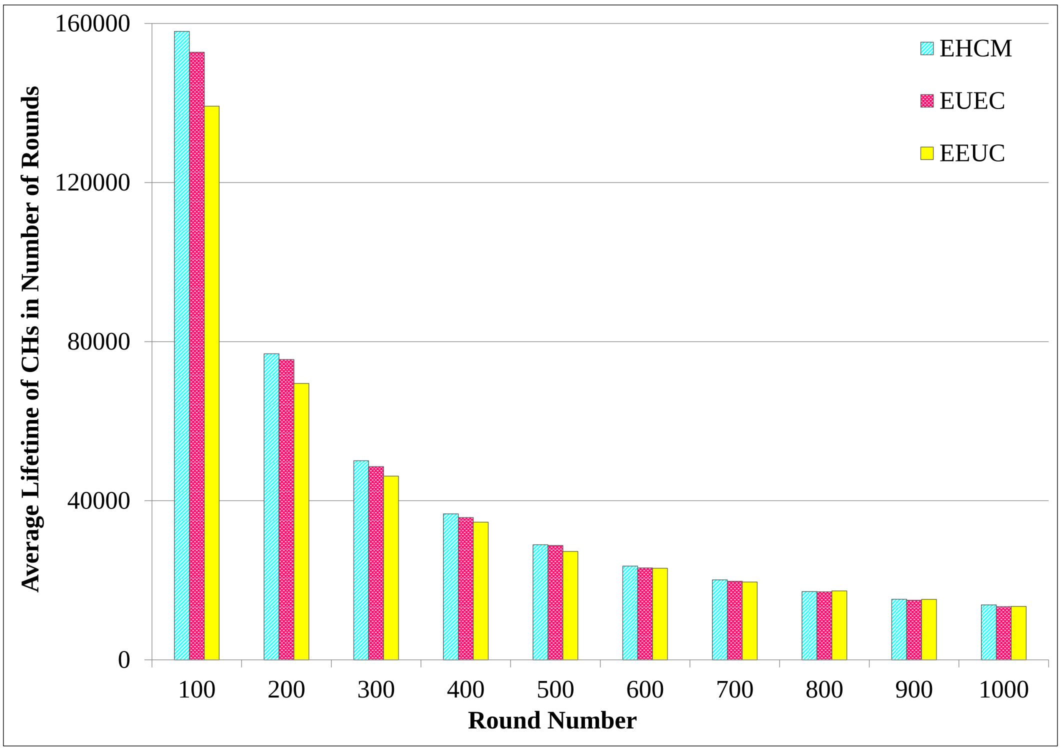
With uniform energy dissipation in both intra-cluster and inter-cluster communication, EHCM raises network lifetime more than EUEC and EEUC networks. Fig. 6.12 illustrates number of sensor nodes alive at various levels of 200 and 400 node network for EHCM and EUEC. From the figure it is observed that the sensor nodes starts falling at same point of time irrespective of their level and all sensor nodes at each levels die at the same time. This highlights the significance of proposed cluster head selection mechanism in enhancing sensor nodes lifetime.

Dynamic and consistent number of clusters at each level promote uniform energy consumption across different levels of the network. Fig. 6.13 represents average lifetime of cluster heads for various data transmission rounds.

