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Improving Network Lifetime through Energy-Efficient  
Protocols for IoT Applications

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Thesis submitted to the School of Food and Advanced Technology, Massey University New Zealand, in partial fulfilment of the requirements for the degree of Doctor of Philosophy

August 2022



## Abstract

Sensors are ubiquitous. They can be found in homes, factories, farms, and just about everywhere else. To meet distributed sensing requirements several sensors are deployed and connected on a wireless media to form a Wireless Sensor Network (WSN). Sensor nodes exchange information with one another and with a base station (BS). We begin with a review of recent work on cross-layer WSN design techniques based on the Open System Interconnection (OSI) model. The distributed sensor nodes are often grouped in clusters and a cluster head (CH) is chosen and used to route data from the sensor nodes to the BS. The thesis evaluates constraints-based routing algorithms, which choose a routing path that satisfies administrative or Quality of Service (QoS) constraints. Different algorithms reduce costs, balance network load, and improve security. Clustering sensor nodes in a wireless sensor network is an important technique for lowering sensor energy consumption and thus extending the network's lifetime. The cluster head serves as a router in a network. Furthermore, the cluster head is in charge of gathering and transmitting sensed information from cluster members to a destination node or base station/sink. To safely elect a cluster head, an efficient clustering approach is required. It continues to be an important task for overall network performance. As a result, in this study, we propose a scheme for cluster head selection based on a trust factor that ensures all nodes are trustworthy and authentic during communication. Direct trust is calculated using parameters such as residual energy and node distance. Further, K-means clustering algorithm has been employed for cluster head selection. The simulation results show that the proposed solution outperforms the LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol in improving network lifetime, packet delivery ratio, and energy consumption. Furthermore, this strategy can significantly improve performance while discriminating between legitimate and malicious (or compromised) nodes in the network.

The use of the IoT in wireless sensor networks (WSNs) presents substantial issues in ensuring network longevity due to the high energy requirements of sensing, processing, and data transmission. Thus, multiple conventional algorithms with optimization methodologies have been developed to increase WSN network performance. These algorithms focus on network layer routing protocols for dependable, energy-efficient communication, extending network life. This thesis proposes multi-objective optimization strategy. It calculates the optimum path for packets from the source to the sink or base station. The proposed model works in two-steps. First, a trust model selects cluster head to control data connection between the BS and cluster nodes. To determine data transmission routes, a novel hybrid algorithm is proposed that combines a particle swarm optimization (PSO) algorithm and a genetic algorithm (GA) .The obtained results validate

the proposed approach's efficiency, as it outperforms existing methods in terms of increased energy efficiency, increased network throughput, high packet delivery ratio, and high residual energy across all iterations.

Sensor nodes (SNs) have very constrained memory, energy, and computational resources. The limitations are further exacerbated due to the large volume of sensing data generated in a distributed IoT application. Energy can be saved by compressing data at the sensor node or CH level before transmission. The majority of data compression research has been motivated by image and video compression; however, the vast majority of these algorithms are inapplicable on sensor nodes due to memory restrictions, energy consumption, and processing speed. To address this issue, we chose established data compression techniques such as Run Length Encoding (RLE) and Adaptive Huffman Encoding (AHE), which require much less resources and can be executed on sensor nodes. Both RLE and AHE can negotiate compression ratio and energy utilisation effectively. This thesis initially evaluates RLE and AHE data compression efficiency. Hybrid-RLEAHE (H-RLEAHE) is then suggested and tested for sensor nodes. Simulations were run to validate the efficacy of the proposed hybrid algorithm, and the results were compared to compression methods using RLE, AHE, and without the use of any compression technique for five different cases. RLE data compression outperforms H-RLEAHE and AHE in energy efficiency, network performance, packet delivery ratio, and energy across all iterations.

## **Acknowledgement**

Research is a systematic and scientific process. It requires great patience and long waiting. During the course of study, the researcher needs not have been possible without the caring supervisors, other professors, non-academic staff and my colleagues assistance from different stakeholders from time to time. In this section, I take the opportunity to thank each one of them who contributed directly or indirectly to my research. Pursuing Doctor of Philosophy in Engineering was a long-awaited dream for me. I have pleasure to turn it into a reality. It would who motivated and guided me all the time in this research journey.

First of all, I thank my family members for always providing all the possible support. The thought-process of PhD started from the family itself, along with my passion. They allowed me to concentrate on the research and dedicate my time and efforts in this direction to make it successful. Secondly, my thanks go to supervisors, Professor Gourab Sen Gupta and Professor Xiang Gui who played the role of guide, friend and philosopher. They proved to be the source of motivation enabling me to get access to the treasure of knowledge, the best practices in order to make my research more comprehensive and meaningful. Dr Gourab Sen Gupta played a key role in this regard. Dr Xiang Gui could create a conducive work environment and generously offering time, support and goodwill while carrying out this research work.

Finally, my research would not have completed without the moral support and timely assistance of Graduate Research School (GRS) team. The contribution of Janene de Ridder is really appreciable who provided extensive support in my visa documentation and giving me sufficient time and support during the course of this study.

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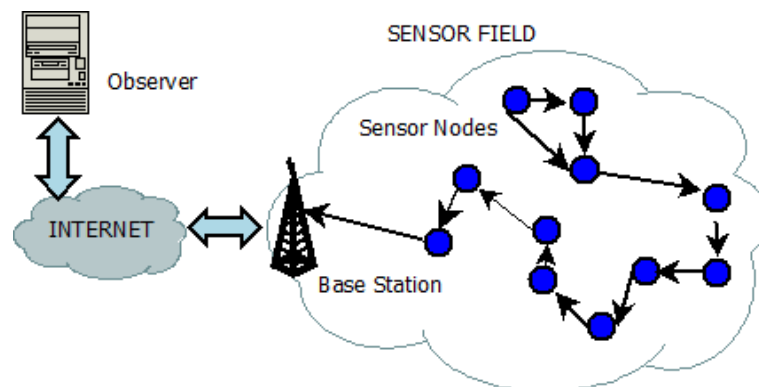
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### 1.1 Outline

Advances in sensor technology in the past few years have transformed the way we live and work. With the rapid technological developments of sensors, Wireless Sensor Networks (WSNs) have become the key technology in information gathering and communication systems. Further, it has gained easier deployment and improved flexibility in addition to enhanced reliability and efficiency of infrastructure systems [1]. WSN is a promising technology that will go through radical developments in the coming years for a wide variety of applications like medical, data logging, water quality monitoring, machine status monitoring, land slide detection, air pollution monitoring, and surveillance to name a few [2]. Along with sensing, WSN finds its applications in control, data collection, and activation as well.

A WSN is a network of a vast number of spatially distributed autonomous sensor devices, called motes or nodes, where each node senses, processes and communicates the sensed phenomenon to the Base Station through wireless links [3]. These expendable nodes can be connected wirelessly in large number for all those applications which demand unattended operations and where human intervention is practically impossible. The nodes interconnected in a network communicate the sensed information to the neighbouring nodes and to the BS. Figure. 1.1 depicts the architecture of a WSN [4].



**Figure 1.1:** Architecture of WSN [4]

The field of WSN constitutes four fundamental components:

1. An assembly of sensor nodes
2. BS for gathering information
3. Wireless network for communication among the nodes and the BS
4. Additional computing resources at BS for handling queries, status mining, events stimuli, and data mining

The computational infrastructure associated with WSN is application specific and depends on various environmental factors. For instance, in network processing like data aggregation, compression techniques are required in sensor networks; likewise, battery life of the nodes is a key consideration while designing these networks. The main characteristics of WSN [5], which differentiate it from the wired network, are:

1. Low cost deployment
2. Energy efficient
3. Limited computation power of nodes
4. Multi-hop communication
5. Robust operations
6. Application specific
7. Self-organization
8. Dynamic network topology
9. Distributed sensing and processing

This revolutionary technology holds promise for a wide number of operations in our homes, work places, and beyond. Most commonly, WSN is deployed in the perspective of security related systems such as military, surveillance, and warning systems [6]. Existing and potential applications include, among others, automatic monitoring of forest fires, natural calamities, traffic, failure of utility equipment, animal tracking, and structures monitoring. WSNs are installed where wireline equipment cannot be deployed, for example a hazardous site or a location that might be contaminated with toxins. The easy deployment, self-healing and self-organizing capability of WSNs make them adaptable for army services, communications, investigation, observation, and target systems [7]. Upcoming business applications include, but are not constrained to, energy, food safety, quality of life and many more. The glorious

prospect is that at last WSNs will encourage clients to monitor their belongings, pets and their kids. Ubiquitous high-dependability and open security are additionally not too far off.

## **1.2 Evolution of WSN Technology**

Technology has permeated almost every aspect of our lives, and indeed connected devices, increasingly meaningful analytics and immersive software have made a huge impact on our lives. As far as sensor technology goes, these advances have affected the quality of life for millions and have had far-reaching implications for the sensor technology at large. We detail the overview of the milestones that this technology has gone through. The origin of WSN, like many other communication systems, can be attributed to different epochs [8]. Concisely, the history of WSN can be segregated into four epochs: The first epoch is demarcated by the cold war era when acoustic sensors were used. Those sensors include Sound Surveillance System (SOSUS) and are still used for surveillance. Second era started in 1980s with DARPA (Defense Advanced Research Project Agency) sponsoring projects on distributed WSN. Other defence and military organizations joined hands to embrace this technology for combat and surveillance purposes. Hence, a nascent technology leaped to new horizons in the early 1990s, which can be classified as the third epoch. Many organizations, other than defence, also started showing interest and spending huge sums of money to make this technology grow faster. The final epoch i.e. the contemporary era witnessed the remarkable growth of the sensor network technology. New Standards like IEEE 802.15.4, ZigBee, and Wireless HART are ratified [9]. Table 1.1 summarizes the generations of WSN that this field has gone through.

With the proliferation of Internet of Things (IoT), WSN has entered into an era, where WSN has found its place in the new generation of commercial products. The cutting-edge sensor nodes are more powerful and are embedded with more computational complexity [10] than the traditional sensor nodes. Evolving technologies like Micro Electro Mechanical Systems (MEMS) and Nanoscale Electro Mechanical Systems (NEMS) are making these sensor devices even more cost effective. Further, advances in the standardization of these technologies are helping WSN to reach to a next level of commercialization. Progress in wireless technologies like IEEE 802.11 , Zigbee, and WiMax are also further adding to the reliability of the ubiquitous connectivity and communication [11]. In addition, advanced processors, having lower requirements of power consumption are also making WSN promising for a wide variety of off-the-shelf products.

**Table 1.1:** WSN Generations

	(1960-1980)	(1980-1990)	(1990-2000)	(2000-Beyond)
	First Epoch	Second Epoch	Third Epoch	Fourth Epoch
<b>Size</b>	Large Shoe Box and above	Pack of cards	Minute Particle	Dust Particle
<b>Weight</b>	Kilograms	Grams or less	Nano grams	Trivial
<b>Deployment</b>	Physically deployed or Air dropped	Hand Placed	Embedded	Fully Embedded
<b>Topology</b>	Point to Point, Star	Client-Server	Peer to Peer, Cluster Tree	Hierarchical
<b>Lifetime</b>	Hours	Hours to Days	Days to Months	Years and More
<b>Architecture</b>	Separate Units for Sensing, Computation and Communication	One Unit for Sensing, Computation and Communication	Integrated Unit	Complete Integrated Structure

During the past few decades, WSN has observed its widespread deployment and real life implementation in various domains. Some of the significant areas that have witnessed widespread deployment are agriculture, healthcare, home automation, and Industry 4.0. In home automation or smart home, WSN enables monitoring and controlling the various parameters like temperature, brightness, and voltage etc. Employment of WSN towards home automation enables significant conservation of electrical energy while maintaining the comfort of occupants. Similarly, the network of various sensory devices can be widely used in agriculture to monitor the soil moisture, humidity, and temperature. Efficient monitoring of these vital parameters aids in yielding maximum crop while minimizing the required resources like water and fertilizers. Continuous monitoring of crops also helps to prevent the crop from insects and hence proves to be a big relief to the farmers. Further, sensory devices also predict the weather conditions so that farmers become better prepared for handling diverse weather conditions [12]. Also WSN has demonstrated significant transformation owing to the revolutionary development in WSN. Advancements in the WSN enables the patients in rural and remote locations to avail best of medical opinion by the experts in the concerned field. It has also led to the significant improvement in patient care and regular monitoring surpassing the limitations of human involvement. Also, it has been deployed for activity monitoring, and

behavioral studies. Apart from these, WSN is also evolving in the direction of its application in industries namely manufacturing, remote monitoring, automated metering, and management of inventory and personnel etc.

### **1.3 Motivation**

Sensor nodes, due to physical constraints, have limited on-board processing and wireless communication capabilities and are equipped with batteries with limited power. Additionally, it is impractical or infeasible to recharge energy by means of replacing batteries on these sensors in many applications. Due to the energy limitation, nodes have a very short transmission range and need multiple hops to communicate with other nodes in the network. These networks have a wide range of applications in different areas (such as, healthcare, defence, environmental monitoring and other fields). WSN has been one of the most interesting research areas with a profound effect on technological developments. The lifetime of a sensor node and thus transmission and receiving, which directly determines the duration of the sensing task, is limited by the amount of energy that each node has. The extremely energy constrained nature of WSN implies that their design and operation be done in an energy aware manner, enabling the system to make trade-offs between performance and energy consumption [13]. In this thesis, several energy efficient routing protocols are proposed, studied, and analysed. First of all, general aspects of WSN are studied, including the current state-of-the-art technology, WSN components, the most important features and applications, etc. According to the main objective of this thesis, a trust based cluster head selection using the K-means algorithm has been proposed. As a result, we propose a cluster head selection method based on a trust factor that ensures all nodes are trustworthy and authentic during communication. To achieve this, direct trust is calculated using parameters such as the residual energy and the distance between the nodes, along with the use of the K-means clustering algorithm. In addition, extensive simulations have been carried out to show the performance of the proposed solution in terms of network lifetime, packet delivery ratio, and energy consumption. Additionally, in this thesis, reliable routing algorithm which involves combination of PSO (Particle Swarm Optimisation) and GA (Genetic Algorithm) for data to the base station. Data aggregation using zig-zag strategy reduces congestion and the data are collected effectively by the sink. This routing protocol reduces routing overhead and packet loss.

In terms of energy consumption, operation of WSN is divided into sensing, processing, and communication of data. Among these operations, receiving and data transmission consumes more energy than data processing. Hence, data aggregation and data compression are two prominent techniques to reduce the amount of data. Data aggregation has been shown to be effective in reducing energy consumption in WSNs by reducing the amount of data that has to be transmitted from one node to another. In later case, is another method of reducing the energy required for data transmission. However, the data compression algorithms used in general-purpose computers are not suitable for the limited hardware in wireless sensor nodes, and low-overhead compression algorithms [14]. However, data compression and aggregation is known for reducing communication cost. In this thesis, Run Length Encoding and Adaptive Huffman Encoding data compression algorithm is integrated and named it as H-RLEAHE and viceversa. Providing security to compressed data will ensure secure data transmission and reception. On the contrary it should be noted that data compression and security have opposite goals. While the aim of the former is to reduce the number of packets to be transmitted, the latter adds a non-negligible cost in order to ensure some security properties [15].

#### **1.4 Problem Statement**

The research initially identifies the various performance metrics of WSNs in order to establish the basis for comparative analysis of the state-of-the art models with the proposed model. Various performance metrics which have been identified are throughput, energy consumption, network lifetime, response time, packet delay, cost, ease of deployment, coverage, and security.

Thereafter, a comprehensive review of the related work is performed so as to unveil the research gaps. The prime research gaps identified are energy consumption, handling of dynamic allocation of nodes to clusters, robustness of loss less data compression [16] and other data compression algorithms, practicality of various data compression techniques, and urgency of developing more robust techniques suitable for dense and sparse networks as both exhibit varying performance. In order to address the research gap, the researcher aims to propose methods for efficient selection of CH, efficient routing, and evaluate data compression techniques. All these methods collectively work towards enhancing the network lifetime.

### 1.4.1 Research Question

According to the survey, sensor nodes functioning as cluster heads are likely to spend more energy than other cluster members due to their long-distance transmissions to the base station, which may result in an uneven energy consumption of sensor nodes in the network. In order to address this issue, in literature hierarchical, flat based and cluster based was proposed rotating the cluster head function among sensor nodes, resulting in a significant advance in cluster-based data collecting in wireless sensor networks. Despite the fact that the energy consumption is dispersed among all sensor nodes, various shortcomings of various protocols have been documented in the literature, including:

- i. Cluster sizes are not guaranteed to be uniform.
- ii. A balanced distribution of cluster heads is not guaranteed.
- iii. The formation of clusters consumes up the available energy of all of the sensor nodes throughout each round.

Furthermore, developing route selection algorithms for such WSNs is critical in order to link all sensors at a low cost and with good reliability. We believe that a network with high reliability will be able to service for a longer amount of time. As a result, reliability should take priority above cost, since no one wants a network that fails most of the time. A comprehensive goal for route selection is to discover the most reliable route plan.

Consequently, researchers are studying data compression, which reduces network data transmission and saves energy. WSNs cannot directly employ most compression techniques. Second, for transferring one byte uses as much energy. Moreover, these calculations only consider local energy consumption at the compressing node; network-wide energy savings due to compression can further compensate for the energy expense of compression. So compression algorithms with some degree of computational complexity are worth exploring. In addition to this, computationally complex algorithms are not worth pursuing. Finally, compression algorithms designed for desktop must be restructured to reduce the code size and dynamic memory usage due to the limited memory capacity of WSN nodes- have less than 50kB of code memory and even less data memory. Researchers overcome these challenges by adjusting compression algorithms and introducing new ones. Traditional compression saves storage, not energy. Thus, energy saving is primary metric in WSNs.

## 1.5 Scope and Main Objectives

Finally, we analyse the research direction on selecting cluster head, routing and data compression. After selection of cluster head, we are the first to systematically investigate the route selection problem for WSNs with connection failure uncertainties. We are the first to systematically investigate the route selection problem. Motivated by route selection methods for wired networks, we propose route selection and (2) Zigzag routing. Finally, with study of data compression objectives. As discussed, the prime objective of the research is to enhance the different performance metrics identified for WSNs. The same can be achieved by efficient selection of Cluster Head (CH) as it significantly contributes towards longevity of the network. Additionally, the selected CH must be reliable so as to ensure secure communication. Consequently, the prime objective of the research is to propose a K-means clustering based CH selection approach. The proposed approach also considers a novel factor viz. trust for CH election. Another objective of the research is to propose a method that minimizes energy consumption as it also leads to network longevity. Hence, CH must also be selected so as to reduce the number of hops which further reduces the energy usage and hence provide an energy-efficient solution. Hence, an objective of the research is to select CH based on the energy and trust value of each node in the WSN.

In order to further enhance the network lifetime, we propose a multi-objective 2-step optimization approach. As per this approach, it selects the optimal route from source to sink or Base Station. During the first step, it employs a trust model to select CHs. Further, during step 2, it suggests a hybrid algorithm that combines Particle Swarm Optimization (PSO) algorithm and Genetic Algorithm (GA) to determine the routes for data transmission.

Apart from the selection of CH and hybrid routing algorithms, the author also aims to analyse a compression algorithm so as to compress the amount of data transferred in the network as it directly impacts the network lifetime. For the same, the researcher has investigated compression techniques that comprises RLE, AHE, H-RLEAHE (Hybrid-RLEAHE) and H-AHERLE (Hybrid-AHERLE).

## 1.6 Significant Contributions

- **Contribution 1 – Identification of challenges and energy efficient protocols for WSN**  
We have checked on the best-in-class energy efficient conventions and difficulties primarily in WSN. We have categorized the realistic WSN model and demonstrate a decrease in WSN utility utilization in terms of lifetime for remote sensing systems. An exhaustive literature survey has been done and difficulties have been identified that affect

the practical WSN models and energy efficient protocols. We have given the brief examinations of them and talked about the additional difficulties and necessities for WSN.

- **Contribution 2 – Trust-Based Cluster Head Selection Using the K-Means Algorithm for Wireless Sensor Networks**

Clustering sensor nodes in a wireless sensor network is a key technique to reduce the energy consumption of sensor nodes which extends the network lifetime. The head of the cluster plays a key role in a network and serves as a router. In addition, the head of the cluster is responsible for collecting and transmitting sensed information from their cluster members to a destination node or base station/sink. Hence, an efficient clustering approach is required to safely elect a cluster head. It remains a critical task for overall network performance [17]. As a result, we propose a cluster head selection method based on a trust factor that ensures all nodes are trustworthy and authentic during communication. To achieve this, direct trust is calculated using parameters such as the residual energy and the distance between the nodes, along with the use of the K-means clustering algorithm. The main contribution of this strategy is that it can significantly improve performance while discriminating against the networks legitimate and malicious (or compromised) nodes.

- **Contribution 3 – Network lifetime improvement through Energy Efficient Reliable Routing Protocol for IoT Applications**

The application of Internet of Things in Wireless Sensor Network poses serious challenges in preserving the network longevity, since the IoTs require a higher amount of energy for data transmission or reception. Most of the conventional algorithms on WSNs enhance the network performance by using some optimisation algorithms at its network layers through the development of routing protocols in energy efficient manner and reliable communication. These models increase the network lifetime by enhancing the energy efficiency while carrying out the data transmission. Hence, it is necessary to increase the network lifetime by optimal formation of clusters and routes, thereby residual energy of the sensor nodes is highly maintained to increase the network longevity. In this thesis, a multi-objective optimisation is conducted to select the optimal route for transmitting the packets from source to sink nodes. As mentioned, initially, the selection of Cluster Heads is done in the grid-based network arrangement using a trust model. Secondly, after the selection of CHs, the study combines Particle Swarm Optimisation algorithm and Genetic Algorithm (GA) to select the reliable routes for data transmission between cluster heads

and sink nodes in an iterated way [18]. Here, we propose an Energy Efficient Reliable Routing Protocol (EERRP) namely PSOGA which is the combination of PSO and GA. Simulation is conducted to test the efficacy of PSOGA method on energy efficient data transmission and compared with the existing LEACH [19] method with random route selection without PSOGA under five different cases. The results of simulation show an increased energy efficiency, increased network throughput, high packet delivery ratio and high residual energy throughout the entire iterations.

- **Contribution 4 – Investigation of energy cost of data compression algorithms in WSN for IoT Applications**

The growth in the remote advancements and integrated circuits prompted the progress of Wireless Sensor Networks. WSN comprises different sensor nodes having extremely restricted resources like memory, energy and handling abilities. Hence, the research investigates a method for data compression. Proposing a method for data compression is advocated by the fact that network lifetime can be enhanced by reducing the amount of sensing data to be sent by sensor nodes, because transmission is one of the most energy-consuming operations of sensor nodes. Such a solution is extremely useful when sensor nodes have to regularly report their sensing data to the sink(s) for a very long time. In order to reduce the amount of sensing data, it is necessary to compress the data inside the network. Hence, the author in this thesis examines and investigates well known data compression algorithms comprising of RLE and AHE and its hybrid named as H-RLEAHE and vice-versa H-AHERLE. In order to validate the efficacy of the algorithms, simulations were conducted and results reveal that the RLE model outperforms the H-RLEAHE and AHE compression algorithms.

## **1.7 Impact on the Society**

Due to the energy crisis WSN researchers have become more worried about their energy efficiency than enhancing throughput. Therefore, focus of this research has moved to maximizing lifetime and energy efficiency, while keeping up a desired level of other performance metrics of WSN. A modified and improved strategy called “Hybrid Routing Algorithm is proposed that divides the whole network into smaller regions based on sensor location and chooses the the routing scheme accordingly”. It tries to address the problem of energy proficiency and lifetime in event detection applications. Thus, the society will be benefited from the findings reported in this research work.

## 1.8 Organization of the Thesis

We begin by describing the state-of-the-art in energy efficient protocols, characteristic requirements, various applications, challenges, design issues and classification of routing protocols in general for WSNs in Chapter 1, which corresponds to **Contribution 1**. The rest of the chapters are organized as under:

- **Chapter 2:** In this part of the thesis, we explain the performance metrics that help in evaluating the performance of WSN. It also defines our performance evaluation criteria and presents the methodology used.
- **Chapter 3:** This chapter of the thesis focuses on the survey of related literature. The chapter also discusses the overview and applications of WSN technology. During the study of related literature, the emphasis is laid on bio-inspired optimization algorithms. Further, the data compression algorithms in WSN are extensively elaborated in order to unveil the research gaps in WSN.
- **Chapter 4:** We have presented the realistic approach towards quantitative analysis and simulation of trust-based Cluster Head selection using the K-means algorithm for WSNs which corresponds to **Contribution 2**. Moreover, we discuss the energy analysis and trust analysis model on the network performance with extensive simulations.
- **Chapter 5:** In this chapter, we explain our insights into designing and proposing an efficient routing for WSN. This corresponds to **Contribution 3**. We compare the performance of the proposed routing algorithm with existing methods and establish its efficacy.
- **Chapter 6:** In this chapter, we detail our insights into investigating, analysing and comparing efficient data compression algorithms for WSN. We compare the performance of various data compression algorithm for WSNs. This corresponds to **Contribution 4**. Results were compared to data compression methods using RLE, AHE, H-RLEAHE and without compression for five different cases.
- **Chapter 7:** We summarize our contributions and conclusions. Further, we highlight the possible future research directions for the problems and solutions discussed in the thesis.