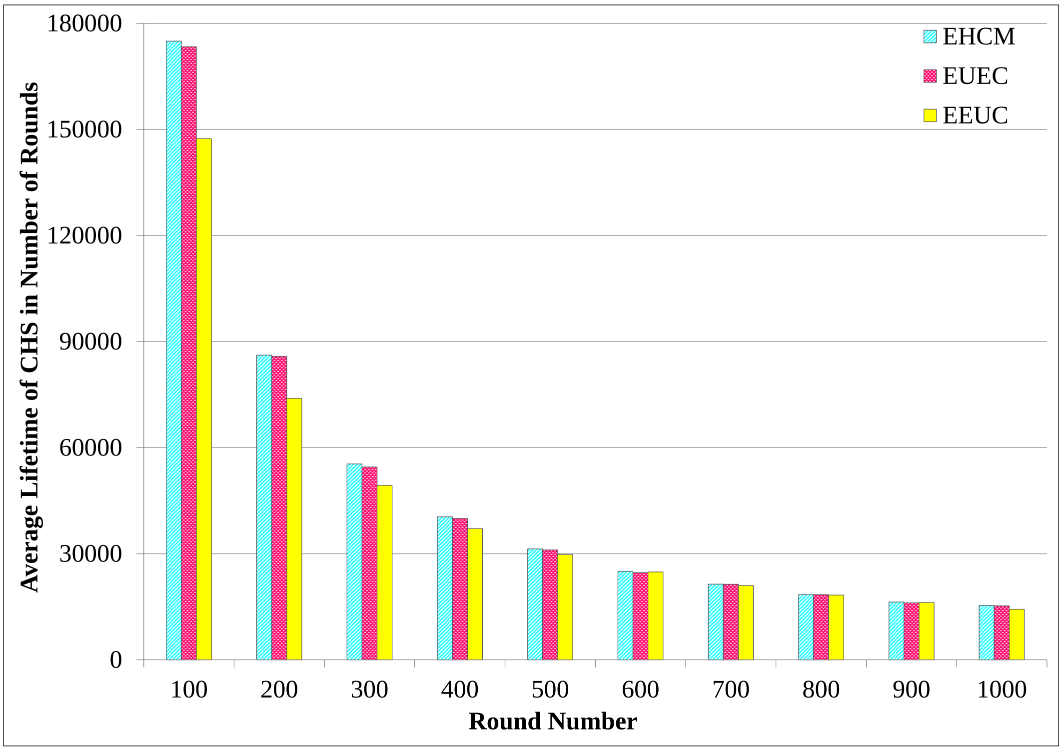
Table 6.11 Percentage rise in cluster heads average lifetime

Clustering Algorithm	**EUEC**		**EHCM**		**Round Number**
# of nodes in the network	***200***	***400***	***200***	***400***	
% Change in Network Lifetime of Cluster Heads w.r.t EEUC	9.76	17.64	13.52	18.72	100
	8.66	16.10	10.74	16.56	200
	5.23	10.53	8.42	12.26	300
	3.34	7.76	6.00	8.99	400
	5.52	4.46	6.16	5.41	500
	0.43	-0.75	2.45	0.68	600
	0.87	1.80	2.68	1.88	700
	-1.27	0.74	-0.88	0.67	800
	-1.53	-0.36	0.15	0.94	900
	-0.43	6.83	2.77	7.77	1000

From the experimental values in Table 6.11 and 6.12, it is inferred that the proposed hybrid clustering mechanism, EHCM, improves cluster heads average lifetime when compared with EUEC and EHCM on both 200 and 400 node networks. However, results in negative are observed for both EUEC and EHCM when compared with EEUC in Table 6.11. Lack of adaptiveness in EUEC cluster selection mechanism caused these negative results. Whereas, EHCM showed much better results compared to EUEC but, it may perform better than this with sophisticated node deployment and coverage schemes. Nevertheless, the importance of dynamic cluster head selection mechanism is highlighted once again with these results.



(a) 200 Node Network



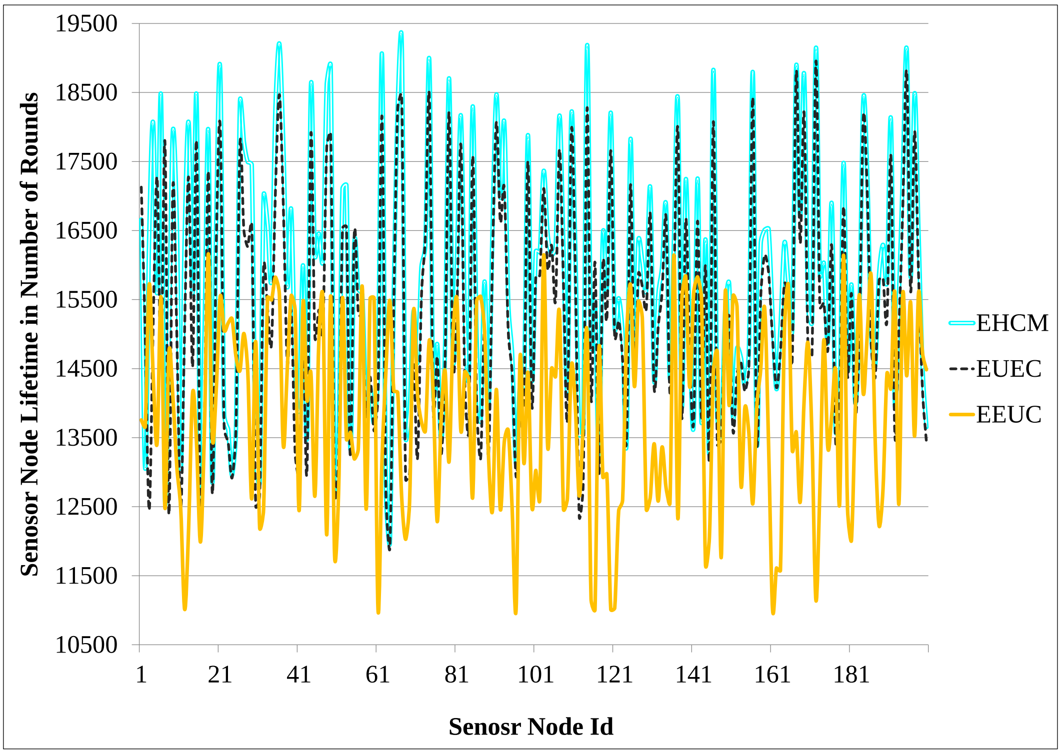
(b) 400 Node Network

Figure 6.13 Average life time of cluster heads in the network

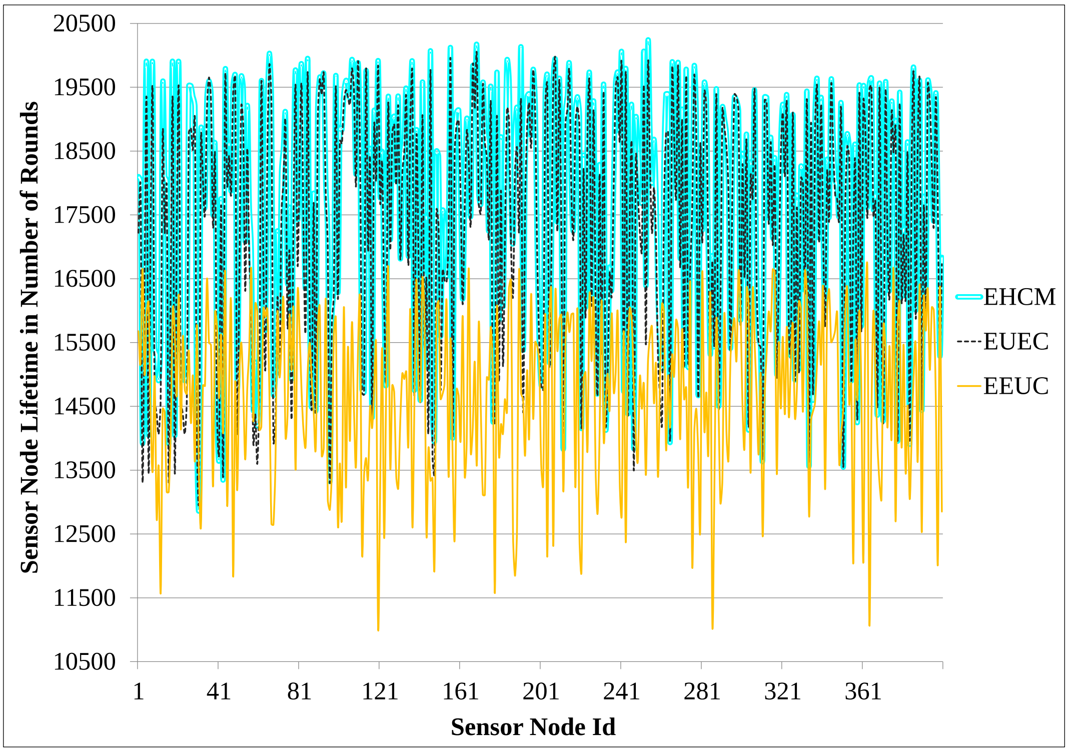
Table 6.12 Percentage change in average cluster heads lifetime

Clustering Algorithm	**EHCM**		**Round**
# of nodes in the network	***200***	***400***	**Number**
% Change in Network Lifetime of Cluster Heads w.r.t EUEC	3.42	0.92	100
	1.91	0.40	200
	3.04	1.56	300
	2.58	1.14	400
	0.60	0.91	500
	2.01	1.43	600
	1.79	0.08	700
	0.39	-0.07	800
	1.71	1.30	900
	3.22	0.88	1000

Fig. 6.14 represents lifetime of every individual sensor node of EHCM, EUEC and EEUC in a 200 and 400 node network. It is observed from the figure that the the proposed hybrid clustering mechanism, EHCM, improves sensor node lifetime by distributing network load uniformly among sensor nodes in the network.