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# Performance Modeling of Wireless Sensor Networks

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### 2.1 Overview

In WSNs, bespoke communication models are required to capture different characteristics of these networks as WSNs are inherently different from traditional communication networks. In this chapter, we discuss the performance modeling of WSN as it will enable the reader to have a comprehensive understanding of the various performance metrics. The discussion of performance metrics is presented in this thesis in a self-contained manner. Existence of multiple performance metrics enables the users to compare different algorithm in accordance with the requirements. For instance, some applications necessitate the highest network lifetime while others may favour packet delivery ratio. Different performance evaluation parameters are discussed in detail in Section 2.2. Basic models involving traffic model, energy consumption model, and network model are investigated in Section 2.3. In Section 2.4, the performance metrics used for evaluation in our thesis are listed. Section 2.5 briefs the toolbox used for simulation.

### 2.2 Performance Evaluation Parameters

The various metrics that can be used to evaluate the performance of a WSN are:

1. **Network Lifetime:** Network Lifetime in WSNs can be measured in several ways [20]:
  - a. The time duration until some predefined number of the nodes depletes all their energy
  - b. The period until the Quality of Service of the applications cannot be assured
  - c. The time duration in which the connectivity of network can be maintained
2. **Packets reaching the Base Station:** In WSNs, this can be defined as the total number of data packets that can be exchanged successfully in the network per unit time. The parameter is affected by several factors like the packet retransmission, communication link failures, packet loss, and routing overhead, which reduce the energy efficiency of the WSNs [21].
3. **Total Residual Energy of network:** The total residual energy of the network is evaluated as the sum of energy left at each individual node in the network after the simulations are over. The energy consumption of a network is the sum total of the energy consumed by

all the existing nodes in the network, where the energy of a node can be consumed in the "effective" or "ineffective" sources [22]. Effective energy consumption can be on the tasks in WSN involving the transmission or reception of data, answering query requests, and forwarding data to the neighbouring nodes or the BS. On the other hand, ineffective energy consumption can be due to idle listening to the media, retransmitting due to packet collisions, overhearing, and generating or handling control packets.

4. **Packet Delivery Ratio (PDR):** PDR can be measured as the ratio of the data packets successfully delivered to the BS to the total number of packets originated by the sensing nodes. PDR of event-driven applications is used as a measure to show how reliable is the WSN to report the sensed event to the BS [23].
5. **Total alive nodes per simulation round:** This is evaluated as the number of alive nodes left after each round of simulation. A few of the sensor nodes become debilitated due to the exhaustion of energy resources, hence become dead. This is an important parameter to evaluate the network lifetime of WSN [24].
6. **Sensing Coverage:** Sensing coverage is the entire sensor area that can be monitored by all the alive sensor nodes deployed in the WSN [25]. If the sensor nodes become debilitated due to the exhaustion of energy resources, then that sensing area cannot be monitored. The coverage is calculated as the ratio of the monitored space by all the alive nodes in the network to the total sensing area.
7. **Throughput:** Throughput of the network is evaluated as the number of data packets communicated successfully in a simulation round. Hence, this metric can be used to evaluate how well the network is connected and how many nodes are sending the data to the BS at a particular point of time.
8. **QoS Metrics:** The deployment of WSN in real life applications demand several characteristics specific to the application requirements. These include delay, error rate, jitter, packet loss ratio, cost, and ease of deployment [26].
9. **Packet Delay:** The delay specifies how long it will take for a packet of data to travel across the network from one node to another; delay is measured in seconds or fractions of seconds. Delay may differ slightly, depending on the location of the specific pair of sensor nodes that communicate [27].
10. **Stability Period:** Stability period of the network is defined as the period from the starting of the operation of the network till the first time a node dies in the network [28].

## 2.3 Basic Models

**A. Traffic Model:** The traffic characteristics in WSNs are quite different from the traditional wired or ad-hoc networks. Hence, the data delivery models and traffic models applicable for WSN are also as per the traffic characteristics pertaining to WSN. Traffic models define the design of a protocol and influence its performance [29]. The traffic models applicable in WSN are as follows:

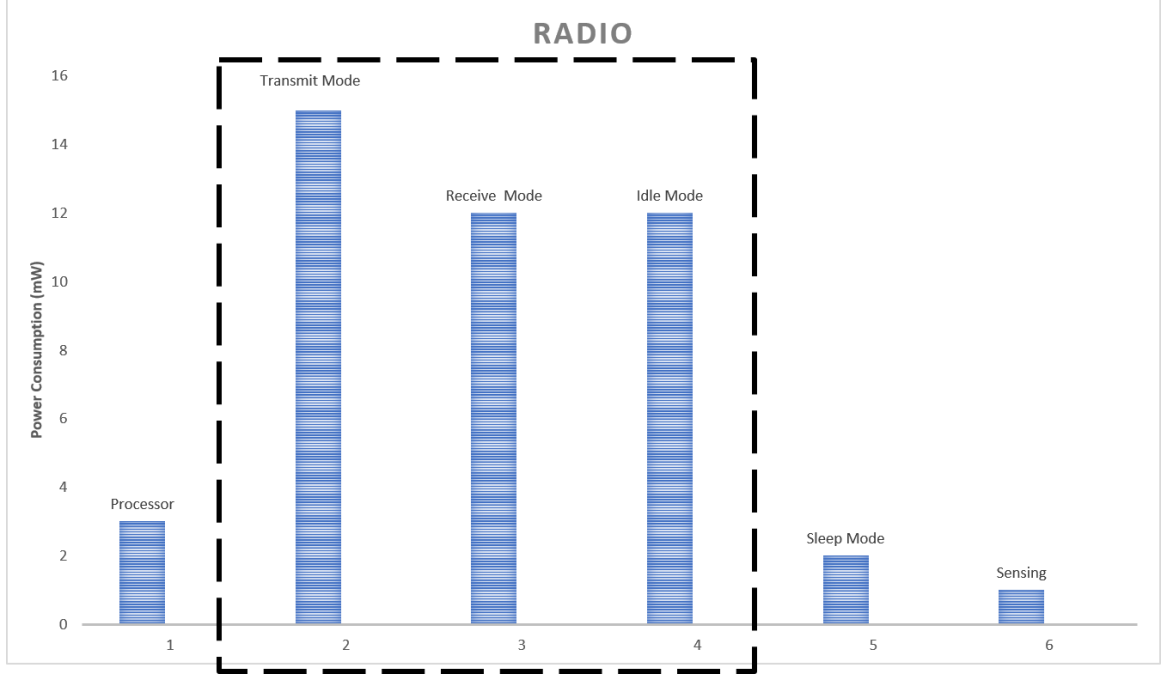
*Event Driven:* Here, the sensor nodes continuously monitor the sensing area for the occurrence of probable and improbable events. As soon as the event happens, the sensing node generates the data packet related to the event and it keeps on reporting the event till the time the event is over.

*Incessant Delivery:* In these types of applications, sensor nodes continuously monitor the sensing area and report the sensed data to the BS continually or periodically.

*Query Driven:* In some cases, the user or the BS is interested in a specific piece of information regarding the sensing field and hence query the sensor nodes for that information. The sensing nodes report back with the up-to-date information as the answer to the query.

*Hybrid Delivery:* This traffic model considers varied types of traffic models in a sensing area. A few of the sensing nodes may be sending the sensed data continuously, a few may be answering the queries, and a few nodes are for reporting specific events [30].

**B. Energy Consumption Model:** Energy model of WSNs describes various functions of sensor nodes consuming energy of the sensor nodes. Communication is the most energy consuming operation of sensor nodes. The actual sensing function consumes the least energy. Hence, two approaches can actually reduce the energy consumption. One approach is to reduce the communication by reducing the volume of data by using in-network processing like data aggregation and compression. Another approach could be to use the communication scheme that conserves energy essentially, like putting the transceiver in sleep mode when it is not being used [31]. Figure. 2.1. shows power consumption in WSN.



**Figure 2.1:** Power consumption of WSN Subsystems [31]

*Model for Sensing:* The study uses a first order radio model as the energy consumption model for the purpose of transmission/reception of messages of the same length, say, n-bits. This model computes energy consumption  $E_i$  for transmission of IoT nodes during one round. The energy consumed to transmit n-bits data to a node located at a distance d (using Euclidean distance metric) is estimated in equation (2.1) as follows:

$$E_{tx}(d) = \left( \frac{n}{r}(\Phi_{amp}d^\alpha + \Phi_{cir}) \right) \quad \text{where } \alpha = \begin{cases} 2, & d < d_{cr} \\ 4, & d > d_{cr} \end{cases} \quad (2.1)$$

where,  $\Phi_{cir}$  represents the power consumption during the operation of the transmitter circuit, and  $\Phi_{amp}$  is the power consumed by amplifier.  $\alpha$  is the exponent indicating the path loss component with the range [2, 4] and  $d_{cr}$  is the cross over distance based on free path loss and multipath loss. Here,  $\alpha$  is 4 and 2 for multi-path loss and free path loss respectively. The consumption of energy at the receiving node depends entirely on the operation of the circuit, which is represented equation (2.2) as follows:

$$E_{rx}(d) = (n/r)\Phi_{cir} \quad (2.2)$$

Thus, for an intermediate sensor node  $i$  at a single hop distance, the energy consumption  $E_i$  for transmission and reception for relay over the distance  $d$  is given as given in equation (2.3):

$$E_i(d) = E_{tx}(d) + E_{rx}(d) = (n/r)(\Phi_{amp}d^\alpha + 2\Phi_{cir}) \quad (2.3)$$

*Model for Computation:* Computation by a sensor node is dependent on the power consumed by the microcontroller in the sensor node. Different microcontrollers consume different power in performing the processing or computation depending on the industry specification. A detailed list of the available microcontrollers for sensor nodes and their power consumption is provided in [32].

**C. Network Model:** The research work considers a two-dimensional network model with sensor nodes, considering the assumptions given below:

- All sensor nodes are considered stationary.
- Study assumes one BS where the data collected from source IoT nodes are destined for. (The study also consider BS location at side and corner edges too)
- Homogeneous SNs with similar processing and communication capability. Also, it considers that SNs are deployed with the same initial energy.
- SNs deployed randomly are always located with its x and y coordinates in the topological area.
- The distance between the two neighbouring SNs is evaluated using Euclidean distance.

## 2.4 Our Performance Evaluation Criteria

Keeping in view a comprehensive set of performance measures and metrics relating to WSNs, the below mentioned performance metrics have been reported in this thesis to assess the performance of the protocol:

1. Packets reaching the Base Station
2. Total alive nodes per simulation round
3. Total Residual Energy of network
4. Packet Delivery Ratio (PDR)
5. Throughput

The above parameters are widely used to assess network performance that influence the network architecture. As a result, the majority of research is focused on increasing the efficiency of these restrictions. Hence, parameters such as throughput, packets sent to BS, PDR, total energy left in the network and number of nodes alive per round are responsible to represent Quality of Service [33].

## **2.5 Simulation Tools**

The simulation environment used to build our WSN sensor bed for simulation is MATLAB. It is a software package that incorporates easily operated environment for computation, visualization and solving problems expressed in mathematical notation. MATLAB provides a customizable set of libraries that facilitates the designing, implementation, and testing of dynamic systems. Several features in MATLAB like flexibility, consistency, accuracy etc., makes it a premier software package for researchers. It provides several built-in functions along with an interactive environment, making it the best possible solution for a broad range of mathematical functions. Besides, these functions offer answers to innumerable mathematical problems for scientific computations. The framework we have used in our research work MATLAB which offers a graphical user interface (GUI) for deploying sensor field. The interface allows to make connections between the sensor nodes and the BS. Along with, MATLAB provides the extensive set of library functions for simulating BS, sensor nodes, linear and nonlinear components, and connecting links. It also offers ways to modify and generate the blocks models representing elementary models which include integrator, gain and subblocks. For post-processing and visualization of the results, the simulation results can further be added in the MATLAB workspace.[34].

## **2.5 Conclusion**

This chapter identifies the several WSN performance evaluation parameters, such as throughput, energy consumption, network lifetime, response time, packet delay, cost, ease of deployment, coverage, security, etc. It presents the tool that has been used in this thesis to carry out the research i.e. MATLAB simulation software. It rolls out our performance criteria such as number of alive nodes per round, total energy consumed per round, number of clusters formed in each round, number of data packets sent to the BS, etc.

### Literature Review and Research Proposal

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M. Mishra, G. S. Gupta and X. Gui, "A Review of and a Proposal for Cross-Layer Design for Efficient Routing and Secure Data Aggregation over WSN," *2017 3rd International Conference on Computational Intelligence and Networks (CINE)*, 2017, pp. 120-125, doi: 10.1109/CINE.2017.30.

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#### 3.1 Outline

This chapter presents a comprehensive review of the work reported in literature related to our work. WSN technology overview and its applications are discussed in detail in Section 3.2. Related work for application of bio-inspired algorithms for clustering and routing protocols are presented in Section 3.3. Further, Section 3.4 briefs about the state-of art techniques related to data compression in WSN.

#### 3.2 WSN Technology Overview and Applications

A WSN is fundamentally a network comprising of small sensor nodes, also known as motes, communicating via radio frequency transmission techniques. The data collected from these motes are communicated to a central server called Base Station (BS). The data between the motes and the BS can be communicated directly, which is called single hop communication, or it can be multi hop communication wherein data is communicated by establishing links between neighbouring nodes till BS. Thus, these sensor nodes serve two purposes, one as a data source, and other as a relay node. All the data received from sensor nodes is aggregated at the BS and further the aggregated data is communicated to a server or a cloud monitoring site. The communication is done wirelessly across the network as well as to the cloud. Therefore, a technological overview of WSN and its related applications are presented in this chapter.

### **3.2.1 WSN Technology Overview**

WSN finds its usage in several monitoring and control applications for the industry as well as home and offices. Several parameters need to be optimized for better utilization of these applications viz. data ratio, communication range, lesser power consumption etc. Nevertheless, the most limiting parameters for WSN are both power consumption and communication range. This section discusses the latest technological inventions for WSN. The analysis is made from the point of view of software as well as hardware technologies deployed in WSN. Likewise, the main impediments in the upcoming area of WSN, along with unsolved problems, and current open issues and challenges in research are discussed.

#### **3.2.1.1 Radio-Frequency Technologies**

Here, we discuss various radio frequency technologies and a brief overview of other related aspects of these technologies. Different radio frequency technologies have different features such as range of data communication, power consumption, integration with other devices, reliability, resistance to interference and secure communication. WSN has its own requirements such as lower power consumption, long range, secure communication, lesser interference from obstacles etc. Hence an analysis of their suitability vs non suitability for WSN deployment has also been presented. Table 3.1 presents a brief review of the radio-frequency technologies.

**Table 3.1:** Radio-Frequency Technologies for WSN

Technology	Proximity	Frequency Band	Features	Suitability for WSN
Bluetooth (IEEE 802.15.1)	PAN	2.4 GHz	Short distance	Not Suitable
Wi-Fi (IEEE 802.11.a/b/h/g)	LAN	2.4 GHz, 5 GHz	Lacks low power mode Not very Integrated	Not Suitable
Ultra-Wideband (UWB) (IEEE 802.15.3)	LAN (short range)	3.1 – 10.6 GHz	Short range	Not Suitable
ZigBee (IEEE 802.15.4)	WPANs	2.4 GHz, 900 MHz, 868 MHz	Secure Communication, Low Data Ratio, Less complexity	Suitable

### 3.2.1.2 Hardware Platforms for WSN

There are several hardware platforms available for providing the wireless connectivity of the nodes. This section focuses on various hardware platforms available for WSNs with details regarding microcontroller, Read Only Memory (ROM), Random Access Memory (RAM), speed, and Operating System (OS) options available. A comparative evaluation of various hardware platforms is displayed in Table 3.2.

**Table 3.2:** Comparative Evaluation of various hardware platforms

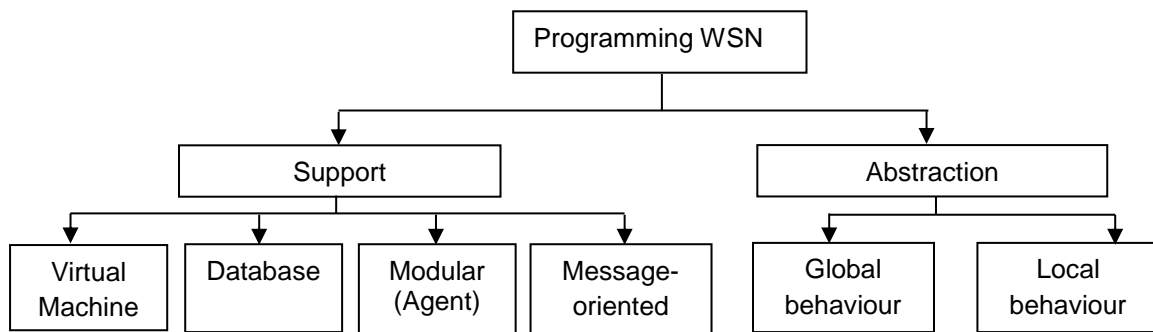
Hardware Platform	Microcontroller	RAM	ROM	Speed	OS
AVID director	Imsys CJIP Java	8 -16 MB	4 -16 MB	160 MIPS	Imsys Java
WMSNP	Microchip PIC 182220	512 bytes	2 KB	8 MHz	None
Smart Mesh-XR	TSMP engine	NS	NS	NS	NS
JN5121	RISC optimized for low power	96KB	64KB	16 MHz	NS
Tmote Sky	MSP 430F 1611	10KB	48KB Flash	8 MHz	TinyOS
MICAx	Atmega 128	4 KB	128 KB Flash	8 MHz	TinyOS
MICA2DOT	Atmega 128L	4KB	128KB Flash	4 MHz	TinyOS
Coronis Wavecard	T1 MSP430F149	2KB	64 KB Flash	4 MHz	None in standard
eyesIFX	MSP430F1611	10KB	48KB	8MHz	TinyOS

### 3.2.1.3 Software Technologies for WSN

Being a resource constrained platform, there are several challenges faced by WSN in terms of various software applications running on the WSN platform. Apart from the resource constraints, there are also other important factors like communication constraints, limited power, no power backup etc. that plays a key role in adding complexity to software applications being developed for WSN. In this section, we review some of the important software related aspects of WSN namely the middleware architectures, agent technologies, and operation and design strategies of WSN software. Different middleware architectures are classified based on the programming languages used. The classification based on programming sensor network is depicted in Figure 3.1. On the basis of programming support, middleware is classified into 5 categories. Virtual machine consists of interpreters and mobile agents. Authors in [35] provide scalability and openness by improving the adaptation and interaction for diverse sensor networks. Further, authors in [36] discuss a virtual machine that has been coded in Java and works on a WSN platform without any operating system. The main

problem with this platform is that it is mainly applied only to devices developed at Sun microsystems laboratories. Further, the entire network, from the perspective of database approach, can also be observed as a virtual database system that offers a user-friendly interface. Such user-friendly interface is helpful to extract useful data related to the network. This is established by the work of Cougar [37] which proposes a dimension that considers network as a database. Further, the method TinyDB proposed in [38] is a query processing system that fetches information pertaining to sensor networks. Continuing the line of research further, authors in [39] presents network as a distributed object. Additionally, Detection Service using Data Service Middleware (DSWare) as proposed in [40] is a database approach that works by detecting events and uses Structured Query Language (SQL) to register such events. Another approach in terms of programming support is modular programming which is also referred to as mobile agents. Authors in [41] suggest usage of architecture model which aids applications to adapt during run time and thus provide a shield against programming errors. Final approach among various available is message oriented middleware (MOM) that exchanges message through a publish-subscribe mechanism and has been implemented in [42] and [43].

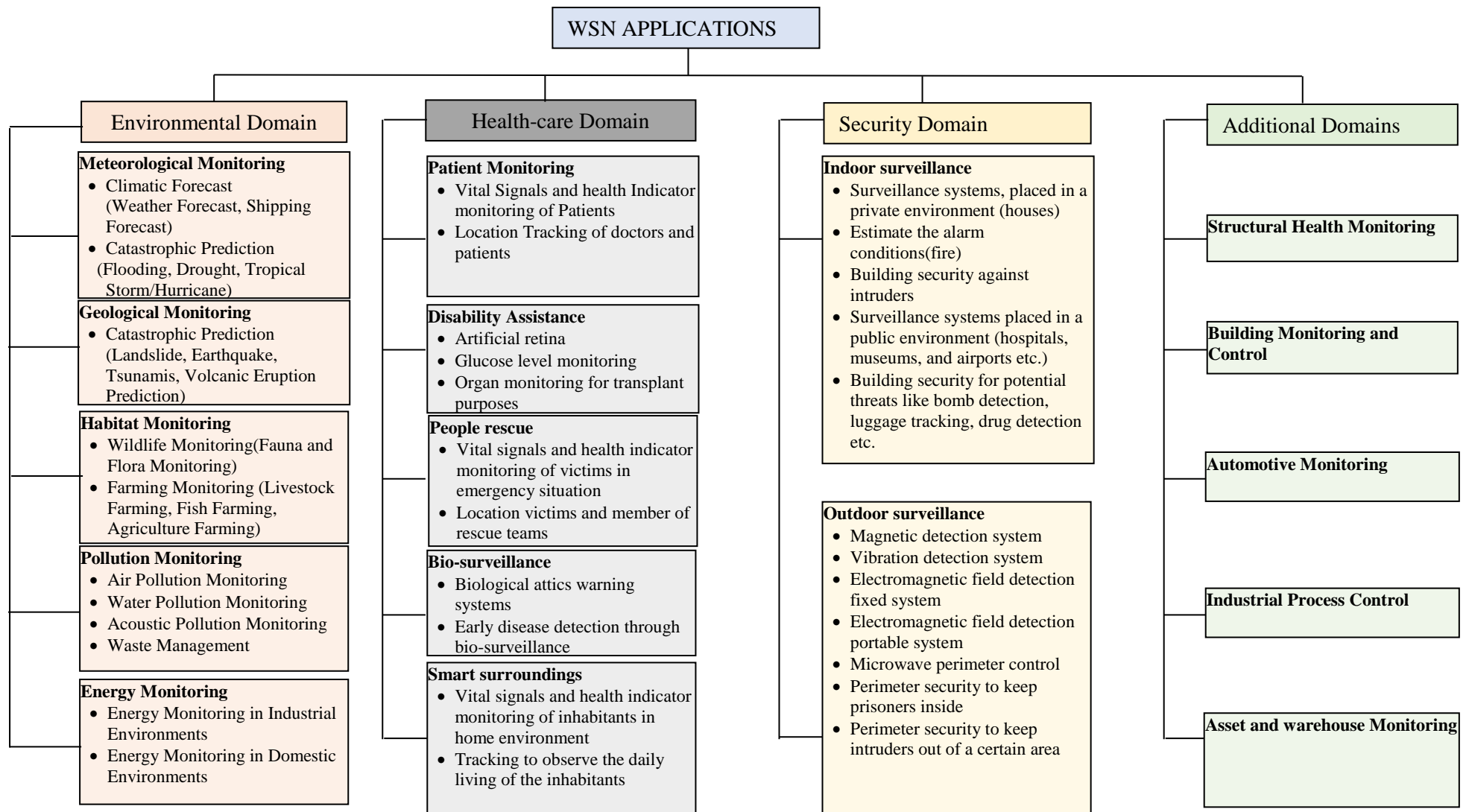
In abstraction, there are two main approaches viz. global behavior and local behavior depending upon looking at the network as a whole or as a subpart respectively. In global behavior, the entire network is programmed as a single unit and allows the node behavior to be automatically generated. This is also called macro- programming. Regiment [44], Kairos [45], Abstract Task Graph [46] and Semantic Streams [47] are the examples of WSN projects which have employed macro-programming model. Another approach is from a local perspective of the network i.e. microprogramming, where the sensed data and the location of node is considered. Here, the behavior at a particular location is considered instead of the entire network. Abstract regions [48] is a local approach based on data aggregation and other computation techniques to reduce the complexity of the network. Madden et. al., 2002 [49] and Romer et. al., 2004 [50] are also research projects based on local behavior of nodes.



**Figure 3.1:** Middleware Approaches based on Programming in WSN [51]

### 3.2.2 WSN Applications

As the technology for WSN become more commercialized, the wide variety of applications based on WSN technology are increasing day by day. Their high utilization is achieved as sensor nodes can work independently without necessitating additional framework. This extraordinary advantage can be seen significantly when taking a glance at the numerous issues tackled by employing WSN technology. The employment of WSN technology has been observed in wide range of domains. However, the most influential role of WSN can be observed in categories such as health care, environmental monitoring, and security etc. A detailed overview of these applications is depicted in Figure. 3.2. Initially WSN was deployed only for traditional applications such as biomedical applications, habitat sensing, environmental monitoring [52-53] but gradually it has been applied to almost all real life applications for instance monitoring, target tracking, field surveillance, and security applications to name a few. WSNs has found its applications in the Internet of Things (IoT) domain e.g. connecting and controlling devices in health care, building automation, factory control, and supermarket management. These applications have different requirements as compared to the traditional ones in terms of applying intelligence for resource optimization, around-the-clock availability requirements, single point of control, security and privacy issues etc. Hence, the various research issues which are still open belong to this category and hence can be worked upon.