(a) 200 Node Network



(b) 400 Node Network

Figure 6.14 Life time of sensor nodes in the network

6.3 SUMMARY

To overcome hot-spot problem without scalability issues, an *Energy-efficient Hybrid Clustering Mechanism* is proposed in this chapter. It creates limited number of unequal and equal clusters at each level to balance energy dissipation among sensor nodes in the sensing field. This encourages minimum and consistent hop-count between source and destination in multi-hop data flow paths. The proposed mechanism generates small clusters near base station than those far-away. Clusters with smaller size preserve some energy for inter-cluster communication. This avoids hot-spot problem by balancing energy consumption among cluster heads with minimum energy wastage. The number of cluster heads selected are dynamically decided using sensor nodes level number as a primary parameter, which avoids scalability problem. Also, a multi-hop routing protocol is proposed for data transmission between source and destination. The intelligent relay node selection process helps cluster heads to choose a node close to base station with greater residual energy as its data forwarding node. Simulation results prove that the proposed clustering scheme guarantees hot-spot free network by balancing energy dissipation in intra-cluster and inter-cluster communications. This is achieved with uniform and limited number of cluster heads distributed across different levels in the network field. The identical cluster head selection mechanism enables uniform energy dissipation among sensor nodes. In addition, the proposed multi-hop routing scheme distributes network load consistently among all the data forwarding routes in the network and helps sensor network to raise its lifetime.

Chapter 7

CONCLUSION & FUTURE WORK

7.1 CONCLUSION

Rapid developments in wireless communications and hardware technology has enabled the development of small-size, low-cost, low-power and multi-functional sensor nodes with the capability of sensing various types of physical and environmental conditions. These tiny devices consist of sensing, data processing and communicating components, realize the objectives of sensor networks. Its emerging applications introduce several new requirements every day, which incur additional cost and demand more productivity from limited network resources. From the current efforts, it is observed that sensor network research has limited its design space solely to the sensor nodes themselves. Therefore, by exploring the characteristics of alternative resource-rich sources like, base station, new possibilities open-up to meet future requirements by simplifying the existing and upcoming algorithms in sensor network research. A *Base-station assisted novel network design space (BANDS)* is proposed for edge-based wireless sensor network to exploit full functionalities of resource rich constraint-free edge-base-station. It is assumed that the base station is equipped with power-controlled directional antenna. Using this, the network is divided into several equally spaced partitions called, *Zones*. The proposed network design space shifts control overhead from sensor nodes to base station while performing control and managerial functions. Introduced intelligent network scan process distributes sensor nodes uniformly across all the levels and provides location information which includes, level number and sector number to identify the nodes uniquely in the network. By using location information, BANDS generates clusters with no extra cost on network resources. The layered network architecture assists network to transmit data incurring little burden on sensor nodes. Simulation results prove that the proposed work consumes less energy resources compared to other network models by reducing control overhead during cluster formation, cluster head rotation and data transmission.

Using the base-station assisted novel network design space proposed earlier, a *Zone-based routing protocol (ZBRP)* is introduced for edge-based wireless sensor networks. ZBRP produces even size clusters by deploying sensor nodes uniformly using BANDS. With this, ZBRP achieves uniform energy dissipation among sensor nodes. The cluster head rotation mechanism selects sensor nodes which have maximum number of neighbors and low communication cost as cluster heads in regular intervals of time to guarantee distributed cluster heads in the network. The proposed multi-hop data transmission mechanism distributes routing load evenly among cluster heads by spreading network load equally among different data forwarding paths. From the experimental results it is observed that the proposed work improves sensor network lifetime by distributing energy consumption among sensor nodes in the network.

When employing clustering technique in multi-hop data transimmison model, *Hot-spot problem* arises due to uneven energy consumption among cluster heads. Unequal clustering mechanism avoids this problem by balancing energy dissipation among cluster heads. However, it balances energy consumption among cluster heads but not between cluster heads and cluster members, and introduce several other problems like, huge number of clusters with variable sizes, increase in hop-count between source and destination, imblance in energy consumption between cluster heads and cluster members etc. To overcome these issues, a novel *Energy-efficient UnEqual Clustering algorithm (EUEC)* is proposed. It produces limited and uniform number of unequal clusters at each level, where cluster size increases with base station distance. This constructs small size clusters near base station to balance energy consumption among cluster heads and avoids hot-spot problem. Cluster heads are primarily selected based on sensor nodes communication cost. To distribute network routing load uniformly among data forwarding routes, a disjoint multi-hop routing protocol is proposed. Equivalent number of clusters in each level employ disjoint multi-path routing for data transmission. Simulation results prove that the proposed algorithm guarantees a hot-spot free network with balanced energy consumption among all the cluster heads in the network. Also, it is observed from the results that the proposed multi-hop routing scheme distributes network routing burden uniformly among data flow paths and elevates network lifetime.

A novel and extended *Energy-efficient Hybrid Clustering Mechanism (EHCM)* is proposed to easily enable scalable networks without hot-spot problem. EHCM produces both even and uneven size clusters to balance energy consumption among sensor nodes. It guides the network to create dynamic number of clusters depending on sensor node's location information in each level, which generates concentrated clusters near base station to share relay traffic uniformly among cluster heads. This helps network to avoid hot-spot problem. The number of clusters decreases as the level number increases. The distributed cluster head rotation mechanism promotes uniform energy dissipation among the sensor nodes. The multi-hop routing protocol proposed here selects relay cluster heads, which are close to base station with greater residual energy. From the experimental results it is interpreted that the proposed clustering scheme guarantees hot-spot free network by consuming uniform amount of energy among cluster heads across different levels. The proposed multi-hop routing scheme distributes network data routing load uniformly among all the data forwarding routes and enhances sensor network lifetime.

7.2 FUTURE STUDY

Base station is resource abundant with huge computational and communicational capacity. It supports any number of levels ranging in variety of transmission power levels. But, it is required to identify optimal number of levels that a network can have for a given number of nodes. The edge-base-station's capabilities need to be studied exclusively to extend its advantages in building resource-efficient fault tolerant techniques. Using power controlled directional antenna, base station can reach any part of the network. This property needs to be explored in detail in employing effective security measures in wireless sensor network. Effective routing protocol with the potentials of edge-base-station would improve wireless sensor network's performance in-terms of packet delivery ratio, throughput, self-reconfiguration techniques etc. with little burden on network resources.

7.3 LIST OF PUBLICATIONS/ CONFERENCE PAPERS

7.3.1 Journal Publications

[1] Muni Venkateswarlu K., A. Kandasamy and K. Chandrasekaran. *"An Energy Efficient Hybrid Clustering Algorithm for Wireless Sensor Networks."* Journal of Unmanned Systems, 2015, 3(2), 109-125.

[2] Muni Venkateswarlu K., A. Kandasamy and K. Chandrasekaran. *"Energy Efficient Unequal Clustering Algorithm With Disjoint Multi-hop Routing Scheme for Wireless Sensor Networks."* International Journal of Modern Education and Computer Science, 2015, 7(5), 24-36.

[3] Muni Venkateswarlu K., A. Kandasamy and K. Chandrasekaran. *"Analysis of Base Station Assisted Novel Network Design Space for Edge-based WSNs."* International Journal of Computer Network and Information Security, 2015, 7(7), 53-60.

[4] Muni Venkateswarlu K., A. Kandasamy, and K. Chandrasekaran. *"Zone-Based Routing Protocol for Wireless Sensor Networks."* International Scholarly Research Notices, 2014, 1-9.

7.3.2 Conference Proceedings

[1] Muni Venkateswarlu K., A. Kandasamy and K. Chandrasekaran, *"Energy-efficient edge-based network partitioning scheme for wireless sensor networks"*, 'International Conference on Advances in Computing, Communications and Informatics, 2013, 1017-1022.

[2] A. Kandasamy, Muni Venkateswarlu K. and K. Chandrasekaran, *"Node - link disjoint multipath routing protocols for wireless sensor networks a survey and conceptual modeling"*, International Conference on Advanced Computing, Networking and Security, 2012, 7135, 405-414.

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