**Figure 3.2:** A broad Classification of various applications in WSN [52]

### 3.3 Bio-Inspired Optimization Algorithms

Optimization implies the application of methods/techniques for achieving a satisfactory viable solution for frequently confronted mathematical problems in all engineering disciplines. These problems are extensive and numerous, and therefore the techniques for deciphering these problems should be a part of latest research. Previous optimization techniques to tackle these mathematical problems entail massive computational complexity and thus may fail in case of large problem size. This motivates the research community to employ bio-inspired optimization algorithms as computationally effective solution in contrast to deterministic optimization techniques.

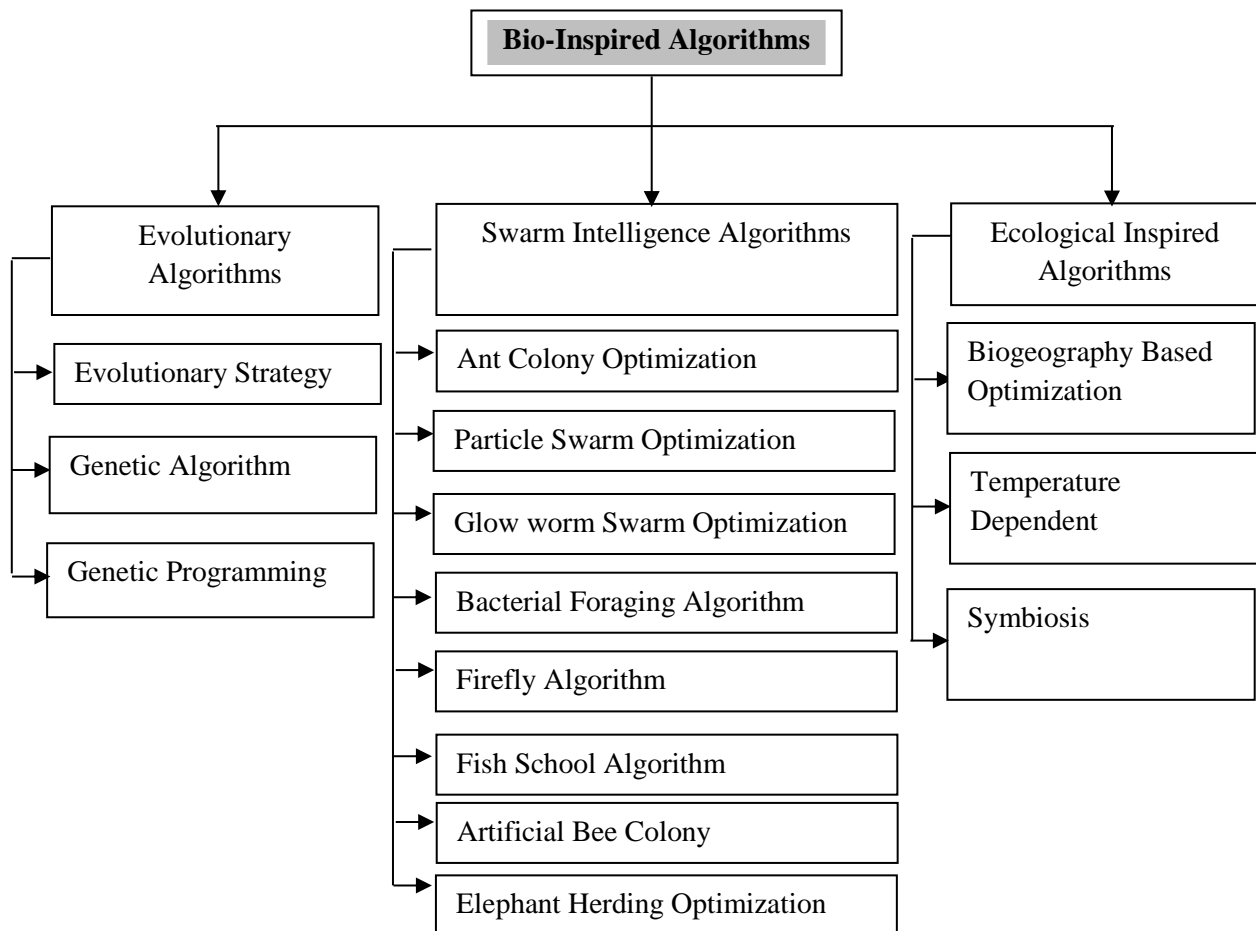
Bio-inspired optimization algorithms derive their sole motivation from the nature for the reason that if we carefully inspect every single characteristic or wonder in nature it generally cracks down to an optimal strategy keeping the diversity, variation, actual wonder like waterfall, swarms, bees, etc. The beauty of nature-based algorithms lies in the capability to solve complicated relationships with very few inputs and conditions without the need of additional knowledge of the problem in hand. Nature is the best instructor, and its plans and capacities are amazingly colossal and puzzling that specialist are attempting to copy nature in technology.

The complex nature of today's problems inspires the researchers to devise efficient and useful methods that find and optimize the solution for complex and optimization problems respectively [54]. During the past few decades, Bio-inspired algorithms (BIA) have demonstrated promising proficiency in handling various kind of optimization problems and as a result has been accepted to be an efficient tool for solving optimization problems. BIA is generally categorized into three classes as follows [55]:

**Evolutionary-based algorithms (EA)** are search methods that work by simulating the living species' natural biological evolution and social behaviour. For example, EA simulates behaviour of reproduction through selection, recombination and mutation. Generally, EA are employed to find optimal solution to complex optimization problems where conventional mathematical methods may fail to perform efficiently. The most well-known EA method is Genetic Algorithm (GA).

**Swarm intelligence (SI)** are inspired by behaviour of social living animals such as birds, ants, bats, and fishes etc. [56]. SI works by developing an intelligent interactive multi-agent system which cooperates in order to obtain a predetermined goal which cannot be achieved using a single-agent. The most common SI algorithm used in the field of computer science is the Ant Colony Optimization (ACO) [57].

**Ecological-inspired algorithm (ECO)** works in the direction of developing cooperative search algorithms. It uses populations of individuals where each population grows using some search strategy. The growth of individual population depends on various ecological concepts such as habitats and ecological relationships. The most common ECO is the Biogeography-Based Optimization (BBO) in the field of computer science. Table 3.3 summarises the biologically inspired algorithms.



**Figure 3.3:** A broad Classification of Bio-Inspired Algorithms for Optimization [58]

### 3.4 Bio-Inspired Algorithm for Clustering and Routing protocol

K-means clustering is among the most conventional and simpler algorithms and resultantly has been applied for solving several applications related to WSN deployment. The algorithm performs efficiently in many cases, however it has a major limitation of converging to the local minima. Also, the obtained solution is influenced by the initial selected centroid values [59]. According to the literature, it is evident that when optimization algorithms are integrated with K-means clustering algorithm, it leads to obtaining global optima with rapid convergence. Resultantly, during survey of literature, it is noticed that many researchers have suggested employment of bio-inspired algorithm for addressing the issue of convergence to local optima [60]. Thus it can be considered that bio-inspired optimization algorithms are competent in addressing the limitations of conventional K-means clustering. However, it must be noted that integration of bio-inspired algorithms with K-means clustering is limited to nearly similar kind of manoeuvres like firefly and PSO [61].

As mentioned, bio inspired algorithms can be employed in order to enhance the efficacy of K-means clustering. For the same reason, some models have also been proposed in the literature. For instance, authors in [52] suggested application of data clustering in ACO to obtain improved bee colony optimization (IBCO). In this model, authors proposed the idea of fairness and cloning so as to efficiently employ it for clustering of text documents. Further, authors integrated it with K-mean algorithm to garner its benefit of fine-tuning power. The obtained results establish the robustness of the proposed approach and hence advocate its supremacy over K-means and other comparative algorithms. Here, it is also mentioned that the said algorithm may not yield optimal results if the number of clusters are not known in advance.

Further, authors in [53] suggested usage of chaotic map for local search for improving efficiency of Artificial Bee Colony (ABC) optimization. The simulation of proposed method yielded quite motivating results in terms of speed and accuracy of results. Similarly, authors in [62] suggested an improved PSO method for clustering by extending a discrete PSO method. The discrete PSO method was extended in the direction of novel representation of particles for dimensionality reduction and efficient evaluation of optimization function. Similarly, authors in [63] also devised a hybrid algorithm that integrates fuzzy C mean and K-means with PSO for document clustering. The performance evaluation of the proposed

algorithm establishes that this approach outperforms traditional methods particularly for overlapping datasets.

Extending the research further, authors in [64] suggested usage of distributed agents in their method. Authors claim that distributed agents have been employed to mimic the behaviour of real ants for finding shortest path to the nearest source of food. The communicating ants have also been used in [65] for clustering that employs backtracking that enables ants to backtrack their previous decision. A firefly-based approach for WSN is also proposed in [66] for clustering that works in two phases viz. micro-clustering and macro-clustering. In micro-clustering, sensors are organized into clusters while macro-clustering works on further refining the clustering through aggregation of small clusters. Further, a GA based algorithm, genetic K-means algorithm (GKA), is proposed by Krishna and Murty [67] that converges to the optimum with rapid convergence in comparison to other clustering algorithms. The traditional ABC has also been modified by Krishnamoorthi and Natarajan [68] in order to optimize the efficiency of clustering process.

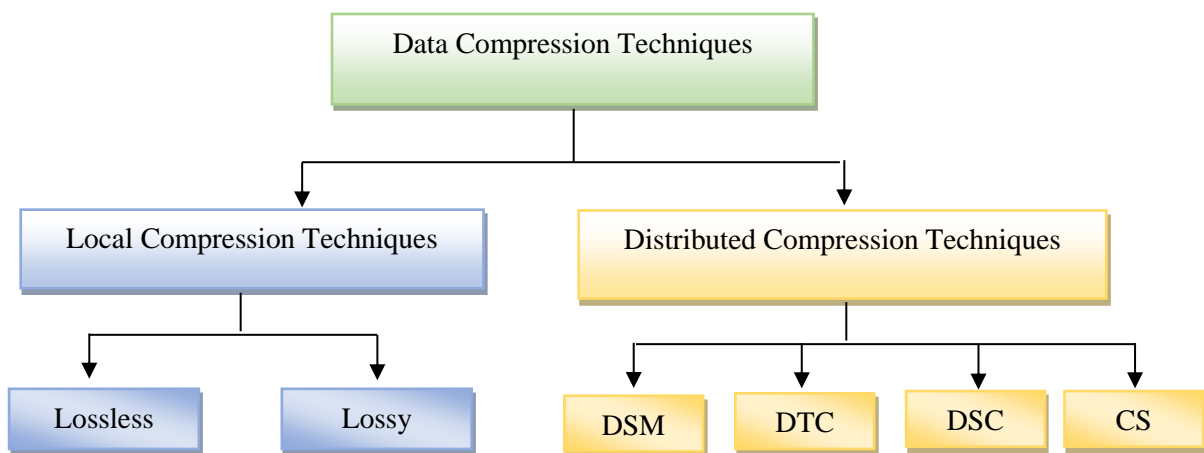
Now from the study of literature discussed above, it becomes evident that bio-inspired algorithms have been widely used for clustering as it outperforms conventional methods of clustering.

### **3.5 Data Compression Algorithms in WSN**

Power saving in WSN is one of the most critical issue for efficient working of WSN. Previous studies reveal that the energy spent on data communication is higher than data computation and hence, its viable to reduce the data before communicating on the network. Thus, reducing the data without losing the relevant information, for instance data compression, is one of the possible strategies to reduce the power consumption. The previously proposed compression algorithms cannot be employed for WSN due to the large size of the algorithms, processor speed, and high complexity. Hence, it is crucial to develop data compression algorithms pertaining to the requirements of the sensor network. In WSN, data can be compressed at three levels i.e., the node, cluster head and to the BS so that lesser energy is spent on data communication. Compression techniques are divided into lossless and lossy technique depending on the data loss during the compression. Wavelet compression technique is a widely employed technique, but it is a lossy technique and hence not much employed in WSN [69]. There are several lossless compression techniques

employed in sensor networks such as Huffman, Lempel-Ziv-Welch (LZW) and Run Length Encoding (RLE) et.al, LZW being the most widely employed algorithm in WSN [70]. LZW works on creating distinct dictionaries for distinct data. This algorithm requires less computational resources and hence is suitable for sensor network. However, the algorithm suffers from the limitation of lower compression ratios, which needs to be worked upon. Sensor Lempel-Ziv-Welch S-LZW [71] is a lightweight lossless compression technique based on the modification of the established dictionary based LZW algorithm [72] especially designed for a resource constrained sensor network. Further, Marcelloni and Vecchio [73] proposed a lossless compression technique especially suited for power constrained sensor nodes. In this research work, authors achieved compression ratio of around 66.9% and 67.3% for the selected datasets. Compared with the state-of-art S-LZW algorithm, the proposed algorithm outperforms the S-LZW in terms of compression ratio, memory occupation and lesser complexity. Also, Zhou et. al. proposed an improvement over LZW algorithm by reducing the dictionary size, reducing the address space to two bytes, limiting the length of substring and achieved significant advantage in lowering dictionary size and achieved higher compression ratio [74]. Similarly, Tuong et. al. also worked on enhancing LZW algorithm for higher compression ratio by introducing the cyclical behaviour of sensor data and considering the fact that distance between consecutive samples of the sensor data is same.

Further, depending on the location of data aggregation in the network, the compression techniques are classified as distributed and local compression schemes. Figure. 3.4 depicts the strategies employed for data compression techniques in WSN. Table 3.3 and 3.4 compare the distributed and local data compression techniques employed in WSN respectively.



**Figure 3.4:** A broad Classification of Data Compression Techniques in WSNs [75]

**Table 3.3:** Distributed Data compression Techniques

Citation	Compression Schemes	Name of the Technique	Location of Data Compression	Process Employed	Compression Ratio	Computational Cost	Lossless/Lossy	Application	Limitation
[76]	Distributed transform coding (DTC)	D-KLT	Sink Node	Data Aggregation	N/A	Low	Lossless	Real Time Operation	Did not evaluate the power consumption performance
[77]		DWT-lifting	Sensor Nodes	Lifting Scheme	Dependent on Signal-to-Noise Ratio (SNR)	Low	Lossless	Optimal Network Configuration	The vector nature of data received at sensor nodes is not handled.
[78]		DWT-Harr	Sensor Nodes	Lifting Scheme	Dependent on Signal-to-Noise Ratio (SNR)	Low	Lossless	Optimal Performance	Limited to specific topologies
[79]	Distributed Source Encoding (DSC)	CBO	Aggregation Node	Data Funnelling Routing	High	Low	Lossless	good compression ratio, less complexity	Complexity of the algorithm increases exponentially as the size of the network grows.
[80]		PIN	Aggregation Node	Data Collection at aggregator node	High	Low	Lossless	Higher compression ratio, Simple	Not adequate Buffer Space available due to the limited memory size of the sensor nodes.
[81]		Low complexity video compression	Cluster Head	Wireless video surveillance	High	Low	Lossless	High compression Quality comparable to	Full software solutions are not available

								MPEG-2, Battery saving	
[82]		DCS	Sensor Nodes (Spatial Proximity of Nodes)	Distributed Source Encoding	High	Low	Lossless	No inter-node communication required, Fast error correcting coding algorithms.	High Complexity due to information communication and processing
[83]		QAM	Sensor Nodes	Quadrature amplitude modulated (QAM) transmission strategy	Optimal	$O(L^2)$  L-Bit Length	Lossy	Tracking/Detecti ng Applications	Higher computational Load on sensor nodes
[84]		HMM	Sensor Nodes	Spatial and temporal Correlation	N/A	Low	Lossy	Detection Application	Applications are limited and high inter-sensor communication
[85]		Distributed non-parametric kernel-based scheme (DNKB)	Sensor Nodes	Non-linear Regression Functions	N/A	Low	Lossy	Tracking/Detecti ng Applications	Limited Applications

**Table 3.4:** Local Compression Technique [86]

Distributed Karhunen-Love transform	D-KLT
Distributed wavelets transform-biased lifting	DWT-lifting
Distributed wavelets transform-based Harr	DWT-Harr
Coding by ordering	CBO
Pipelined in-network	PIN
Distributed Compression Scheme	DCS
Optimizing quantization-based target scheme	OQPT
Data representation-based hidden Markov model scheme	DRHMM
Distributed non-parametric kernel-based scheme	DNKA

### 3.6 Research Gaps

From the above literature study related to WSN, clustering and data compression, following research gaps are identified:

1. Many optimizations and variations are proposed for the basic K-means clustering algorithm for making clusters in WSNs. Nevertheless, most of the research works found in the literature focus on searching for global optima as well as getting faster convergence. To the best of our knowledge, when the number of clusters is unknown, scalability is important for optimal WSN performance. Authors have identified this as a research gap where modification to the basic K-means can be explored for unknown number of clusters and dynamic allocation.
2. One critical challenge of lossless data compression is the robustness, which indicates whether or not a data compression algorithm can be widely and effectively applied for diverse real-world sensor data in various WSN applications, because different sensor data can exhibit very different temporal characteristics.
3. The practicality of various data compression techniques applicable for a specific application is nonetheless an open research issue demanding additional research.
4. Lastly it is found that each approach has advantages and disadvantages in different ways. Thus, no data compression approach is the most suitable for all WSNs. Distributed compression techniques are based on several assumptions and are not robust. On the contrary, the local approaches which are based on less assumptions, are more robust for different situations in sensor networks and their performance

is better. Local compression techniques do not work well in dense network, nevertheless the distributed techniques may perhaps exhibit the worst performance in sparse network. Hence, in our study, authors have found that there is ample scope of developing more robust techniques applicable for both dense and sparse networks.

After rigorous review of the related literature, it is evident that researchers primarily aim to propose methods to enhance the different performance metrics despite constrained resources in the WSN. Cross-layer WSN design techniques based on the Open System Interconnection (OSI) model are also studied during the literature survey. Researcher has also reviewed constraints-based routing algorithms which select a routing path satisfying administrative-oriented or Quality of Service-oriented constraints so as to minimize costs, balance network load, or increase security. As the previous works had some scope of improvement, the author also proposes a novel design.

The proposed approaches aims to select efficient cluster head selection, reliable routing and data compression technique to enhance network lifetime to ensure secure and confidential data collected by the sink.

### **3.7 Conclusion**

In this chapter, we have reviewed, compared, and summarized the latest technology and applications for WSN. WSNs have unique characteristics such as low battery life, lesser resources, deployment in constrained regions, which makes the applicability of existing algorithms challenging in these kinds of networks. Therefore, researchers have developed new algorithms keeping these constraints in mind. Authors have focussed on the clustering, routing problem and compression techniques for WSN. The complex nature of the problems inspire the researchers to devise efficient and useful methods that optimize the solution. The chapter focusses on bio-inspired optimization for different solutions. We have identified the probable research gaps in these domains.

### **Trust-Based Cluster Head Selection Using the K-Means Algorithm for Wireless Sensor Networks**

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M. Mishra, G. S. Gupta, and X. Gui. "Trust-Based Cluster Head Selection Using the K-Means Algorithm for Wireless Sensor Networks." 2019 International Conference on Smart Systems and Inventive Technology (ICSSIT). IEEE, 2019.

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#### **4.1 Outline**

Clustering is a widely employed technique for energy saving in sensor network, consequently extending the network lifetime and performance of the network. Here, the cluster head acts as a router as well as collects, aggregates, and transmits the data from cluster nodes to the base station. CH plays a key role in extending the lifetime of a network. If a node with less energy is elected as a CH, this may hinder the routing process and network operation. Also, the CH selected must be trustworthy and reliable so as to ensure the secure communication across the network. Thus, it is imperative to employ an efficient CH selection approach to elect a CH having high residual energy, is trustworthy and reliable. This chapter proposes a K-means clustering based CH selection approach by introducing a new factor called trust for CH election using parameters like residual energy, distance among nodes.

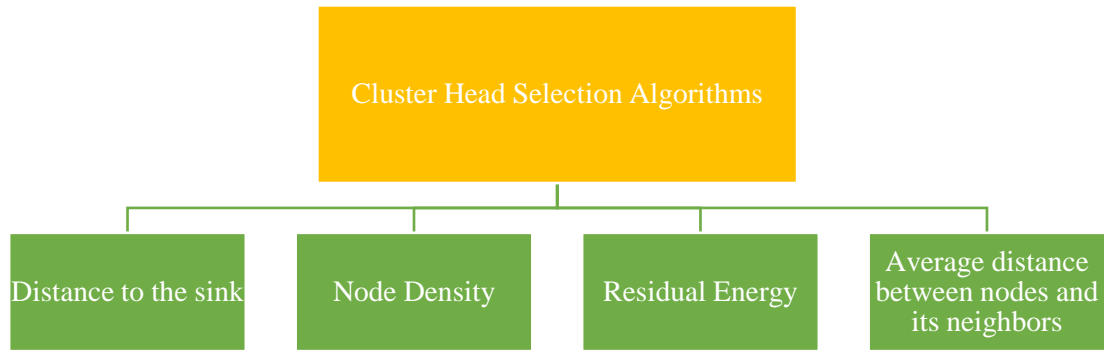
When number of sensor nodes are clustered together, it can be considered as a efficient practice in terms of conservation of energy of network node [87-88]. For example, if all nodes in the network initiate communication and get involved in data transmission, it may lead to data congestion which further causes frequent collisions in the network. As a result, clustering is employed when the CH collects the data from its neighbouring nodes ahead of transferring the same to BS [89]. Additionally, clustering also enables minimizing the number of hops thus reducing the size of routing table [90-91]. This reduction in the size of routing table leads to conservation of communication bandwidth, overhead reduction and minimization of redundant data packets [92]. Resultantly, the communication among sink node and sensor nodes takes place through CHs. This causes drainage of more for energy CHs in comparison to generic nodes in the cluster. Thus it becomes imperative to provide an energy-efficient solution in order to minimize the energy consumption.

Selection of CH is an important aspect as it affects the energy efficiency in the network. As a result, several researchers have undertaken this problem and have suggested different methods for selection of CH. In general, the selection of CH may be random or based on some criteria [93]. For instance, authors in [94-95] have proposed an algorithm that selects CH on the basis of distance and energy or sensor trust management [96-97]. The proposed approaches still have a scope for improvement as selection of the CH is the most vital decision and greatly influences the network performance. WSNs, in general, have constrained resources and are vulnerable to security attacks. Apart from selection of the most appropriate CH, it must also be ensured that the selected CH is secure and is not tampered with properties of sensor deployed in open environment [98].

This chapter proposes an efficient approach to select CH based on the energy and trust value of each node in the WSN. In addition, the proposed approach uses K-means clustering algorithm to conserve the energy of nodes. It maintains that the selected CH will not get compromised upon its deployment in the environment owing to intrusion or change in physical nodes. In order to establish the validity of the proposed approach, it is simulated, and the obtained results are compared with traditional CH selection methods that uses distance, trust factor, fitness and energy.

## **4.2 Related Work**

This section gives a brief overview of some established and promising state-of-the-art approaches for clustering in WSN. The related work is mainly classified in 2 parts as shown in Figure. 4.1. These two classes of cluster head selection algorithm are distance and energy-based cluster head selection and trust-based cluster head selection. The details of these methods are presented in table 4.1 and table 4.2 respectively.



**Figure 4.1:** Classification of Cluster head selection Algorithms [99]

**Table 4.1:** A survey of Distance and Energy-based Cluster Head Selection

Clustering Algorithm	Clustering Criterion	Advantages	Limitations
Low-energy adaptive clustering hierarchy (LEACH) [100]	Hierarchical routing by balancing energy consumption of network	Enhances Network Lifetime Significantly	Does not consider remaining energy of nodes. Single Hop communication makes it ineffective for large-scale networks [101].
Efficient cluster head election (EECHE)[102]	Density of cluster members (CMs) and effective CH distance.	Prolonged Network Lifetime and Stability	Not effective for larger distance
A fuzzy-based enhanced cluster head choice (FBECS) [103]	residual energy, distance from BS and node density.	Enhanced stability, network lifetime and the data packet forwarded to BS.	Performance of the network dependent on separation distance
Multi Objective Evolutionary Algorithms (MOEAs)[104]	The number of CHs, clustered nodes, the link quality	Energy-efficient, reliable, and scalable clustering protocol.	Limited application for resource constrained network nodes
Energy efficient clustering protocol based on K-means (EECPK)[105]	Mid-point selection algorithm based on load balancing.	Increasing network lifetime by balancing sensor nodes.	Considers residual energy as well as the distance between nodes.

**Table 4.2:** A survey of Trust-based Cluster Head Selection

Clustering Algorithm	Clustering Criterion	Advantages	Limitations
A Heuristic Approach based Trust Worthy Architecture for WSN. [106]	A statistical method employed for evaluating the trust among sensor nodes.	Inhibits the selection of spurious or negotiated nodes as CHs	Computationally Expensive
Trust-based LEACH(T-LEACH) [107]	CH-assisted monitoring is employed for power minimization	Outperforms LEACH	Persistent loss of data.
Node Behavioural Techniques Trust Analysis Algorithm Banding Belief Theory (NBBTE)[108]	Integration of node behavioural strategy and Dempster-Shafer (D-S) evidence theory.	Realistically assess the reliability of nodes.	Additional computational complexity in terms of energy and time
CH is chosen by firefly algorithm [109]	Trust based intrusion detection and clustering approach	Reduce the delay, increase the broadcast energy and throughput	Security is not achieved
Heuristic Routing approach [110]	Routing of Intercluster kind stands for routing among BS as well as CHs	By using the cluster formation can decrease the overhead ratiom	Computational complexity

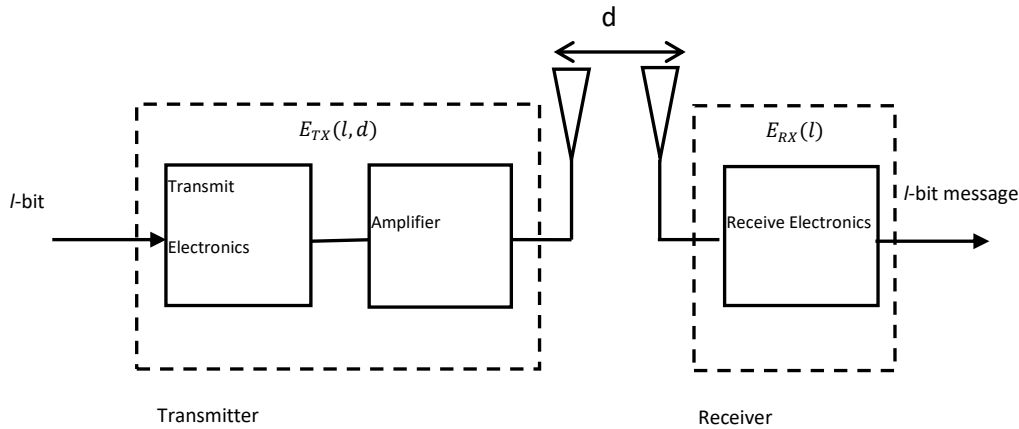
### 4.3 System Model

This section gives a detailed overview of the proposed approach. For the same, let us discuss the traditional LEACH protocol where nodes are deployed in the environment without constraining any special region [109]. This leads to the fact that each node has an equal probability of getting selected as a CH. This implies that a node with minimum energy or elongated distance from BS may also be considered as CH. If such a node gets selected as CH, it will lead to quick depletion of stored energy leading to reduction of lifespan of the network. This is owing to the fact that a CH may get an increased number of nodes leading to its overload and requirement of huge energy. Here, we propose that the network is divided into 8 grids of equal size where each grid has equal number of nodes. Thus, it can be considered that entire nodes are distributed and clustered in 8 grids. Further, the proposed approach allows the network to select the CH based on energy, distance and trust value. By using the cluster formation one

can decrease the overhead ratio, reduce the node failure rate and increase the throughput. This helps to reduce the collision rate and traffic rate [110].

### 4.3.1 Energy Model

The radio model which is widely used in the literature [100] for sensor network simulation is illustrated in Figure. 4.2.



**Figure 4.2:** Radio Model [100]

In the Figure. 4.2, it is illustrated that a  $l$ -bit packet is to be transferred to a receiver at a distance of  $d$  meters. Here,  $E_{Tx}(l, d)$  and  $E_{Rx}(l)$  indicates the energy dissipated during transmission and reception respectively in the given scenario. The mathematical formulation for  $E_{Tx}$  in equation (4.1) is as follows:

$$E_{Tx}(l, d) = \begin{cases} lE_{elec} + l\epsilon_{fs}d^2, & \text{if } d \leq d_0 \\ lE_{elec} + l\epsilon_{mp}d^4, & \text{if } d \geq d_0 \end{cases} \quad (4.1)$$

where  $E_{elec}$  indicates the energy consumed per bit in order to operate electronic circuitry. Further  $\epsilon_{fs}$  are power consumption of the free space and  $\epsilon_{mp}$  power consumption of multipath propagation . finally,  $d$  and  $d_0$  are the symbols used to illustrate distance among communicating nodes and the threshold transmission distance respectively. The value of threshold distance  $d_0$  in equation (4.2) is evaluated using:

$$d_0 = \sqrt{\frac{\epsilon_{fs}}{\epsilon_{mp}}} \quad (4.2)$$

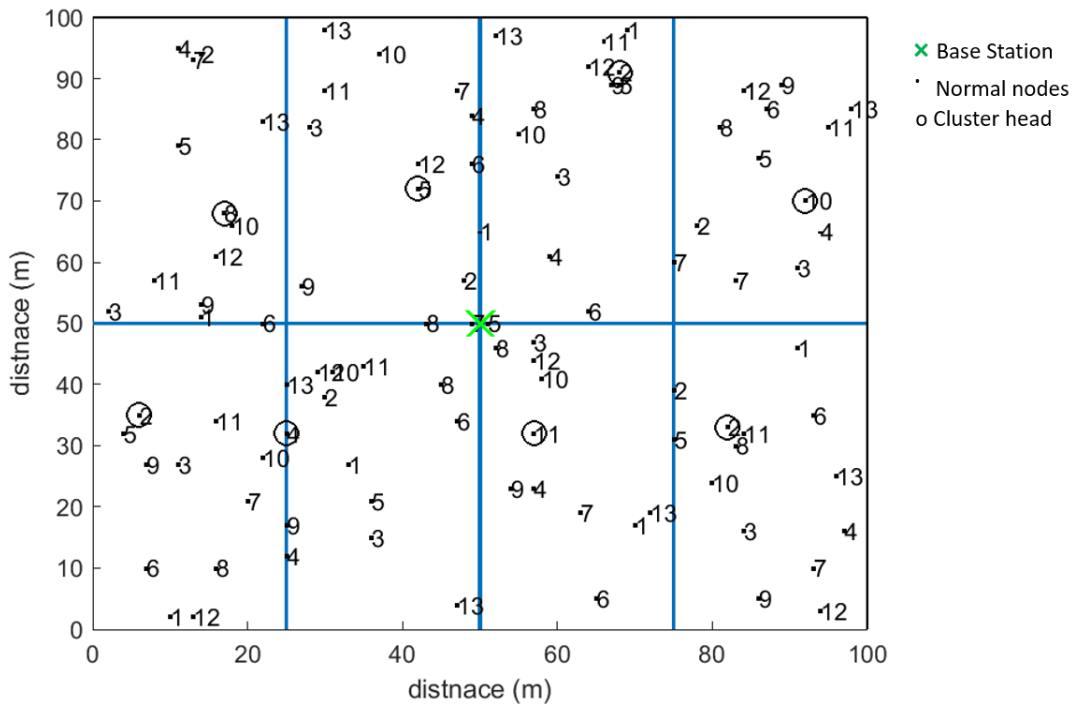
If the communication distance between nodes is  $d \leq d_o$ , the data transmission adopts the free space channel model, and the amplifier energy increases by  $d^2$ . If the communication distance between nodes is  $d \geq d_o$ , the energy consumption of data transmission will increase sharply, as the fading channel model applies and the amplifier energy increases by  $d^4$ .

Further, the mathematical formulation for  $E_{Rx}(l)$  in equation (4.3) may be given as follows:

$$E_{Rx}(l) = l * E_{elec} \tag{4.3}$$

### 4.3.2 Proposed network architecture

The proposed network architecture is illustrated in Figure 4.3. Here in the proposed model, we consider the first-order radio energy method to calculate energy dissipation incurred during data communication such as reception and transmission:



**Figure 4.3:** The network architecture of the proposed model

Now, once we have discussed the mathematical formulations for energy consumption, let us discuss the various characteristics involved in the proposed architecture:

- As mentioned earlier, the proposed architecture consists of a number of grids that basically divide the area where the nodes are deployed.

- Each grid consists of an equal number of nodes as illustrated in Figure. 4.3. The nodes under consideration are static and have 0.2 J of initial energy. The network lifetime and the rate of packet delivery to Base Station increased with increasing initial energy. On the other hand dead nodes number decreased with increasing initial energy [111].
- Further, each grid has a CH that manages the overall communication. CH basically employs communication through single hop or multiple hops.
- The BS is placed in the middle of the network that enables easier communication among different CHs.
- In the proposed approach, each node sends the data to corresponding CH which further sends it to BS/sink.

The proposed network architecture leads to the reduction in the load of CH which further reduces the requirement of energy utilized during communication. This reduction in requirement of required energy increases the network lifetime over traditional approach. Further, the proposed model also considers a trust factor in order to ensure enhanced network performance. Among various nodes, a node is basically selected as a CH on the basis of various service parameters viz. energy consumption and sink distance etc. Such parameters are considered for all nodes in the network and CH is selected among various nodes in accordance.

Here, it is worth mentioning that traditional techniques do not consider various parameters such as trust factor and security. This may lead to selection of a malicious node as a CH in the network. If any such malicious node is selected as CH, it adversely affects the efficiency of network during transmission of data from source to destination or to the sink. Nevertheless, consideration of factor such as trust factor and other security aspect prevents selection of any malicious node as CH and hence achieves enhanced efficiency [112]. This also leads to prevention of network from various intruders [113].

## 4.4 Selection of CH

### 4.4.1 CH selection Algorithm

<b>Algorithm 1:</b> Cluster Head Selection Algorithm	
1. Node=N;	% Total Number of node
2. AreaX= x meter;	% Area in X dimension
3. AreaY= y meter;	% Area in Y Dimension
4. Gsplit=8;	% Total number of Grid Splitting
5. Sections=Gsplit x Gsplit;	% Number of grids in network
6. XareaS=AreaX/Gsplit;	% Area in each grid in X dimension

```

7. YareaS=AreaY/Gsplit;      % Area in each grid in X dimension
8. For i= 1 : XareaS : (AreaX- XareaS)
    For j= 1 : YareaS : (AreaY- YareaS)
        % Edge Points Generation of Grids
        Xpoints(i,j)=[ i , i + XareaS];
        Ypoints(i,j)=[ j , j + YareaS];
    End
end

9. Ne=N/8;      % Number of nodes in each section
10. % Deployment of Nodes in Network
For sec = 1 to Sections
    For i = 1 to Ne
        XSxy(sec,i)=RandomCoord(Xpoints);
        YSxy(sec,i)=RandomCoord(Ypoints);
    End
End
% CH selection Phase
11. For i= 1 to Sections
    For j= 1 to Ne
        For k= 1 to Ne
            Dist(i,j,k)= $\sqrt{(XSxy(I,j) - XSxy(I,k))^2 + (YSxy(I,j) - YSxy(I,k))^2}$ 
        End
    End
    % Apply Kmean Approach
12. Temp=Dist( i, :, :);
13. JDist= $\sum_{m=1}^j \sum_{n=1}^k Temp(m, n)$ ;
14. CalcentroidXY(JDist);
15. For io=1 to Ne
NearDist(io)=
 $\sqrt{(XSxy(I,j) - CalcentroidXY(1,1))^2 + (YSxy(I,j) - CalcentroidXY(1,2))^2}$ 
    end
16. [minDistance, NodeCH]=min(NearDist);
17. CHmatrix(i)=NodeCH;
18. End

```

In the first stage of the proposed network, the total number of nodes is selected, and the network is then partitioned into a certain number of grids. Further, the trust between the nodes is evaluated and then the K-means algorithm is applied. After that, the fitness of the individual node is calculate and the node which has highest fitness value is suitable to become a cluster head. Once the CH is selected, data transmission initiates among selected CHs and BS in the network

#### 4.4.2 Proposed methodology for selecting CH

As mentioned in the previous section, the traditional approach to select CH has some associated challenges and issues that have a direct impact on the longevity and

performance of the network. In order to address these issues and challenges of a traditional method such as LEACH approach, we propose a method that utilizes trust based mechanism in order to select a CH [114]. According to the proposed method, a node having the highest trust value will most probably be selected as CH [115]. Additionally, proposed approach also uses K-means method to select the CH. The step by step methodology of the proposed approach may be given as follows:

- Step 1. Start
- Step 2. Initialization of the initial parameters viz. number of grids, network area, nodes in the network, initial energy for a node, packet size, and energy utilized to transfer per bit etc. once the network parameters have been initialized, network is deployed.
- Step 3. Once the network is deployed, it is segmented into 8 grids. Further, nodes in the network are uniformly distributed across grids and thus each grid has equal number of nodes in the network.
- Step 4. Further, it is followed by evaluation of direct trust among nodes.
- Step 5. After evaluation of trust factor, K-means clustering algorithm is utilized in order to select the CH. According to K-means algorithm, nodes are clustered on the basis of a particular criterion. According to the proposed method, the considered criterion is distance among nodes. Further, nodes for which average distance is less than a predetermined threshold are selected as CH. The equation for K-means clustering may be formalized as in equation (4.4) as follows:

$$\arg \min \sum_{i=1}^k \sum_{x \in S_j} \|xy_i - xy_j\|^2 \quad (4.4)$$

In this formulation,  $k$  indicates the number of nodes. Further  $xy$  represents the  $x$  and  $y$  coordinates of node.  $xy_i$  indicates the coordinates of node  $i$ . Once the mean distance is computed, it is followed by determination of threshold distance for the cluster. This is used to determine CH as the node located in the threshold region are promising choices for CH and hence are recommended for the same.

- Step 6: Thereafter, selection factor indicated by  $F(f)$  may be evaluated using the following weight function in equation (4.5).

$$F(f) = w_1 * \left(\frac{e}{d}\right) + w_2 * \text{trust value} \quad (4.5)$$

Here,  $w_1$  and  $w_2$  indicates the weight values. Here  $w_1 \in [0,1]$  and  $w_2 = 1 - w_1$ . Further,  $e$  and  $d$  represents energy and distance respectively.

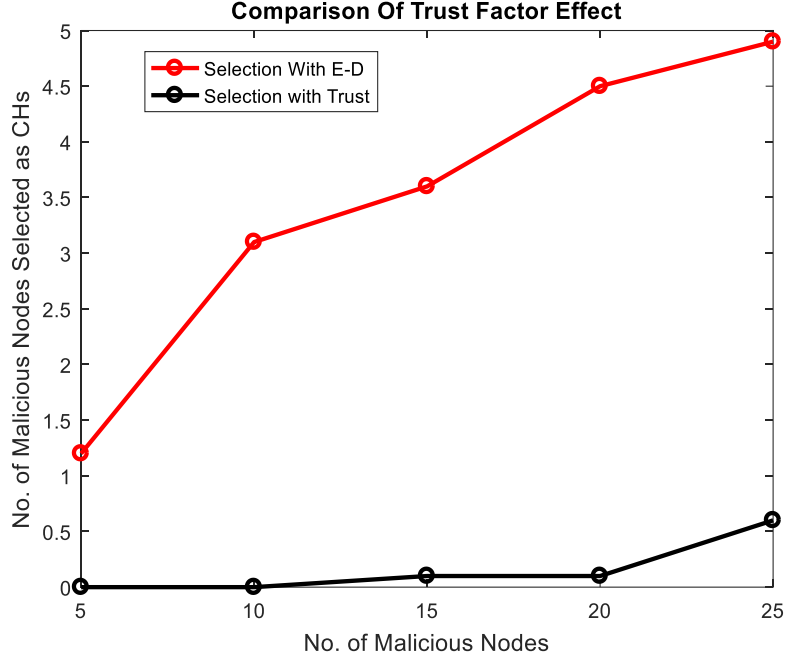
Step 7: Evaluation of fitness function is followed by selection of CH. For the same, the node having highest value of fitness value is selected as CH.

Step 8: Once the CH is selected, data transmission initiates among selected CHs and BS in the network.

Step 9: End.

#### **4.4.3 Impact of Trust Factor on Cluster Head selection**

After considering the various network performance metrics, let us understand the significance of trust factor in the proposed approach which is demonstrated in Figure 4.4. Here, Figure 4.4 illustrates the comparative analysis when a CH is selected using trust factor versus when trust factor is not considered. Here, black line represents the scenario when trust factor is considered during selection of CH while red line demonstrates the scenario when trust factor is not considered. From the Figure 4.4, it is evident that when trust factor is not involved, it has a huge probability of establishing malicious node as CH. On the contrary, consideration of trust factor as suggested in the proposed approach ensures that malicious nodes are rarely selected as CH [116]. Adopting a dependability enhanced trust approach for cooperation between CHs can effectively detect and prevent malicious, selfish and faulty CHs [117]. Trust factor is evaluated for each node in the network so as to prevent malicious nodes to become CH. Thus it maintains that only non-malicious nodes get involved in data transfer among source and sink



**Figure 4.4:** Impact of trust factor on CH selection

The mathematical formulation to evaluate the node's trust factor  $T_f(i, j)^l$  in equation (4.6) is as follows [117]:

$$T_f(i, j)^l = \gamma_1 \times P_j(i, j)^{l-1} - 1 + \gamma_2 \times N_j(i, j)^{l-1} + T_{lds}(i, j)^l \quad (4.6)$$

Here,  $P_j(i, j)^{l-1}$  represents the direct trust value of node of node  $j$  for node  $i$  based on node  $j$ 's past well-behaved behaviour, while  $N_j(i, j)^{l-1}$  is the direct trust value of node  $j$  for node  $i$  based on the nodes's  $j$ 's past malicious behaviour.  $\gamma_1$  and  $\gamma_2$  are constants. The  $T_{lds}(i, j)^l$  denotes the assessment for current behaviour of device  $j$  and is given in equation (4.7).

$$T_{lds}(i, j)^l = \begin{cases} P_j, & \text{for } 0 < P_j < 1 \\ 0 & \text{for uncertain} \\ N_j & \text{for } -1 < N_j < 0 \end{cases} \quad (4.7)$$

Here,  $P_j$  and  $N_j$  illustrates the previous positive and negative assessment for device  $j$ 's behaviour behavior of the node.

## 4.5 Results and Discussion

This section presents the results of the proposed approach. The proposed approach is implemented in MATLAB. Here, Table 4.3 enlists the parameters pertaining to the network used during implementation of the proposed approach.

**Table 4.3:** System Configuration Values

Parameters	Values
Network Area	100m x 100m
Total Number of Nodes	104
Initial Energy	0.2 J
Power amplification ( $\epsilon_{fs}$ )	10 pj/bit/m <sup>2</sup>
Power amplification ( $\epsilon_{mp}$ )	0.0013 pj/bit/m <sup>4</sup>
Transmitter/receiver Energy ( $E_{elec}$ )	50 nJ/bit
Base station location	(50, 50)
Number of Rounds	1200

Performance of the proposed work is evaluated in terms of various parameters, as follows:

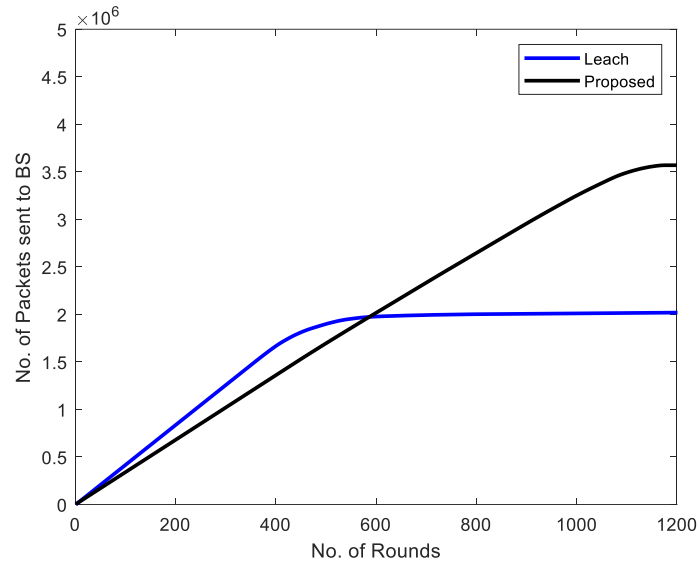
- the number of packets transmitted to the BS
- number of alive nodes
- energy consumption of the network
- throughput of the network
- packet delivery ratio of the network.

The considered parameters are evaluated and are compared with the traditional LEACH protocol. Here, it is worth noting that lifespan of a network refers to the time during which network is alive and does not terminate. Although, in the literature, network lifespan is also considered as the elapsed time between termination of first and last node. Irrespective of the definition of network lifetime, elongated network lifetime is always preferred as it leads to escalated transmission [118]. The comparative analysis of various parameters has been given in the following subsections.

### 4.5.1 Number of Packets Transmitted in the Network

Figure 4.5 illustrates the state-of-the-art value for number of packets sent to the BS. Figure. 4.5 illustrates that the number of packets transferred to BS is higher in the proposed method when compared with LEACH method. For a few initial number of rounds, the number of packets transmitted to the BS is nearly similar in both

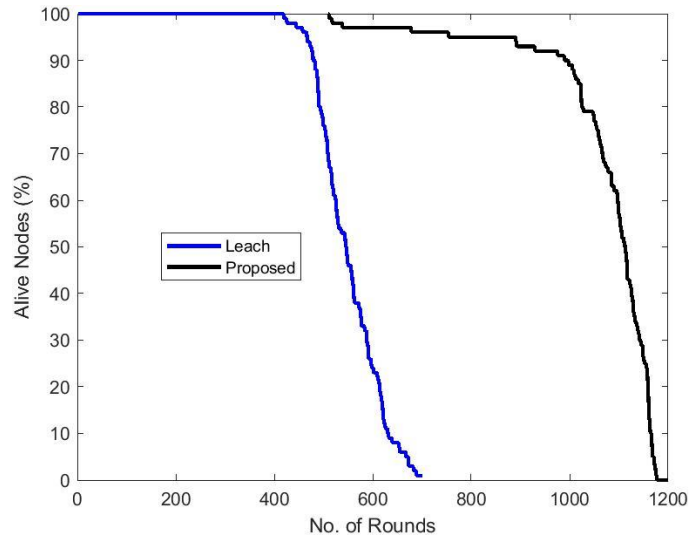
approaches and hence the improvement is not evident. However, when the number of rounds increases, data transmission shows an improvement for proposed approach when compared with traditional method. Thus the outperformance of proposed approach becomes apparent when number of rounds increases beyond a certain limit.



**Figure 4.5:** Comparison of the number of packets transmitted to the BS with respect to the communication rounds

#### 4.5.2 Number of Alive Nodes in the Network

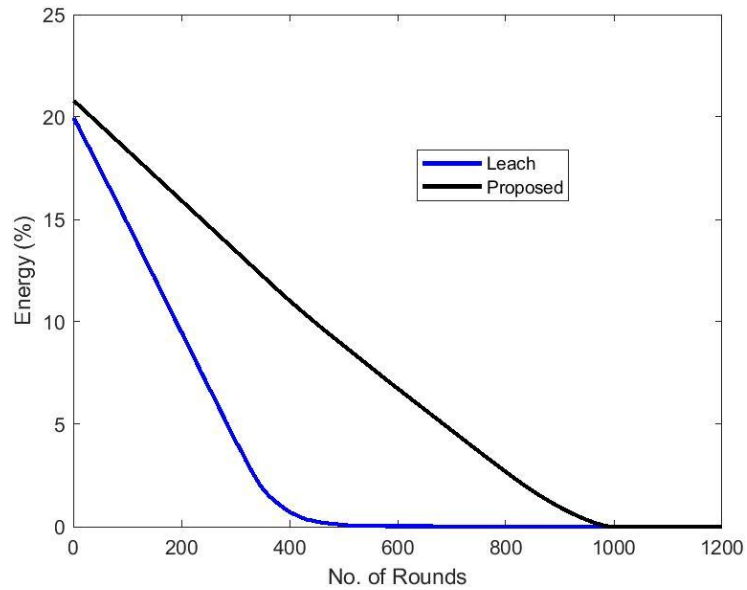
Figure 4.6 illustrates the number of alive nodes in the network for the traditional LEACH method and the proposed method. From the Figure 4.4, it is evident that increased number of live nodes leads to longer network lifetime. From the obtained results, it is clear that the number of live nodes in the proposed method is higher than the traditional LEACH procedure which establishes the supremacy of the proposed approach.



**Figure 4.6:** Comparison of alive nodes with respect to the communication rounds

### 4.5.3 Energy

Energy is undoubtedly the prime resource for survival of nodes in a wireless sensor network. Hence, each node utilizes a portion of energy during transmission of data to the destination node. In an ideal scenario, this energy utilized for data transmission should be low so as to have an elongated network lifetime. Elongated network lifetime enables transfer of more information for a longer duration. The comparative analysis of energy consumption of proposed approach with LEACH method is illustrated in Figure 4.7. The Figure 4.7 clearly illustrates that energy in traditional network get exhausted after approximately 500 rounds of communication. On the other hand, it can perform communication for around 1000 rounds in the proposed approach. This outperformance in terms of energy consumption is an exciting aspect of proposed approach.



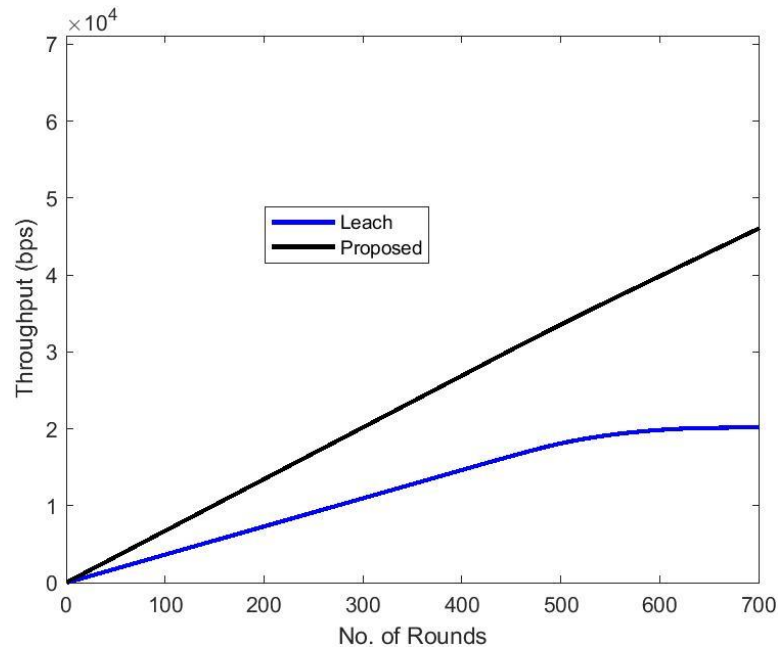
**Figure 4.7:** Comparison of network energy with respect to the communication rounds

#### 4.5.4 Throughput

Figure 4.8 demonstrates the comparative analysis of throughput for proposed and the traditional LEACH approach. Throughput of a network may be defined as the average data delivered during each round, generally calculated in terms of bits per round. The mathematical formulation for throughput can be considered as shown in equation (4.8).

$$\textit{Throughput} = \frac{\textit{Amount of data delivered in bits}}{\textit{Number of rounds}} \quad (4.8)$$

From Figure 4.8, it is visible that the throughput is higher in proposed approach when compared with LEACH approach. It is calculated in bits per round. The network throughput is determined from the formula below:



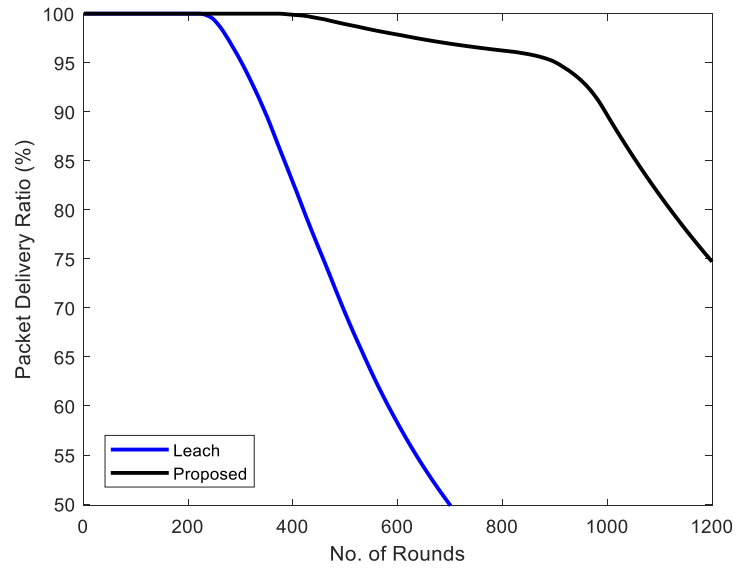
**Figure 4.8:** Comparison of throughput with respect to the communication rounds

#### 4.5.5 Packet Delivery Ratio (PDR)

Packet Delivery Ratio (PDR) may be defined as the ratio of packets received by sink node to the number of packets sent from source. Thus, the mathematical formulation for PDR can be given as in equation (4.9):

$$PDR = \frac{\text{Total data packets received by the target}}{\text{Total data packets sent by the source}} \quad (4.9)$$

The comparative analysis of PDR for the proposed approach and traditional LEACH method is given in Figure 4.9. From Figure 4.9, it is clear that during initial few rounds of communication, the PDR for both are somewhat similar and high. However, when the number of communication rounds increases beyond a certain limit, a quick drop is noticed in the PDR of LEACH in comparison to the proposed method which establishes the effectiveness of proposed method.



**Figure 4.9:** Comparison of packet delivery ratio with respect to the communication rounds

#### 4.6 Conclusion

This chapter presents a novel cluster head selection based on direct trust and K-means clustering to outperforms the traditional LEACH approach. The proposed method segregates the network into grids and each grid is assigned the same number of nodes. A fitness value based on distance, energy and a trust value is calculated for all the nodes and the node with the highest value is chosen as CH. The presented work employs a novel parameter called trust quality. The simulations are done to establish the efficacy of the proposed model and it is found that the proposed methods outperform the traditional LEACH approach with respect to all the performance metrics. The presented work is extended to achieve reliable routing protocol. This work has been proposed with static nodes and BS at centre. Furthermore this study has the limitation of mobile nodes and mobile base station. Where BS will be away from the sensing field.

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# Network lifetime Improvement through Energy-efficient Hybrid Routing Protocol for IoT Applications

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M. Mishra, G. S. Gupta, and X. Gui, “**Network lifetime improvement through energy-efficient hybrid routing protocol for IoT Applications,**” *Sensors*, vol. 21, no. 22, p. 7439, 2021.

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### 5.1 Routing protocols and network lifetime

Application of Internet of Things (IoTs) in Wireless Sensor Networks (WSNs) poses serious challenges in preserving the network longevity, since the IoTs necessitate a considerable amount of energy usage for sensing, processing, and data communication. As a result, there are several conventional algorithms that aim to enhance the WSN network performance by incorporating various optimization strategies. These algorithms primarily focus on network layer by developing routing protocols to perform reliable communication in an energy efficient manner, thus leading to the enhanced network life. For increasing the network lifetime in WSNs, clustering has been widely accepted as an important method that groups sensor nodes (SNs) into clusters. Additionally, numerous researchers have been focusing on devising various methods to increase the network lifetime. The prime factor that helps to maximize the network lifetime is minimization of energy consumption. Authors in this paper propose a multi-objective optimization approach. It selects the optimal route for transmitting packets from source to sink or Base Station (BS). The proposed model employs a two-step approach. The first step employs a trust model to select the Cluster Heads (CHs) that manages data communication among BS and nodes in the cluster. Further, a novel hybrid algorithm, combining Particle Swarm Optimization (PSO) algorithm and Genetic Algorithm (GA), is proposed to determine the routes for data transmission. To validate the efficacy of the proposed hybrid algorithm, named PSOGA, simulations were conducted, and results were compared with the existing LEACH method, and PSO with random route selection for five different cases. The obtained results establish the efficiency of the proposed approach as it outperforms existing methods with increased energy efficiency, increased network throughput, high packet delivery ratio and high residual energy throughout the entire iterations.

Wireless sensor network (WSN) is a collection of small sensing devices (nodes) that performs communication with other devices through wireless channel. The prime characteristics of SNs in WSN are low cost, small size, low computational power, communication within short distances, and multifunctional abilities like sensing, routing, and data processing, [119]. The processing capabilities of the SNs includes sensing data from the environment and communicating the collected data to the BS [120]. This transmission of data among the SNs and the BS requires energy to be expended. Many a times the energy consumed is more than the actual energy requirement as there may be wastage of energy due to various factors. An example of a factor that causes wastage of energy is transmission of redundant data [121]. Further, transmission of data between the SNs and BS may get demanding in case of larger geographical area owing to hostile nature of the environment [122-123]. Furthermore, the energy consumption may also vary significantly in single or multi-hop communication [124]. To address these issues, hierarchical routing and clustering of SNs has demonstrated proven competence to enhance the lifetime of the network [125]. The selection of CHs further reduces the energy consumption as it collects data from the cluster members (CMs) and forwards the same to BS through the CH [126]. In general, most of the modern IoT devices are faster in data collection and hence require faster data processing and transmission to the BS [127].

The routing protocol aims to select the optimal path for data transmission, which is a challenging task. Selection of an optimal path highly depends on the various network parameters viz. channel characteristics, network type and performance metrics [119]. In smaller IoT networks, BS and SNs are in closer proximity and hence communication may take place directly in a single hop. On the contrary, the communication in large-scale IoT networks uses multi-hops, as direct communication with BS may not be feasible. This can be attributed to many reasons: radio power, bandwidth, energy, and memory [120]. Hierarchical Routing algorithms aim to enhance the network throughput and lifetime of WSN in various geographical deployments. However, it may achieve energy efficiency only to a limited extent, which motivates the authors to present a cluster-based optimization, centralizing on energy efficiency, scalability, complexity, and robustness. Additionally, the efficacy of hierarchical clustering approaches can be further enhanced using Particle Swarm Optimization-Genetic Algorithm, a multi-objective optimization model.

Optimization of network lifetime is a challenging and vital issue in WSN and thus has grabbed attention of various researchers as it is required in order to conserve energy [128-129]. According to some researchers, network lifetime can be considered as the elapse when the first sensor node loses all its energy in the network. In order to optimize the network lifetime, researchers have been working in the direction of optimizing various parameters viz. hop count, path reliability, and energy consumption etc. This chapter attempts to improve routing protocol through optimization of network lifetime, hop count and reliable path. In the proposed approach, authors use factors such as residual energy, hop count and reliable path to the sink in order to maximize network lifetime. The performance of the proposed approach is validated in terms of various metrics such as packet delivery, throughput, and energy consumption etc.

This chapter proposes a new technique for selecting CH by evaluating the trust value and energy of each node. Additionally, the K-means clustering algorithm is employed for CH selection to conserve the energy of nodes in a network. This is to ensure that the recently selected CH will not be compromised when deployed in an open environment due to malicious intrusion or changes in the physical node. To validate our technique, we have simulated CH selection based on trust and compared it with traditional CH selection based on energy and distance.

The outline of the chapter is as follows: Section 5.2 presents the related works.. Section 5.3 discusses proposed methods and techniques. Section 5.4 demonstrates the network energy model and energy consumption model. Section 5.5 discusses the proposed hybrid model for path calculation. Section 5.6 elaborates network setup. Section 5.7 compares the results of proposed PSOGA model with the PSO and LEACH protocol. In the end, the chapter concludes the entire work with possible avenues of future research.

## 5.2 Related Work

Numerous authors have undertaken research in the direction of devising effective routing for WSNs. This section presents some of the prominent results and findings by such researchers in the related domain.

Anees, J., et al. [130] suggested a Delay Aware and Energy-Efficient Opportunistic Node Selection in Restricted Routing (DA-EEORR). Authors claim the suggested model to be novel and suitable for delay-sensitive environment. The proposed model attains a promising balance between energy consumption and average end-to-end delay by finding an optimal path. The model uses the idea of an Opportunistic Connection Random Graph (OCRG) to select the next hop. OCRG is further used to calculate optimal path connectivity using factors like transmission frequencies, residual energy, and link quality etc. The concept of restricted research space is also employed in the proposed model to find the minimum distance next-hop node. The simulation findings advocate that the proposed method outperforms the current standards. This outperformance of the suggested approach is witnessed in terms of network lifespan, power usage, overhead of control packet and packet delivery ratio. Most of the findings show only a marginal improvement since the study focuses more on path correction and tracking of routes rather than establishing optimal path in hierarchical network. Thus, the proposed work achieves a great balance between energy consumption and end-to-end delay, however the work can still be extended further in the direction of incorporating multiple sink nodes to realize realistic delay sensitive applications.

The authors in Ullah, F., et al. [131] have presented research on optimal route selection in wireless Body Area Network (WBAN). WBAN is a network of miniaturized wearable sensing and computing devices which communicate the sensed data around the human body, and hence has been excessively used in remote patient monitoring, sports activity monitoring etc. It may be used to monitor vital physical parameters such as Electro-Cardiograph (ECG), and Electro-Encephalography (EEG) etc. Now, as WBAN are resource constrained, it necessitates efficient and energy efficient routing mechanisms. Authors in [131] propose an Energy-Efficient and Reliable Routing Scheme (ERRS) to increase reliability and resource stability in WBAN. To achieve this, the suggested approach implements two solutions viz. selection of forwarder node and rotation of forwarder node. ERRS employs adaptive static clustering routing to achieve enhanced stability period and prolonged network

life. During the simulation of the proposed approach, it is observed that EERS achieves an improvement of 26% over the established protocols. The performance of EERS is measured in terms of throughput and network stability. Additionally, it achieves an improvement of 17% and 40% in terms of end-to-end delay over Stable Increased Throughput Multi-Hop Protocol for Link Efficiency (SIMPLE) and Mobility Supporting Adaptive Threshold Based Thermal Aware Energy-Efficient Multi-Hop Protocol (M-ATTEMP) protocol respectively, establishing the supremacy of the proposed algorithm. Although the work has given an efficient solution for WBANs during simulation, motivating the researchers, however scalability and mobility remains a challenge that needs to be addressed in order to have its real-life and widespread deployment.

Similarly, the authors in [132] also employ an energy-efficient dynamic clustering technique to organize nodes in WSNs. The model estimates the count of active nodes using signal received from neighbouring nodes. Also, it computes the probability of an active node to become a CH based on energy requirement for inter-cluster and intra-cluster communication. The objective of the model is to maximize the network life. The simulation of the proposed approach demonstrated that the clustering method has the ability to scale well for large-scale WSNs also. The authors aim to extend the work by evaluating the application feasibility of proposed technique to general WSNs. Similarly the work has been extended in [133] for cloud-assisted Mobile Ad-Hoc Networks (MANETs) in 5G.

The need for longer network lifetime and fast data transmission for unattended time-sensitive nodes is also recognized by Maurya, S., et al. [134]. Here, authors claim that most of the routing approaches for such applications rarely consider all related issues like network traffic, loss of packets, and energy consumption at once. Another associated challenge mentioned by authors is the consideration of homogeneous sensor network while real-life deployments need to handle heterogeneous nodes. To address these challenges, authors in [134] have proposed a novel Delay Aware Energy Efficient Reliable Routing (DA-EERR) technique that considers heterogeneous nodes. The proposed approach defines a restricted search space to ensure timely delivery of time-sensitive data. Thereafter, an algorithm selects an energy delay balanced path between source and sink within the search space to ensure fast communication. The suggested approach attains an improve-ment in successfully receiving data packets at

sink in large networks. The proposed routing method achieves significant improvement over comparative models for large and densely deployed networks. However, for smaller and sparse networks, the proposed approach will introduce control packet overhead that may cause quick cessation of ring node, thus limiting the application of the proposed approach to large networks only.

The authors in [126] have addressed the obstruction of energy constraints in wireless sensor networks as a motivating factor for rigorous research in the direction of developing energy efficient routing protocols. Here, authors attempted to propose a new protocol namely Equalized CH Election Routing Protocol (ECHERP) that conserves energy using balanced clustering. The proposed model uses the Gaussian elimination algorithm to evaluate the node combination to select the CH. The comparative evaluation of the pro-posed model establishes its effectiveness over standard protocols in terms of energy efficiency. Similarly, the authors in [135] also employ an energy-efficient dynamic clustering technique to organize nodes in WSNs. The model estimates the count of active nodes using signal received from neighbouring nodes. Also, it computes the probability of an active node to become a CH based on energy requirement for inter-cluster and intra-cluster communication. The objective of the model is to maximize the network life. The simulation of the proposed approach demonstrated that the clustering method has the ability to scale well for large-scale WSNs also. The authors aim to extend the work by evaluating the application feasibility of proposed technique to general WSNs.

From the above studies done by various researchers, it is evident that significant research is taking place in the direction of energy efficient routing in various network models. Among the various approaches, clustering has demonstrated its competence in achieving energy efficiency and thus has motivating the authors to pursue research in this direction.

### **5.3 Proposed Methods and Techniques**

This section details system model employed for the proposed approach. As in the traditional LEACH protocol, nodes are casually deployed in the environment without defining any particular areas. In fact, the probability of a node being selected as a CH is equal. A node with little energy or a node farther away from the BS may be selected as CH. For such scenarios, the node selected as CH will have its energy storage

depleted very quickly and this will result in the reduction of the network lifespan. A cluster head possibly gets an uneven number of nodes that result in the high load over the cluster head and high usage of energy. Thus, it decreases the network lifetime. We are proposing a network divided into eight equal grids in which the same number of nodes are clustered and distributed. This allows the network to build the cluster heads according to the number of grids and the load on the cluster heads is also minimized as there is an equal number of nodes present in each grid. The lower load will consume less energy, so the network will be able to live longer.

### 5.3.1 PSO Algorithm-Based Routing

PSO is a stochastic algorithm based on optimizing a candidate solution (or particle) [136-139]. It is a competent method used in numerous domains like architecture, research, education etc. Owing to the proven effectiveness of PSO due to its efficiency, robustness, simplicity, and extreme ease of use, it is suited for various optimization problems [140]. PSO particles travel in swarm inside a search space to find the optimum swarm solution by updating its location and speed as shown in Figure 1.

In PSO, the swarm refers to the population and particle of the swarm corresponds to the solution. During flight process, each particle moves in the problem space with velocity that depends upon its previous position and best position of the swarm. Now consider  $x_i$  and  $v_i$  are the position and velocity of the  $i^{th}$  particle where the swarm has  $N$  particles. Here, particle  $i$  with a set of solution is generally represented as  $X_1 = (X_{i1}, X_{i2}, X_{i3} \dots X_{iN})$ . The position and velocity update of each particle during subsequent iterations is shown by following equations (5.1-5.3) [139]

$$x_{i,m}(t) = x_{i,m}(t-1) + v_{i,m}(t-1) \quad (5.1)$$

$$v_{i,m}(t) = w * v_{i,m}^{(t)}(t-1) + c_1 * rand1() * (pbest_{i,m} - x_{i,m}(t-1)) + c_2 * rand2() * (gbest_m - x_{i,m}(t-1)) \quad (5.2)$$

Here,  $m$  is the dimension of the solution space.  $rand1()$  and  $rand2()$  are the stochastic variables with uniform distribution and these variables are considered as independent functions i.e.  $rand1(), rand2() \in [0,1]$ .  $c_1$  and  $c_2$  are the positive constants that refer to cognitive and social constant respectively.  $pbest_{i,m}$  is the best position that depends on the minimum path buffer, network lifetime and hop count with  $m$  solutions that is

attained using the neighboring particles. Further,  $gbest_m$  indicates the global optimal. PSO can also be employed for routing in WSN by performing the following mathematical operations:

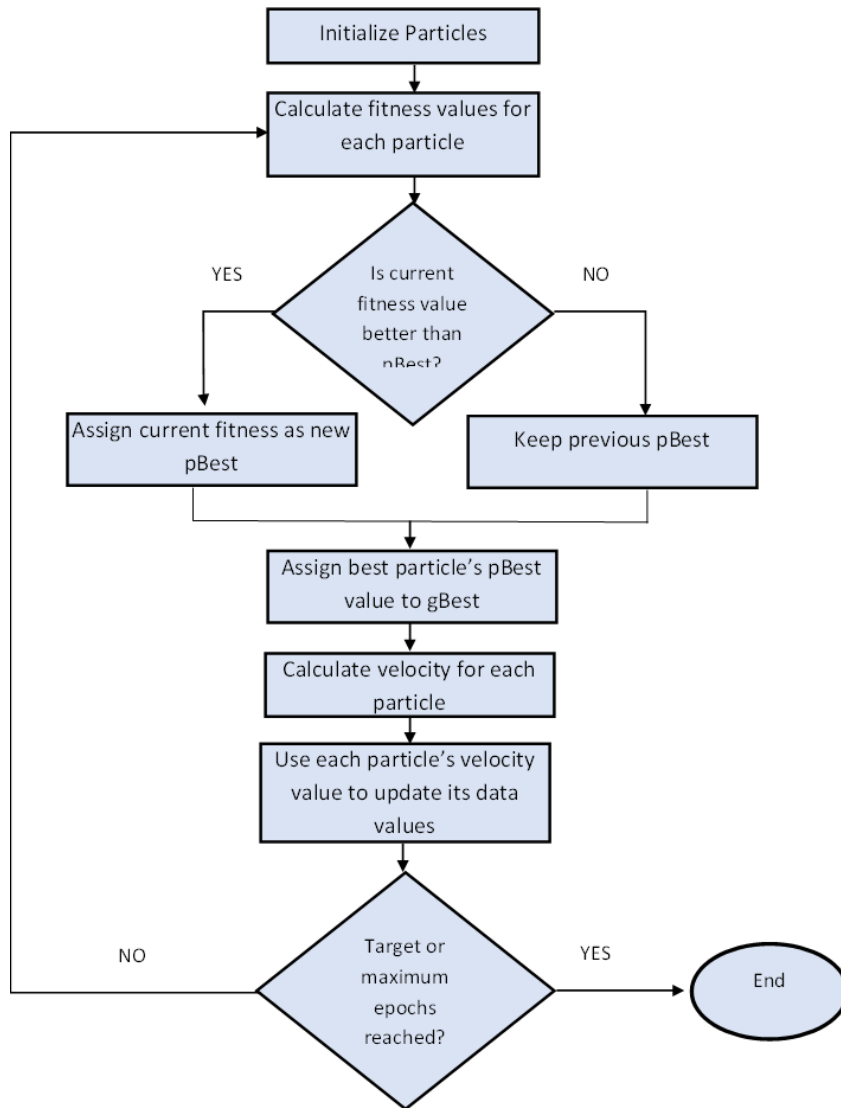
**Particle Representation:** A string of cluster heads is used to represent a particle that represents a feasible route in a swarm. Here, CH has a significant contribution to initialize route during swarm initialization. BS generates a list  $M_i$  having all single hop cluster heads  $j$  for cluster head  $i$ . There must be a communication link from  $i$  to  $j$ .

**Fitness Function:** For each particle that represents a route, the fitness function is computed indicating the maximum lifetime of WSN. A WSN is alive until the energy of each CH along the route is exhausted. Fitness function  $L$  may be defined as [139]

$$L = \frac{P_{initial}}{P_{max}} \quad (5.3)$$

Here,  $L$  indicates the network lifetime in terms of number of rounds.  $P_{initial}$  and  $P_{max}$  refer to the initial energy and maximum energy respectively used during each round of communication.

**Velocity:** Velocity illustrates a binary operation which generates a new position for a cluster head. For instance, velocity (1,6) implies that the position of CH 1 will be updated to 6.



**Figure 5.1:** The flowchart of the PSO Algorithm

**Position plus Velocity:** if  $x$  and  $v$  indicate the position and velocity respectively, the addition operation may be performed as follows [139]:

For instance

$$x = (2, 7, 7, 4, 3, 5, 8)$$

$$v = (1, 6)(5, 5)$$

on performing  $x + v$ , for (1,6) the new position of CH 1 will be 6 thus giving results (6,7,7,4,3,5,8). Further, after applying velocity (5,5) we get (6, 7, 7, 4, 5, 5, 8)

**Position minus position:** Minus operation for position produces a velocity. Suppose route  $r_1 = \{2,4,5,6,8,8\}$  and  $r_2 = \{2,6,5,7,8,8\}$  then minus operation indicates the replaced cluster heads and is  $((4,6), (6,7))$ .

**Velocity plus Velocity:** The addition of velocity  $v_1$  and  $v_2$  refers to the list of transpositions of CH in  $v_1$  followed by those in  $v_2$ . During addition of velocity, the id of CH never has a copy in resultant velocity.

**Coefficient times velocity (Multiplication):** Consider  $m$  and  $v$  represent the coefficient and velocity respectively. Here, velocity  $v = (i, j) | i \in \{1, 2, \dots, N\}$ . Now,  $m$  times  $v$  yields another velocity  $v' = (i, j) | i \in \{1, 2, \dots, N\}$  and  $j \in N_i$  (neighbor of CH  $i$ ).

### 5.3.2 Genetic Algorithm-Based Routing

GA is a search-based optimization approach that employs the principle of genetics and natural selection [141-143]. It is often used to provide optimal or suboptimal solutions to challenging real life problems that might take a longer time to resolve. Steps performed for applying GA in solving energy optimization problem in WSN are given as below:

<b>Algorithm:</b> Genetic Algorithm
<p><i>Step 1:</i> Initially, the chromosome is encoded in an efficient manner.</p> <p><i>Step 2:</i> In order to maximize network lifetime, the individual with the highest value of fitness function is taken in upcoming generation.</p> <p><i>Step 3:</i> The mating pool of good individuals is created through selection.</p> <p><i>Step 4:</i> Among the pools of good individuals, two parents are selected to exchange their genes to create new offsprings. The newly created offsprings are expected to have better fitness value over parents [130].</p> <p><i>Step 5:</i> Mutation is also employed to achieve diversity in offsprings generated during Crossover</p>

### 5.3.3 PSO-GA-Based Routing Algorithm

The Genetic Algorithm uses its individuals to find the local solution that feeds the PSO. The PSO is allowed to find only the global solution, since the process of finding the local solution i.e. local best is found by GA. The main aim is to reduce the premature convergence by the PSO that falls in local optima. Hence, to obtain matured solution, the study considers mainly the formation of local solution by the genetic individuals or chromosomes. Here each individual represents a potential solution. Further in GA, each particle is regarded as an individual chromosome and the swarm refers to the entire population.

PSO-GA starts with the process of generating random individuals that considers the total iterations as a parameter for the algorithm. The population aims at providing solutions to the route planning and the solution is considered in a distributed manner over the whole IoT network. The initial population is allowed to pass through the GA at its initial iterations. This helps in reducing the route selection score as the GA performance entirely depends on encoding the solutions in particles and chromosomes. Also, it considers the measurement of fitness function, population size and total number of iterations. Such parameters are adjusted after the evaluation of GA on initial trails. The PSO starts its operation after obtaining the local solutions by GA during initial iterations. The PSO uses particles to find the global solutions that represents the overall solutions in finding the optimal routes. The steps are enlisted below:

<b>Algorithm:</b> Particle Swarm Optimization
Step 1: Initialize a swarm of particles with random position and zero velocity
Step 2: Evaluate objective value of particles
Step 3: Evaluate fitness function for each particle
Step 4: Determine the local and global best
Step 5: Till the termination condition is reached Update velocity and position of each particles Update local and global best
Step 6: Arrange individuals in decreasing order of fitness value and find $M$ best particles
Step 7: GA Evolution Reproduce $Pop\_size-M$ (performing subtraction), GA individuals Implement crossover and mutation operators to create $Pop\_size-M$ particles

Step 8: Combine and form  $Pop\_size$  individuals

Step 9: End

Application of PSOGA is followed by updating the  $V^*$  (refer Table 1). Further, equation 4 is used to evaluate the route score followed by Zig-Zag scan that starts at upper-left corner of the grid. It sequentially scans the diagonals of the grid to determine the route score. Once the evaluation has been done, CH communicates the same to the neighbouring grid. The same pattern is followed subsequently for the remaining grids.

#### 5.4 Network and energy model

This section presents the models employed for the research work. Initially, the system model is presented which discusses the necessary assumptions that have been made. Further, the energy consumption model based on first order radio model for transmission and reception is presented. Subsequently, the proposed network model is also presented.

##### 5.4.1 System Models and Assumptions

In this section, the study considers a two-dimensional network model [144] with sensor nodes, considering the assumptions given below:

- All sensor nodes are considered stationary.
- Study assumes one BS where the data collected from source IoT nodes are destined for [145].
- Homogeneous SNs with similar processing and communication capability. Also, it considers that SNs are deployed with the same initial energy.
- SNs deployed randomly are always located with its x and y coordinates in the topological area.
- The distance between the two neighbouring SNs is evaluated using Euclidean distance.

##### 5.4.2 Energy Consumption Models

The study uses a first order radio model as the energy consumption model for the purpose of transmission/reception of messages of the same length, say,  $n$ -bits. This model computes energy consumption  $E_i(d)$  for transmission of IoT nodes during one

round. The energy consumed to transmit  $n$ -bits data to a node located at a distance  $d$  (using Euclidean distance metric) is estimated as follows in equation (5.4) [126] :

$$E_{tx}(d) = \left(\frac{n}{r}\right) (\Phi_{amp}d^\alpha + \Phi_{cir}) \mid \alpha = \begin{cases} 2, d < d_{cr} \\ 4, d > d_{cr} \end{cases} \quad (5.4)$$

where,  $\Phi_{cir}$  represents the power consumption during the operation of the transmitter circuit, and  $\Phi_{amp}$  is the power consumed by amplifier.  $\alpha$  is the exponent indicating the path loss component with the range  $[2, 4]$  and  $d_{cr}$  is the cross over distance based on free path loss and multipath loss. Here,  $\alpha$  is 4 and 2 for multi-path loss and free path loss respectively. The consumption of energy at the receiving node at rate  $r$  depends entirely on the operation of the circuit, which is represented as follows in equation (5.5):

$$E_{rx}(d) = (n/r)\Phi_{cir} \quad (5.5)$$

Thus, for an intermediate sensor node  $i$  at a single hop distance, the energy consumption  $E_i(d)$  for transmission and reception for relaying over the distance  $d$  is given as shown in equation (5.6)

$$E_i(d) = E_{tx}(d) + E_{rx}(d) = \left(\frac{n}{r}\right) (\Phi_{amp}d^\alpha + 2\Phi_{cir}) \quad (5.6)$$

### 5.4.3 Proposed Network Model

The details of the proposed model are given below:

*Step 1:* All the SNs are static in the network.

*Step 2:* Initial step is to define the network dimensions; the proposed model will be having  $A \times B$  dimensions.

*Step 3:* The network area will be split into multiple grids or block clusters. In our model, it can be  $2 \times 4 = 8$  grids clusters (comprising of 100 nodes),  $4 \times 4 = 16$  grids clusters (comprising of 100 and 200 nodes) and  $10 \times 10 = 100$  grids clusters (comprising of 625 and 1250 nodes).

*Step 4:* A CH for each grid is selected by using the concept of trust model [147].

*Step 5:* Then all the SNs in a particular grid sense the environment and transmit the sensed data to the CH.

*Step 6:* The path between CHs towards sink will be generated by considering the paths between adjacent grids in a zigzag fashion. Zigzag fashion basically divides the area of interest into numerous Zigzag patterns so that each pattern has line segments and corners and each node is deployed in the corner of the Zigzag pattern. Zigzag pattern enables high coverage efficiency of 91%. Also, it helps to cover the whole area of interest using minimum number of nodes, thus generating minimum coverage redundancy [150]. The score of each route is calculated using the Score equation (5.7) [148], where the weight factors are designated to assign the weights to the subcomponents and are configured as  $\alpha+\beta+\gamma+\delta = 1$ .

$$Score(P) = \omega\alpha + min.buffer(p)\beta + \left(\frac{1+maxHC-HC(P)}{maxHC}\right)\gamma + \left(1 - \frac{no.DelayedPkts}{totalPkts Recv}\right)\delta \quad (5.7)$$

The first component ( $\omega$ ) of equation (5.7) refers to the energy consumption on a particular path P and is calculated using equation (5.8).  $\omega$  is calculated from the energy consumed on a particular path till a critical point in the network and afterwards it calculates the value from the energy reserve along the path. The critical point in the network ( $\Omega$ ) is preset and normally considered as 20% of the initial energy. If the minimum energy on the path  $min.energy(P)$  is less than  $\Omega$ , the component  $\omega$  is calculated from power consumed along the path  $P_w(P)$ , otherwise it is evaluated from the energy reserve in the path and is calculated using equation (5.9).

$$\omega = \begin{cases} min.energy(P), & min.energy(P) < \Omega \\ P_w(P), & min.energy(P) \geq \Omega \end{cases} \quad (5.8)$$

The power consumption,  $P_w(P)$ , is calculated from equation (5.9), otherwise it is equal to the minimum remaining energy calculated along path P.

$$P_w(P) = \sum_{d \in P} E_{tx}(d) + \sum_{s \in P} E_{rx}(d) \quad (5.9)$$

$E_{tx}(d)$  and  $E_{rx}(d)$  are average power consumed during transmission and reception by the node along path p and calculated from equation (4) and equation (5) respectively.

The second component ( $min.buffer(p)$ ) of equation (5.7) represents the minimum buffer of a node along the path  $P$  [149].

The third component,  $\frac{1+maxHC-HC(P)}{maxHC}$  of equation (5.7) estimates the number of hop counts.  $maxHC$  is the maximum hop count allowed in the network, whereas  $HC(P)$  is the hop count of the calculated path.

Finally,  $1 - \frac{no.DelayedPkts}{totalPktsRecv}$  is the fourth component in equation (5.7) which calculates the reliability of the path, i.e., the ratio of packets delivered to the BS without delay to the total packets received.

*Step 7:* Once the scores are calculated for the current set of solutions, the solution with the best score is saved and the same method is followed for each CH in the network.

*Step 8:* Later the optimization algorithm will process all the iterations and select a final route to transfer data from CH to the BS

## 5.5 Proposed Hybrid model for path calculation

The proposed algorithm works on two important criteria: selection of cluster heads using the trust mechanism and secondly finding the routing path using PSOGA Algorithm. The Selection of cluster head using Trust based mechanism is given in section 4.4 and the set of routing paths using PSOGA is given in section 4.3 The parameters used in the algorithm description are given in Table 5.1:

**Table 5.1:** Parameters used in the proposed PSOGA algorithm

Parameter	Description
$Ir(N_i)$	Information register having information of individual node $N_i$ in the network
A	Area
$N_i$	Node i
$L_s$	Sink Location
$N_s$	Number of grids in a network
$F_{ch}$	Farthest CH
S	Network sink
$V^*$	set of random routes of a grid to adjacent grids in the network for example from farthest CH to sink from ( $F_{ch}$ to S)
BestScore	Best Route score

$N_a$	All nodes in route
$R_{score(i)}$	Global route score
Score <sub>(i)</sub>	Individual Route score
$G_{BestScore}$	Global best score
$L_{bestScore}$	Local best score

The algorithm for the proposed model is given below:

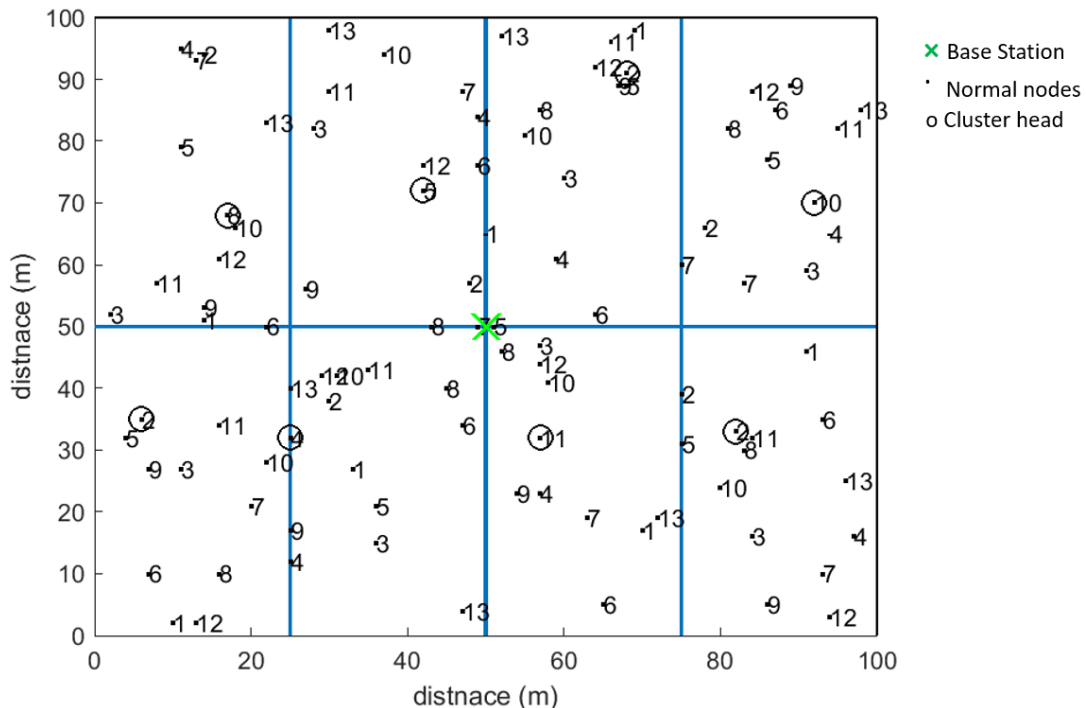
<p><b>Algorithm:</b> Proposed Trust-based PSOGA</p> <ol style="list-style-type: none"> <li>1. For <math>i=1</math> to number of grids While <math>Fch \neq S</math> Generate <math>V^*</math> using zigzag method</li> <li>2. <math>BestScore=0</math>;</li> <li>3. For <math>it = 1</math> to <math>Max\_Iterations</math> For <math>i=1</math> to rows (<math>V^*</math>) Temp=<math>V^*(i, N_a)</math> For <math>j=1</math> to length(Temp) For <math>k=Temp(j)</math> extract score factors from <math>Ir(N_i)</math> End for  End for <math>R_{score(i)} = Score_{(i)}</math>; // from equation 4 calculated End for <math>G\_BestScore, index = \max(R_{score})</math>; if <math>L\_BestScore &gt; G\_BestScore</math> <math>G\_BestScore = L\_bestScore</math> ; <math>SelR = V^*(index, :)</math>; End if Update <math>V^*</math> using PSOGA Algorithm End for End while End for</li> <li>4. Perform Communication between CH to sink using selected final route</li> <li>5. Evaluate Network performance</li> <li>6. Stop Algorithm</li> </ol>
--

In the proposed algorithm, step 1 generates the random routes for each grid in the network. The process of determining random route continues while the farthest CH is not equal to the sink node. Step 2 initializes the best score to 0. Step 3 updates the path  $V^*$  determined in step 1. For this, it uses the concept of local score and global score. Step 4 initiates communication from CH to sink node through the path obtained in step 3. The performance of the network is evaluated as per step 5 to obtain the performance metrics such as longevity of nodes, network lifetime, packet delivery ratio and throughput etc. The most prevalent genetic algorithm (GA) and swarm intelligence

technique (PSO) benefits are taken into account for getting better convergence and path to improve the network lifetime.

## 5.6 Network Setup

In the simulation, authors have used multi-hop networks with various numbers of homogenous sensor nodes. The region under consideration is rectangular which is divided into number of grids. The BS is located at the centre or at one of the edges. A rectangular grid of sensor nodes is used for relaying packets and the model for transmission is considered to be fixed power transmission. In this scenario, authors have simulated different routing approaches namely PSOGA (Proposed), LEACH and PSO. Simulation of different approaches enable authors to establish the efficacy of proposed approach vis a vis state-of-the-art method. As per the proposed method, Sensor nodes are assumed to have initial energy and the BS has unlimited energy. BS also has the knowledge of deployed nodes. The basic structure of network is shown in Figure 5.2 where number circled in each grid represents the CH and the green cross mark represents BS.



**Figure 5.2:** Grid Formation in WSN

This grid-based approach is popularly known for its features namely uniformity in energy consumption, scalability, and simplicity [146, 147, 148 ]. However, there are some major challenges associated with grid-based approach such as determination of

optimal number of grids for a particular scenario, non-uniform grid size, and improper selection of CH [149]. These challenges further worsen owing to the dynamic behaviour of WSN. The authors in this paper primarily focus to develop a robust model that can handle various issues like heterogeneity in node density, deployment area and grid size [150, 151, 152].

The applicability of our strategy is immense, for example, vast horticultural fields where environmental parameters such as atmospheric temperature and humidity, soil moisture, soil temperature, and soil pH are to be measured [153]. In addition, it can be applied to any event detection application such as wildfire detection and seismic monitoring. Apart from these it can also be used in structural health monitoring where parameters such as humidity, temperature, stress and strain are required to be measured [152]. In several of these above scenarios it is cost effective to use non-rechargeable nodes.

In real-life deployments, the geographical area may not be rectangular. Our thinking is that a rectangle can be fitted to any irregular geographical area by using its extents, much like how irregular features in images are processed in a bounded rectangle. This is likely to have the effect of having some grids on the periphery of the geographic region where there may be very few nodes, even none. An empty grid will not require a cluster head and will thus not participate in the path selection process.

It is assumed that a large number of radio channels are available for transmission, which will mitigate interference issues [154].

In this section, the evaluation of PSOGA is conducted with various performance metrics that includes total energy consumed, network throughput, total number of alive nodes at the end of each iteration and packet delivery ratio. The PSOGA is compared with conventional LEACH protocol with the parametric setting given in Table 5.2.

**Table 5.2:** Network Parameter setup

Parameters	Values
Network Area	100 m × 100 m, 200 m × 200 m and 500 m × 500 m
Total Number of Nodes	100, 200, 625 and 1250
Initial Energy	0.2 J
Power amplification ( $\epsilon_{fs}$ )	10 pj/bit/m <sup>2</sup>
Power amplification ( $\epsilon_{mp}$ )	0.0013 pj/bit/m <sup>4</sup>
Transmitter/receiver Energy (Eelec)	50 nJ/bit
Base station location	(50, 50), (125, 125) and (250,250)
Number of Rounds	2500

## 5.7 Results and Discussion

The study is further tested in five different scenarios with varying network area, number of grids/clusters, and total number of nodes as shown in Table 3., where the number of grids varies at different cases and ranges between 8 and 100 with node population ranging from 100 to 1250 based on the size of the network area. The details of these scenarios are given in Table 5.3.

**Table 5.3:** Different network setups for simulation

Case Study	Network Area	Number of Grids	Total Number of Nodes
1	100 m × 100 m	2×4	100
2	100 m × 100 m	4×4	100
3	200 m × 200 m	4×4	200
4	500 m × 500 m	10×10	625
5	500 m × 500 m	10×10	1250

The entire setup is in an area with the base station located at the centre as shown in Figure 5.2. The proposed PSOGA method is compared with conventional LEACH protocol with the parametric settings given in Table 2 and the grid formation is shown in Figure 5.2. The performance evaluation is done based on total number of packets reaching BS, total number of alive nodes, residual energy of the network, packet delivery ratio (PDR), and throughput of the network. Packet Delivery Ratio (PDR) indicates the ratio of packets that the sink or destination receives to the entire number of packets sent by source. Following subsections demonstrate the performance evaluation based on different grid configurations and network settings. For each scenario the simulation has been done ten times and mean has been plotted for each metric.

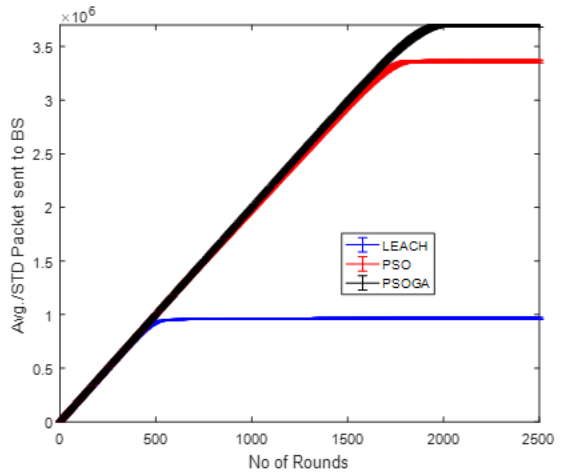
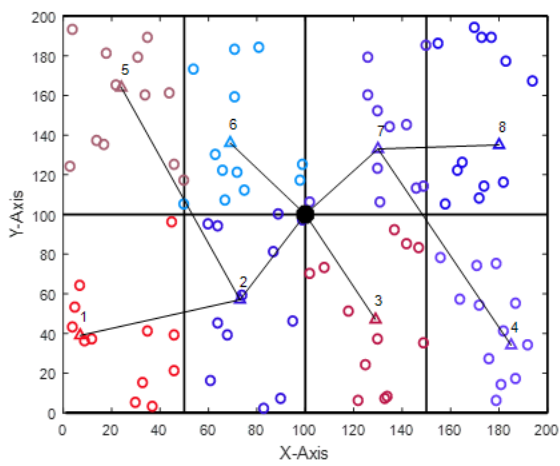
## 5.7.1 Case Study 1: Performance Metrics for 2x4 grids, 100 nodes

### 5.7.1.1 Base Station-Centre (BS-C)

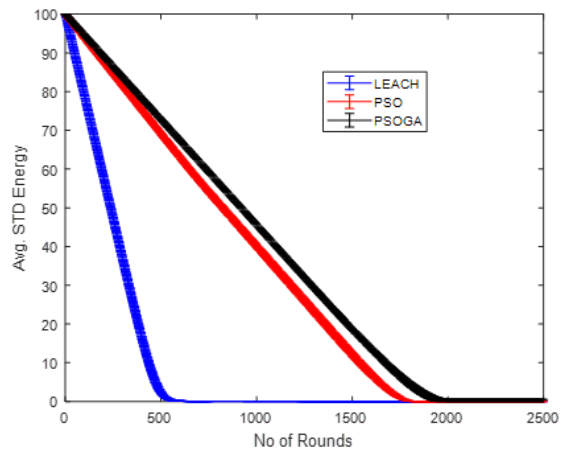
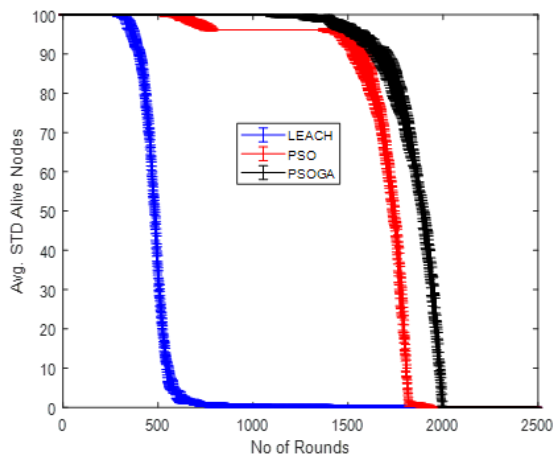
Figure 5.3 shows the results of Case Study 1: 2x4 grids, 100 Nodes, where the network structure (Figure 5.3 (a)) shows 8 grids with the selected cluster heads marked in numbers in triangular shape and connected by black lines. The comparative results of performance metrics are shown in Figures 5.3(b) to 5.3(f). For each metric, the network was generated, and simulation performed 10 times. Average of the 10 simulations, each over 2500 rounds, have been plotted, together with the standard deviation.

The number of packets reaching the BS are shown in Figure 5.3(b). After 2500 rounds the packets sent to BS for PSOGA is improved by 278.94% and 5.55% as compared to LEACH and PSO respectively. Figure 5.3(c) shows the number of nodes alive at each round. The time when all the nodes are dead for LEACH, PSO and proposed PSOGA are 700, 1900 and 2000 rounds respectively, which is a significant improvement of 185.7% and 5.26% over LEACH and PSO respectively. Residual energy also demonstrates promising improvement as shown in Figure 5.3(d). The energy gets depleted in 500, 1700, 1800 rounds for LEACH, PSO and proposed PSOGA respectively. Thus, network energy in the proposed PSOGA achieves an enhancement of 259.06% compared to LEACH and 9.97% compared to PSO. Figure 5.3(e) demonstrates an improvement in PDR by 298.75% and 67.5% compared with LEACH and PSO respectively. Furthermore, the throughput in PSOGA is increased by 7.13% and 49.5% as compared to PSO and LEACH as shown in Figure 5.3(f).

Figure 5.3(g) is a representative graph which shows the nodes alive for each of the 10 simulations for LEACH, PSO and PSOGA. The average of the 10 simulations have been shown in Figure 5.3(c). As mentioned earlier, 10 simulations were similarly performed for each of the other metrics. The bar graph in Figure 5.3(h) shows the simulation time taken for LEACH, PSO and PSOGA.

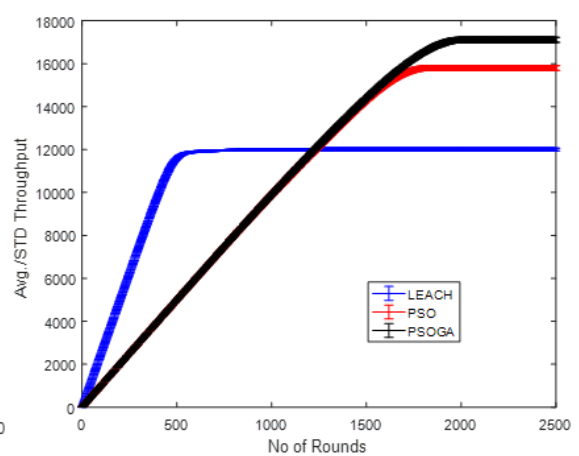
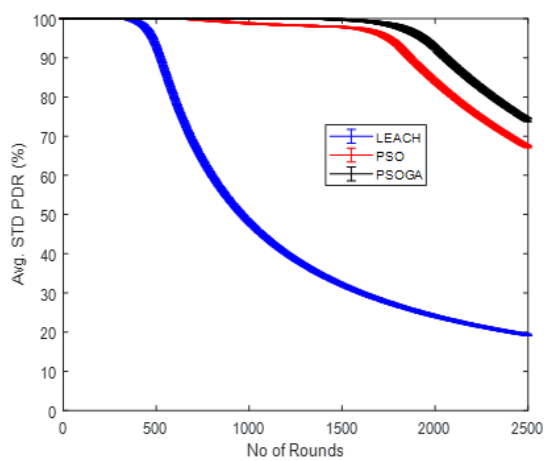


**Figure 5.3(a).** Network structure for Case Study 1 **Figure 5.3(b).** Packets reaching the BS



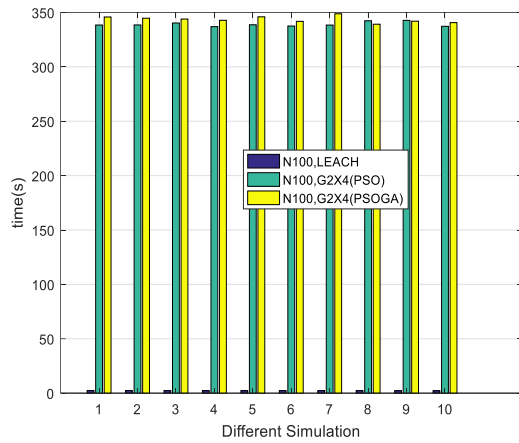
**Figure 5.3(c).** Total alive nodes

**Figure 5.3(d).** Total Residual Energy

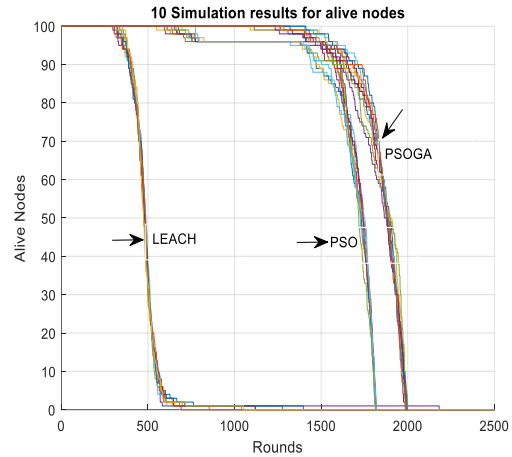


**Figure 5.3(e).** PDR

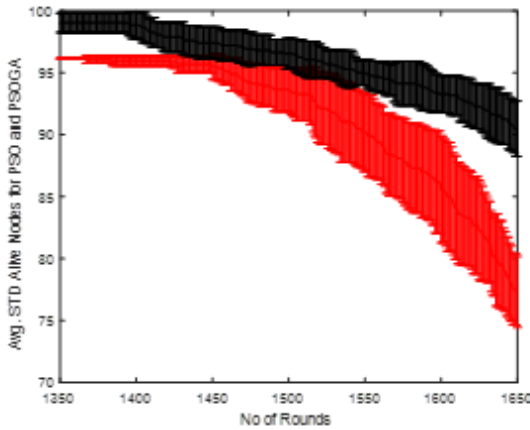
**Figure 5.3(f).** Throughput



**Figure 5.3(g).** Simulation time for 10 simulations



**Figure 5.3(h).** Graph showing data plots of 10 Simulations



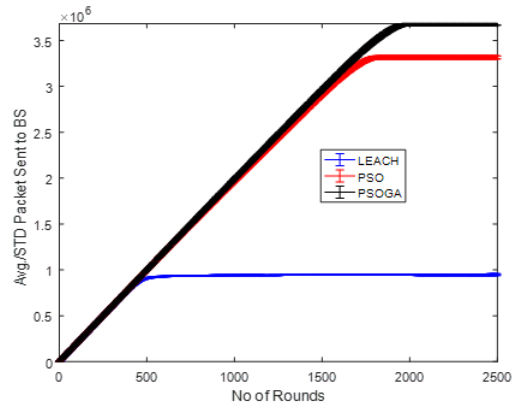
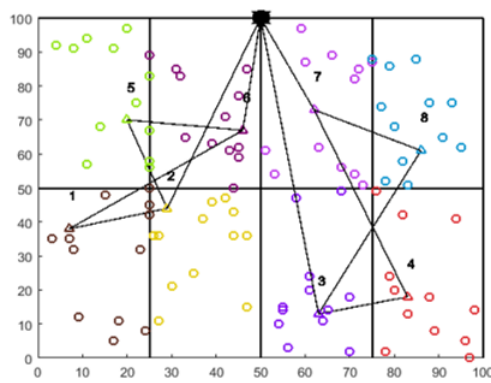
**Figure 5.3 (i).** Error bound for Alive Nodes.

**Figure 5.3:** Results of Case Study 1: 2x4, 100 Nodes (BS-Center)

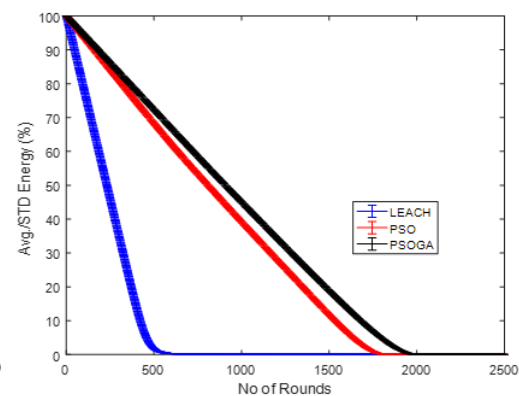
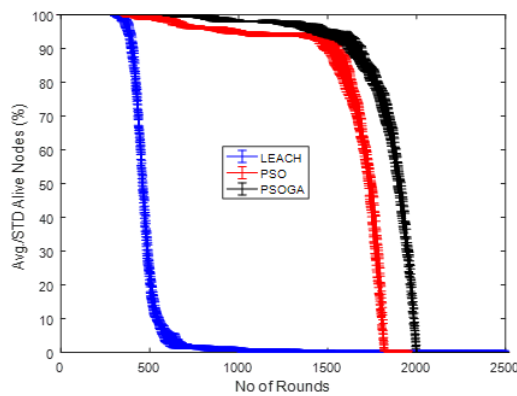
### 5.7.1.2 Base Station-Top Edge (BS-TE)

To complete the study and evaluate the efficacy of the proposed algorithm, the BS was placed at the edge of the network. This case study depicts the evaluation of the performance of PSOGA when the location of the base station is at the edge of a 2x4, 100 nodes configuration. Here also the PSOGA depicts notable improvement in various performance metrics. Figure 5.4(b) depicts the significant improvement in packets sent to BS in PSOGA exhibiting 278.94% and 9.0% improvement compared to LEACH and PSO respectively. As shown in Figure 5.4(c), PSOGA achieves an improvement in number of alive nodes by 192.93% and 12.47% as compared to LEACH and PSO respectively. Further, Figure 5.4(d) demonstrates the enhancement of 281.4% and 611.85% in residual energy for PSOGA comparing with LEACH and PSO respectively. On similar grounds a substantial enhancement

of PDR by 302.96% and 66.28% in PSOGA vis-à-vis LEACH and PSO is visualized in Figure 5.4(e). Additionally Figure 5.4(f) depicts the improvement of 45.87 % and 6.54% in throughput of the network in PSOGA compared with LEACH and PSO respectively. The plotted curves are again the average data for 10 simulations.

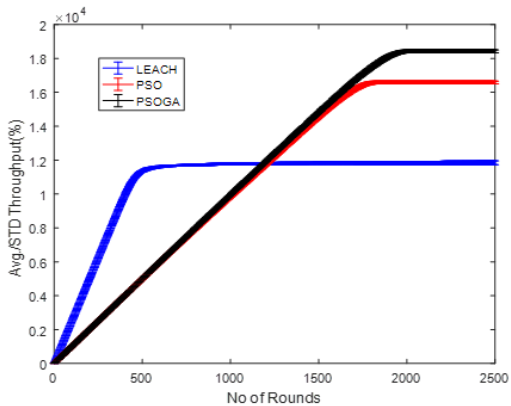
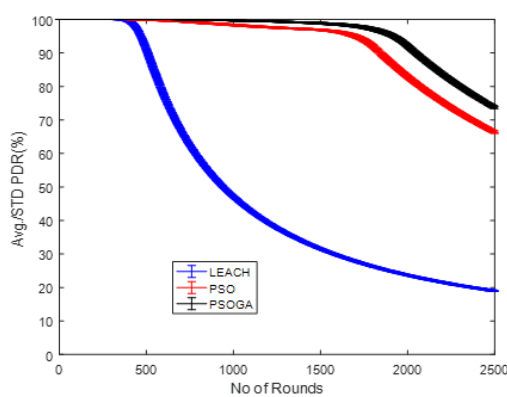


**Figure 5.4(a)** Network structure for Case Study 1 **Figure 5.4(b)** Packets reaching the BS



**Figure 5.4(c)** Total alive nodes

**Figure 5.4(d)** Total Residual Energy



**Figure 5.4(e)** PDR

**Figure 5.4(f)** Throughput

**Figure 5.4:** Results of Case Study 1: 2x4, 100 Nodes (BS-Top Edge)

### 5.7.1.3 Base Station-Left Edge (BS-LE)

To complete the study and evaluate the efficacy of the proposed algorithm, the BS was also considered to be placed at the left edge of the network. This case study depicts the evaluation of the performance of PSOGA when the location of the base station is at the edge of a 2x4, 100 nodes configuration. Also in this scenario, it is noticed that PSOGA depicts notable improvement in various performance metrics. For instance, Figure 5.5(b) depicts the significant improvement in packets sent to BS in PSOGA exhibiting 286.40% and 11.17% improvement compared to LEACH and PSO respectively. As shown in Figure 5.5(c), PSOGA achieves an improvement in number of alive nodes by 129.09% and 9.95% as compared to LEACH and PSO respectively. Further, Figure 5.5(d) demonstrates the enhancement of 248.67% and 8.09% in residual energy for PSOGA comparing with LEACH and PSO respectively. On similar grounds, a substantial enhancement in PDR is achieved by 317.48% and 46.75% vis-à-vis LEACH and PSO respectively as demonstrated in Figure 5.5(e). Additionally, Figure 5.5(f) depicts the improvement of 57.05% and 9.74% in throughput of the network in PSOGA compared with LEACH and PSO respectively. The plotted curves are again the average data for 10 simulations.

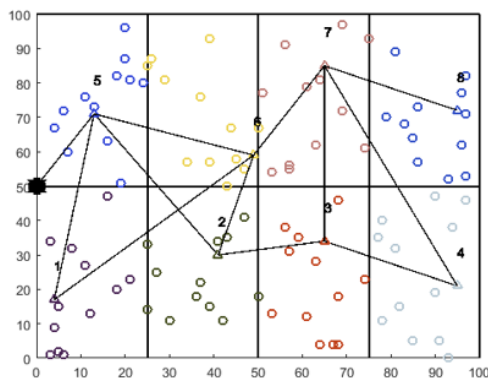


Figure 5.5(a) Network Structure for case study 1

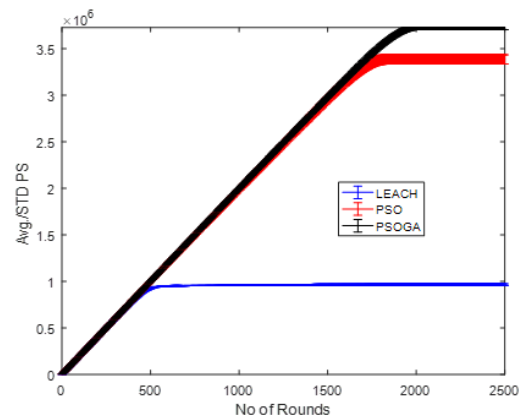


Figure 5.5(b) Packets reaching BS

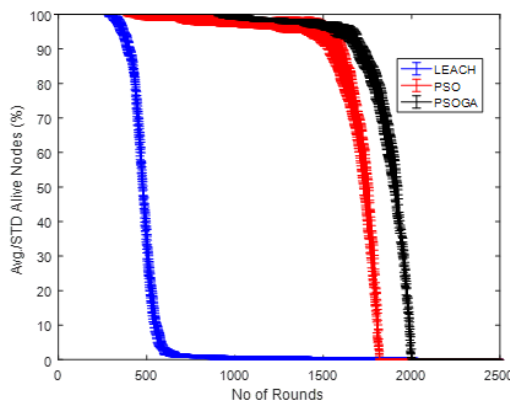


Figure 5.5(c) Total Alive Nodes

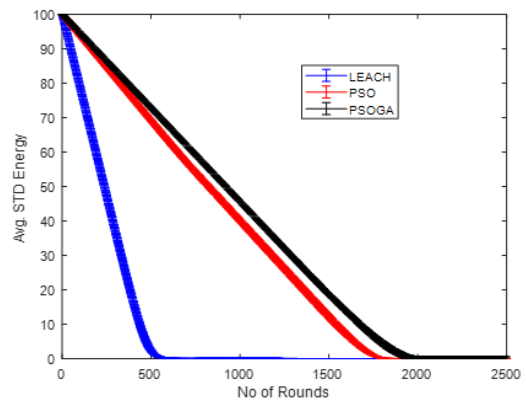
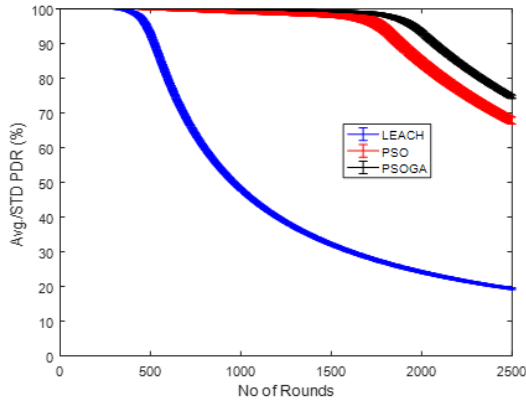
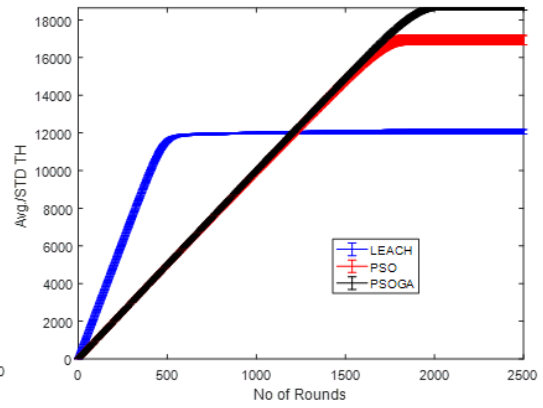


Figure 5.5(d) Total residual energy



**Figure 5.5(e)** PDR

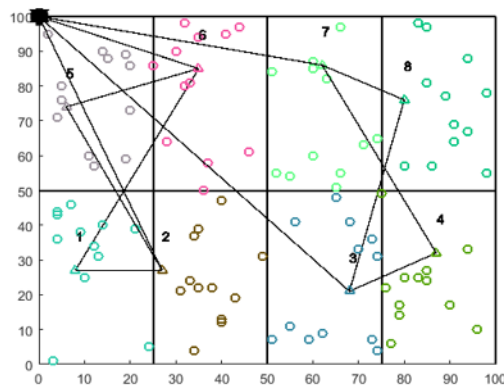


**Figure 5.5(f)** Throughput

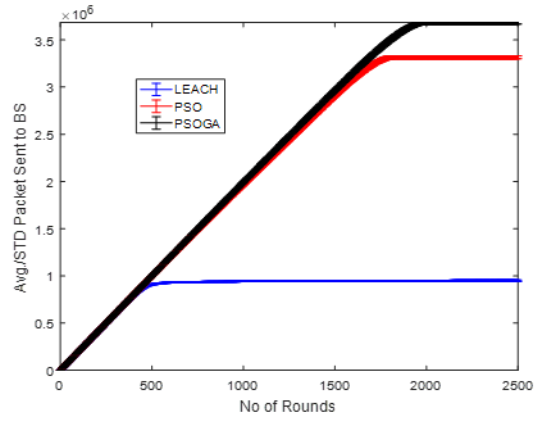
**Figure 5.5:** Results of Case Study 1: 2×4, 100 Nodes (BS-Left Edge)

#### 5.7.1.4 BS-Corner (BS-C)

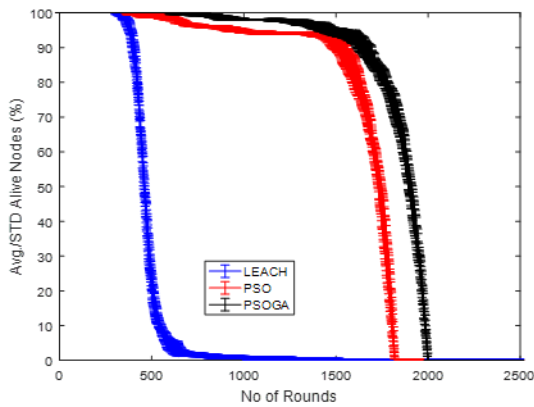
To complete the study and evaluate the efficacy of the proposed algorithm, the BS was placed at the edge of the network. This case study depicts the evaluation of the performance of PSOGA when the location of the base station is at the edge of a 2x4, 100 nodes configuration. Here, PSOGA achieves notable improvement in various performance metrics. Figure 5.6(b) depicts the significant improvement in packets sent to BS in PSOGA exhibiting 319.40% and 11.44% improvement over LEACH and PSO respectively. As shown in Figure. 5.6(c), PSOGA achieves an improvement in number of alive nodes by 106.94% and 9.18% as compared to LEACH and PSO respectively. Further, Figure 5.6(d) demonstrates the enhancement of 234.71% and 10.74% in residual energy for PSOGA comparing with LEACH and PSO respectively. Additionally, a substantial enhancement of PDR by 263.38% and 5.16% in PSOGA vis-à-vis LEACH and PSO is visualized in Figure 5.6(e). Further, Figure 5.6(f) depicts the improvement of 63.82 % and 5.24% in throughput of the network in PSOGA compared with LEACH and PSO respectively. The plotted curves are again the average data for 10 simulations.



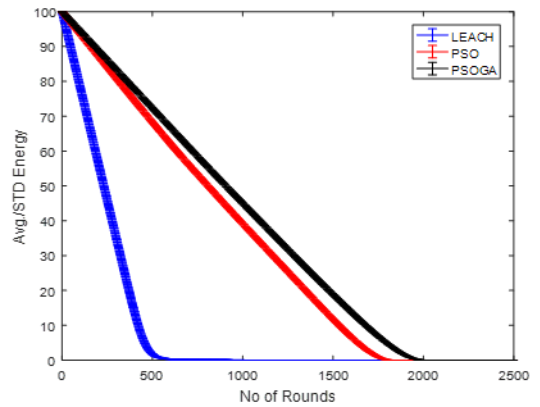
**Figure 5.6(a)** Network Structure for case study 1



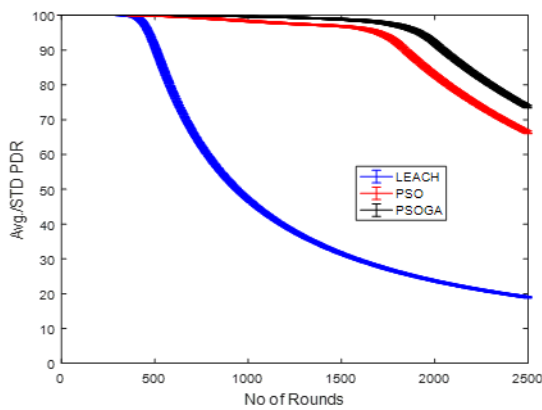
**Figure 5.6(b)** Packets reaching BS



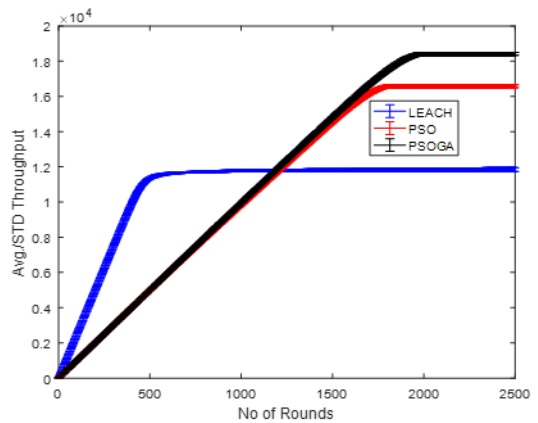
**Figure 5.6(c)** Total Alive Nodes



**Figure 5.6(d)** Total residual energy



**Figure 5.6(e)** PDR



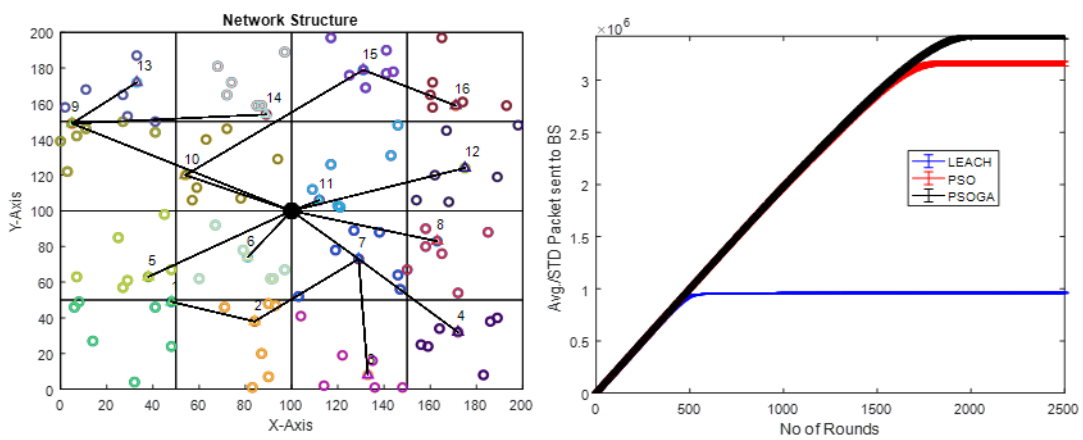
**Figure 5.6(f)** Throughput

**Figure 5.6:** Results of Case Study 1: 2x4, 100 Nodes BS-Corner

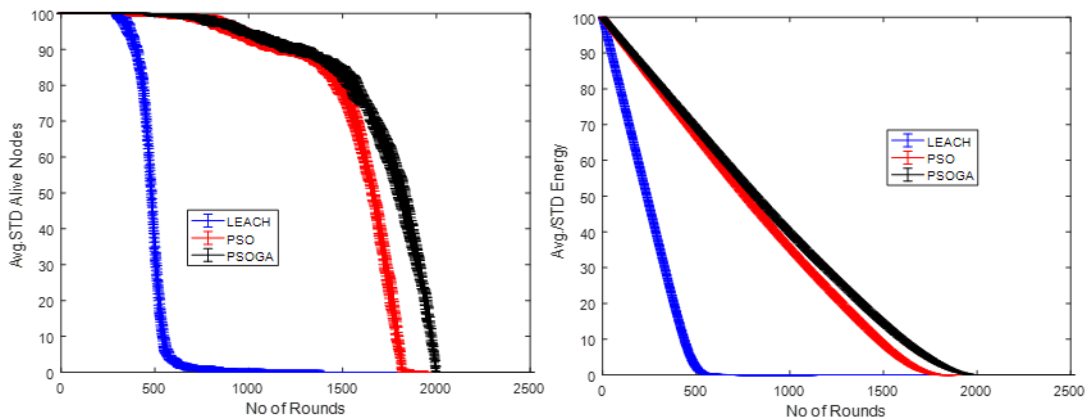
### 5.7.2 Case Study 2: 4x4 grids, 100 nodes

Figure 8 shows the results of Case Study 2: 4x4 grids, 100 nodes, where the network structure Figure 5.7(a) shows 16 grids with the selected cluster heads marked in numbers and connected by a black line. The results of performance metrics show that with 100 nodes, the packets sent to BS Figure 5.7(b) is improved by 268.42% and

9.36% when compared to LEACH and PSO respectively. Further PSOGA demonstrates an increase in the number of alive nodes by 155.43% and 10% as compared to the PSO and LEACH respectively. The results in Figure.8d illustrates that number of alive nodes becomes zero at 500, 1850 and 1994 rounds for LEACH, PSO and proposed PSOGA algorithm respectively leading to a significant gain of 274.64% and 10.4% vis-à-vis LEACH and PSO respectively. Similarly, the PDR is improved by 314.25% and 72.48% in comparison to LEACH and PSO respectively Figure 5.7(e). Finally, proposed PSOGA demonstrated the throughput enhancement by 37.5% and 4.84% compared to LEACH and PSO respectively as shown in Figure 5.7 (f).

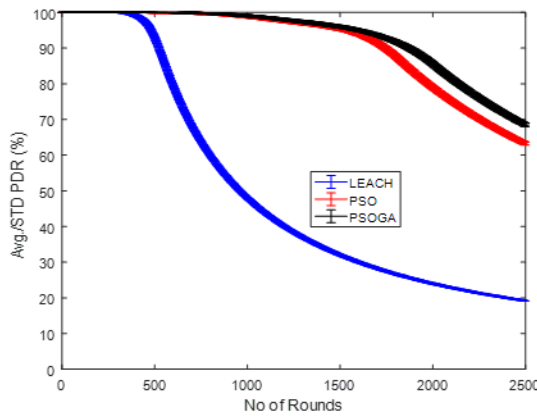


**Figure 5.7(a)** Network structure for Case Study2 **Figure 5.7(b)** Packets reaching the BS

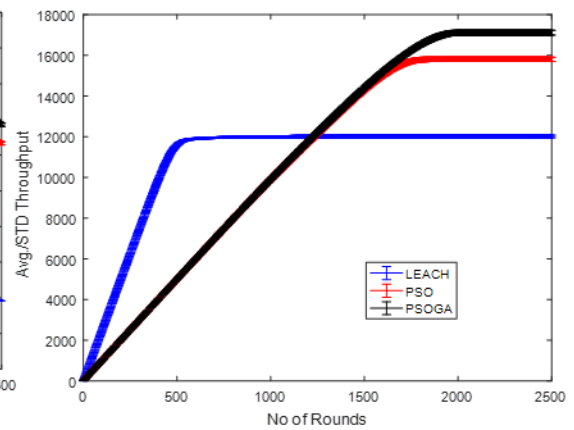


**Figure 5.7(c)** Total alive nodes

**Figure 5.7(d)** Total Residual Energy



**Figure 5.7(e)** PDR



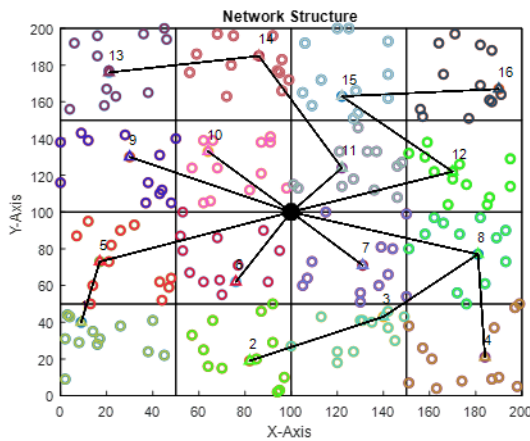
**Figure 5.7(f)** Throughput

**Figure 5.7:** Results of Case Study 2: 4×4, 100 Nodes

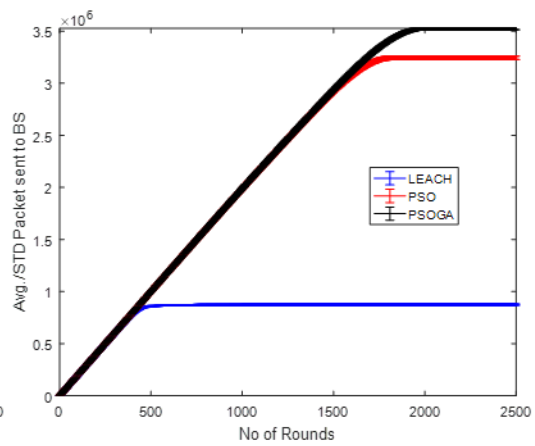
Further, as compared to Case study 1: 2×4 grids, 100 nodes, it is evident that although the number of nodes in both the case studies are the same, the difference lies in the grid structure. In case of 4×4 grid, the network performs better in terms of the evaluated parameters. For instance, the no. of packets sent to BS in case study 2 are  $3.5 \times 10^6$ , almost  $3 \times 10^5$  higher than the case study 1, which is  $3.2 \times 10^6$  packets. Similarly, the network structure has demonstrated a slight improvement in throughput with an increase of almost 17,500 as compared to 16,000 in the 8-grid structure.

### 5.7.3 Case Study 3: 4×4 grids, 200 nodes

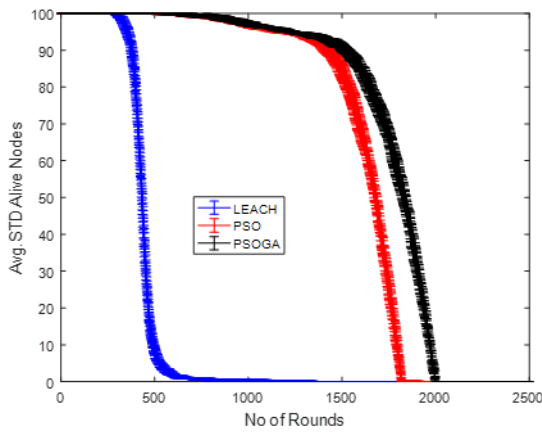
The Figure 5.8 shows the results of Case Study 3: 4×4 grids, 200 nodes, where the network structure Figure 5.8(a) shows 16 grids with the selected cluster heads marked in numbers and connected by a black line. The results of performance metrics show that with 200 nodes, the packets sent to BS Figure 5.8(b) with PSOGA gets improved by 288.7% and 9.36% compared to LEACH and PSO respectively. Further, the number of alive nodes is improved by 189.44% and 11.65% as compared to LEACH and PSO respectively Figure 5.8(c). Figure 5.8(d) also demonstrates the similar trend with respect to residual energy i.e., the energy of the network reduces to 0 at approx. 500 rounds, 1850 rounds and 1994 rounds for LEACH, PSO and proposed PSOGA respectively contributing to percentage improvement of 279.2% and 12.5% respectively. Similarly, PDR is also enhanced by 304.9% and 67.3% compared to LEACH and PSO respectively Figure 5.8(e). Figure 5.8(f) further demonstrates the efficacy of PSOGA in terms of throughput improvement by 44.53% and 5.96% compared to LEACH and PSO respectively.



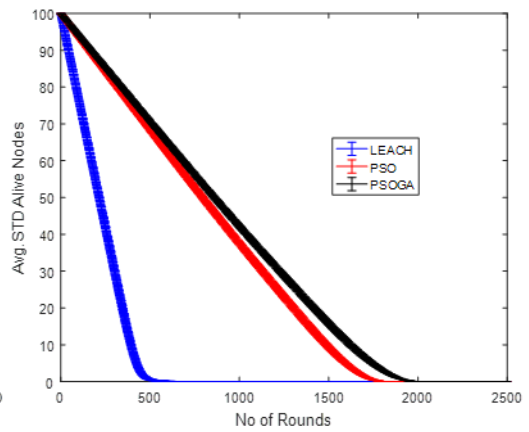
**Figure 5.8(a)** Network structure for Case Study 3



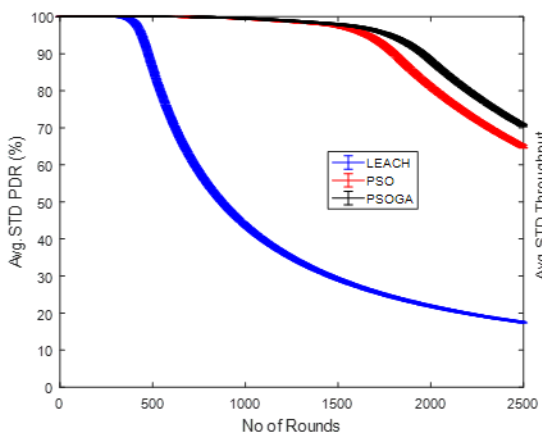
**Figure 5.8(b)** Packets reaching the BS



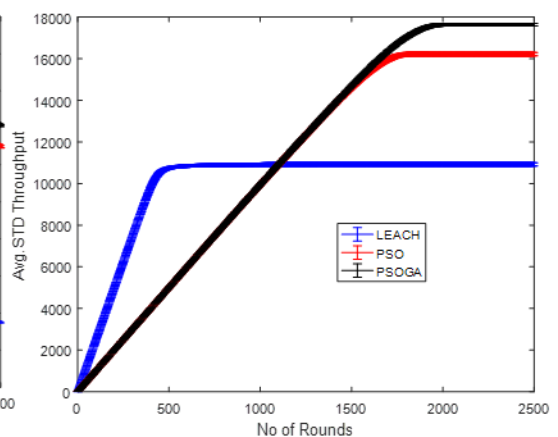
**Figure 5.8(c)** Total alive nodes



**Figure 5.8(d)** Total Residual Energy



**Figure 5.8(e)** PDR



**Figure 5.8(f)** Throughput

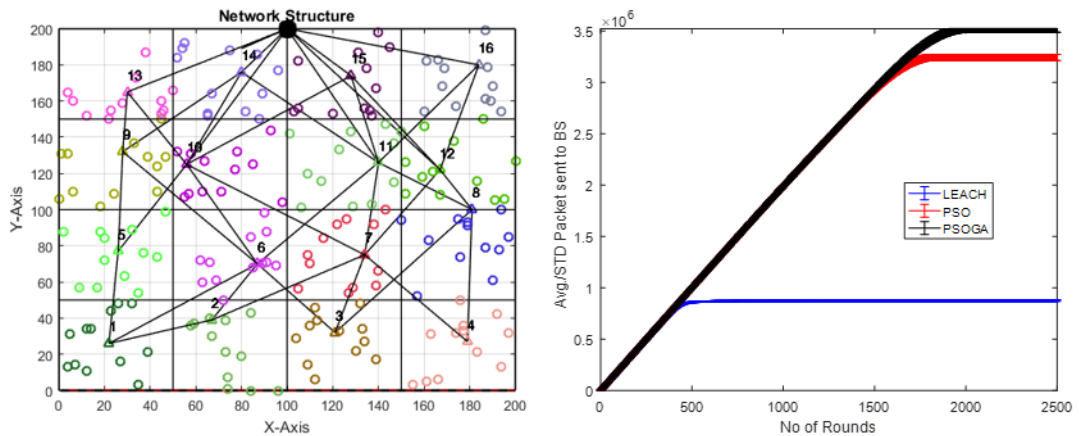
**Figure 5.8:** Results of Case Study 3: 4x4, 200 Nodes

To draw the comparison of performance metrics with respect to the case study 2, where the number of grids is same i.e., 16 but the number of nodes is higher i.e., 200

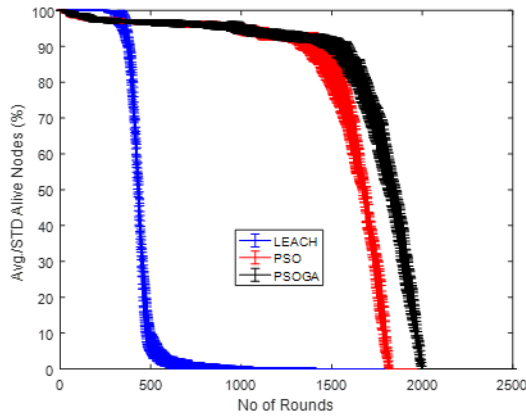
nodes. The packets reaching the BS in the presented case study here are higher, e.g.,  $3.6 \times 10^6$  vs  $3.5 \times 10^6$  demonstrating a slight improvement of around  $1 \times 10^5$  packets.

### 5.7.3.1 BS-Top Edge (BS-TE)

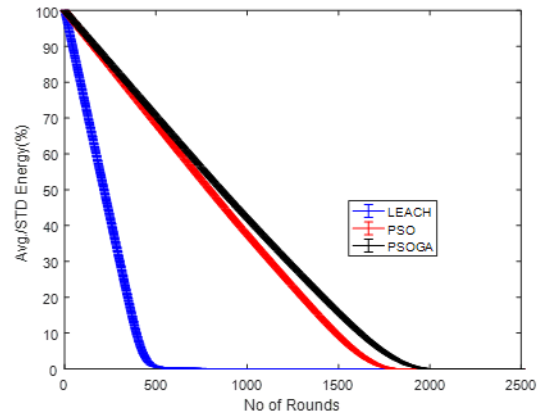
The Figure 5.9 shows the results of Case Study 3:  $4 \times 4$  grids, 200 nodes, where the network structure Figure 5.9(a) shows 16 grids with the selected cluster heads marked in numbers and connected by a black line. The results of performance metrics demonstrate that with 200 nodes, the packets sent to BS Figure 5.9(b) with PSOGA gets improved by 340.31% and 9.20% compared to LEACH and PSO respectively. Further, the number of alive nodes is improved by 128.75% and 9.84% as compared to LEACH and PSO respectively as illustrated in Figure 5.9(c). Figure 5.9(d) demonstrates the similar trend with respect to residual energy. Here, it is seen that the energy of the network diminishes to 0 at approx. 500 rounds, 1850 rounds and 1994 rounds for LEACH, PSO and proposed PSOGA respectively contributing to percentage improvement of 290.72% and 11.06% respectively. Similarly, PDR is also enhanced by 340.75% and 75.51% compared to LEACH and PSO respectively as demonstrated in Figure 5.9(e). Figure 5.9(f) further showcases the efficacy of PSOGA in terms of throughput improvement by 69.26% and 10.06% compared to LEACH and PSO respectively.



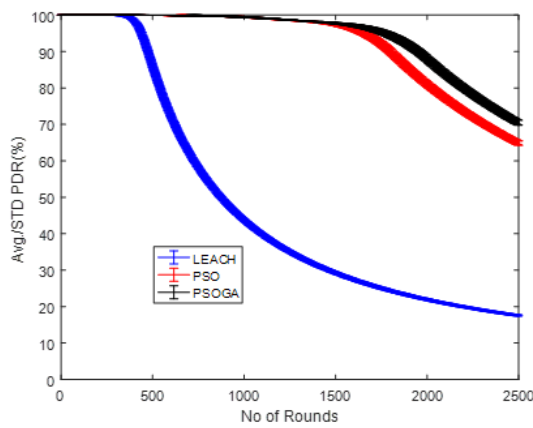
**Figure 5.9(a)** Network Structure for case study 3 **Figure 5.9(b)** Packets reaching the BS



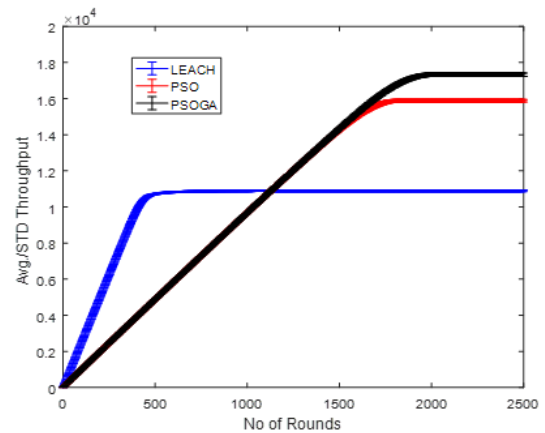
**Figure 5.9(c)** Total Alive Nodes



**Figure 5.9(d)** Total residual energy



**Figure 5.9(e)** PDR



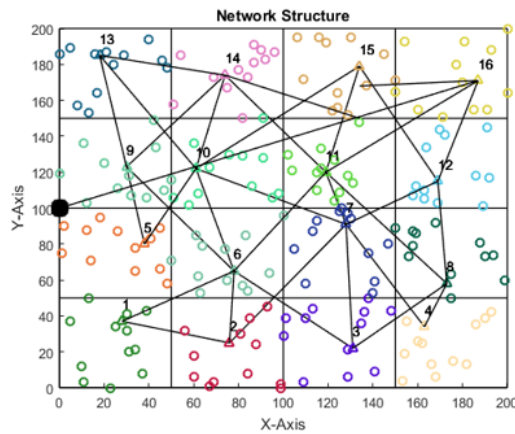
**Figure 5.9(f)** Throughput

**Figure 5.9:** Results of Case Study 3: 4x4, 200 Nodes

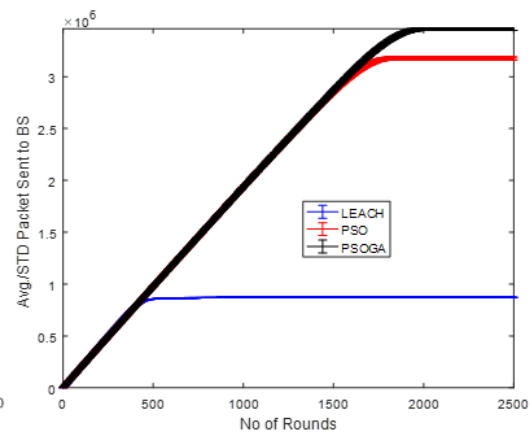
### 5.7.3.2 BS-Corner (BS-C)

Figure 5.10 shows the results of Case Study 3: 4x4 grids, 200 nodes, where the network structure Figure 5.10(a) shows 16 grids with the selected cluster heads marked in numbers and connected by a black line. The results of performance metrics show that with 200 nodes, the packets sent to BS Figure 5.10(b) with PSOGA gets improved by 332.95% and 7.41% compared to LEACH and PSO respectively. Further, the number of alive nodes is improved by 155.56% and 9.13% as compared to LEACH and PSO respectively as shown in Figure 5.10(c). Figure 5.10(d) also demonstrates that the energy of the network reduces to 0 at approx. 500 rounds, 1850 rounds and 1994 rounds for LEACH, PSO and proposed PSOGA respectively contributing to percentage improvement of 292.46% and 11.13% respectively. Similarly, PDR is also enhanced by 380.75% and 21.17% compared to LEACH and PSO respectively Figure 5.10(e). Figure 5.10(f) further demonstrates the efficacy of PSOGA in terms of

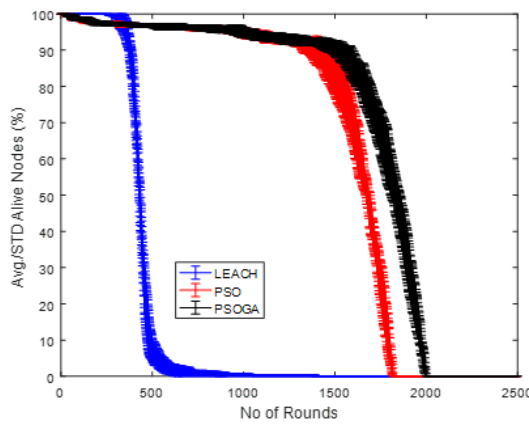
throughput improvement by 74.16% and 7.81% compared to LEACH and PSO respectively.



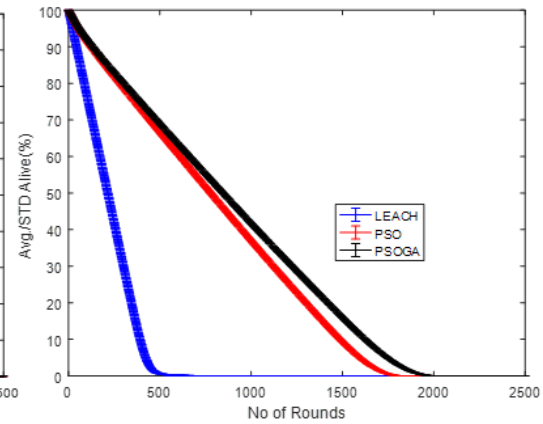
**Figure 5.10(a)** Network Structure for case study 3



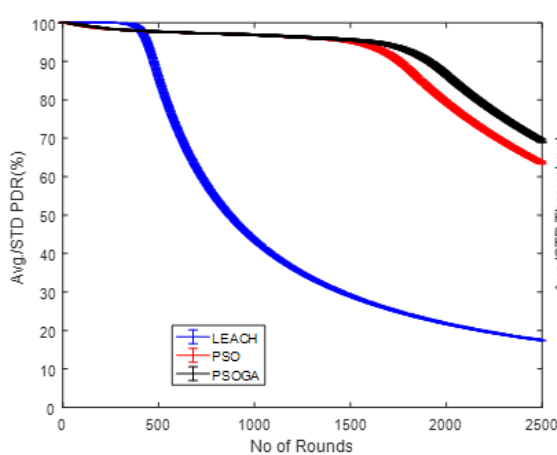
**Figure 5.10(b)** Packets reaching BS



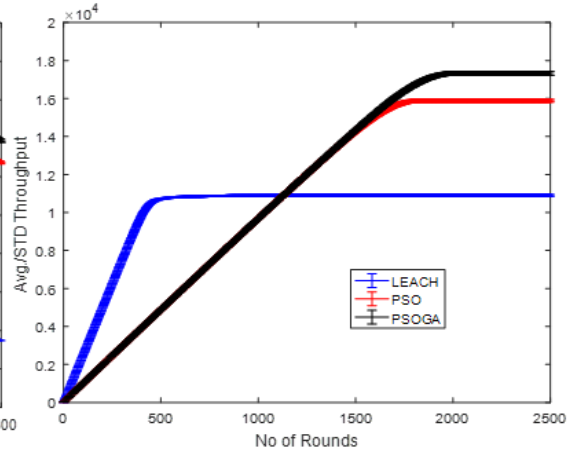
**Figure 5.10(c)** Total Alive Nodes



**Figure 5.10(d)** Total residual energy



**Figure 5.10(e)** PDR

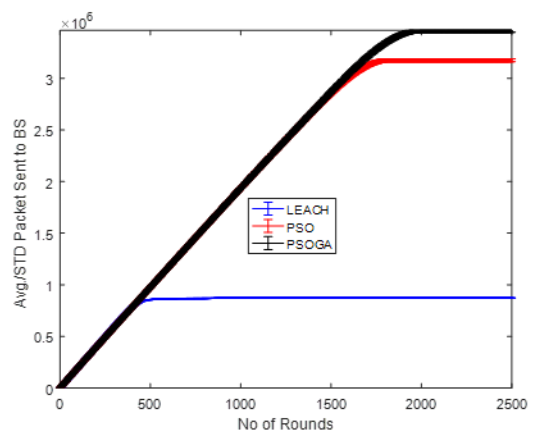
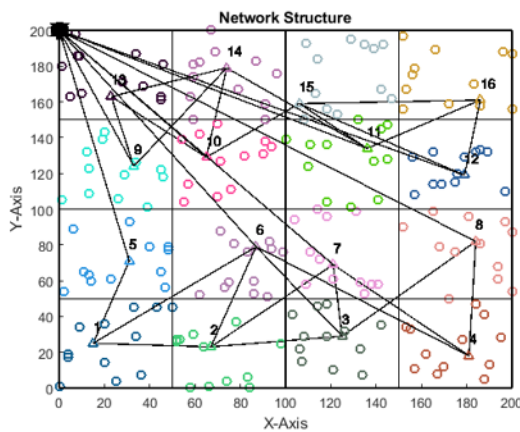


**Figure 5.10(f)** Throughput

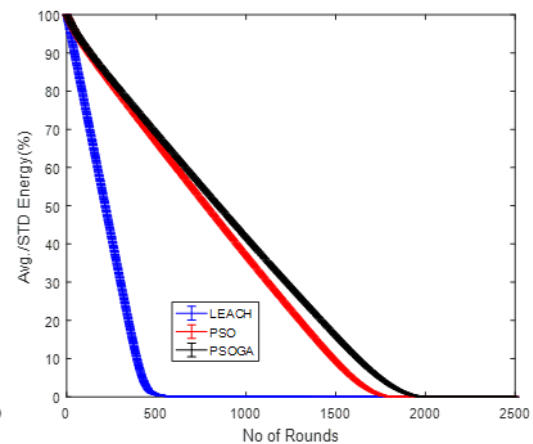
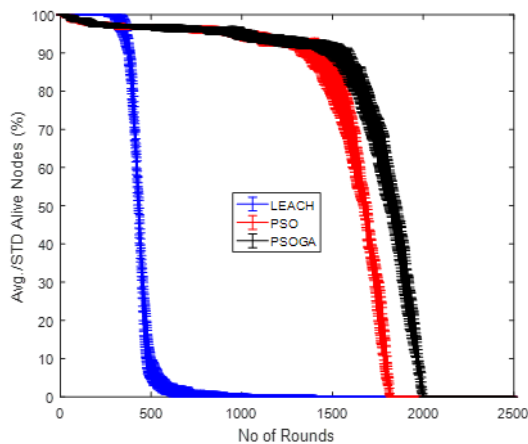
**Figure 5.10:** Results of Case Study 3: 4x4, 200 Nodes

### 5.7.3.3 BS at the corner

Figure 5.11 shows the results of Case Study 3: 4×4 grids, 200 nodes, where the network structure as shown in Figure 5.11(a) shows 16 grids with the selected CH marked in numbers and connected by a black line. The results of performance metrics for PSOGA show that with 200 nodes, the packets sent to BS as shown in Figure 5.11(b) improves by 326.21% and 8.89% over LEACH and PSO respectively. Further, the number of alive nodes is improved by 165.29% and 8.71% as compared to LEACH and PSO respectively as shown in Figure 5.11(c). As evident from Figure 5.11(d), the residual energy reaches 0 at approx. 500 rounds, 1850 rounds and 1994 rounds for LEACH, PSO and proposed PSOGA respectively gaining an improvement of 282.34% and 10.30% respectively. Similarly, PDR is enhanced by 388.80% and 71.75% compared to LEACH and PSO respectively as shown in Figure 12(e). Further, Figure 5.11(f) further demonstrates the efficacy of PSOGA in terms of throughput improvement by 85.00% and 9.00% compared to LEACH and PSO respectively.

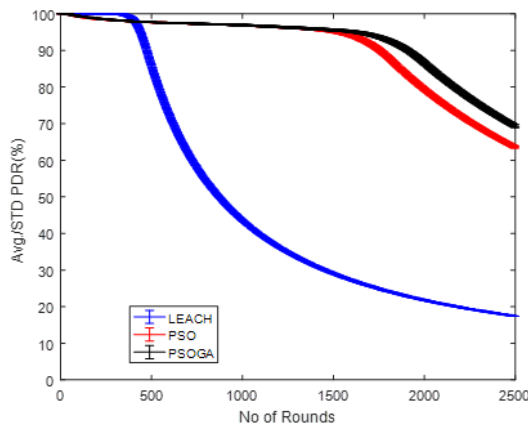


**Figure 5.11(a)** Network Structure for case study 3      **Figure 5.11(b)** Packets reaching BS

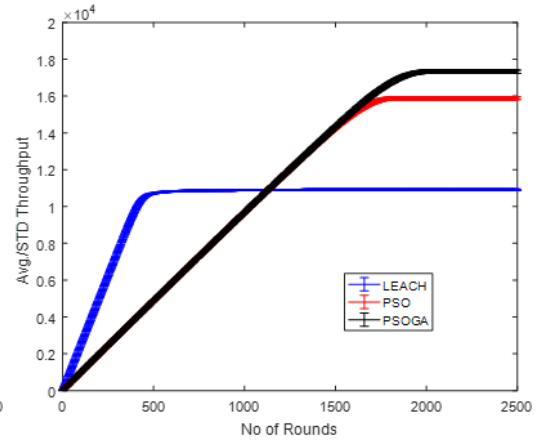


**Figure 5.11(c)** Total Alive Nodes

**Figure 5.11(d)** Total residual energy



**Figure 5.11(e)** PDR

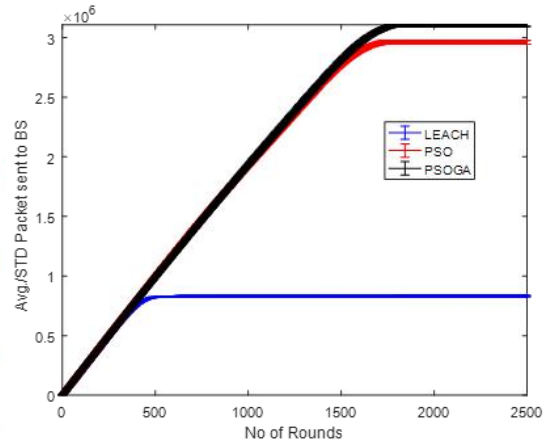
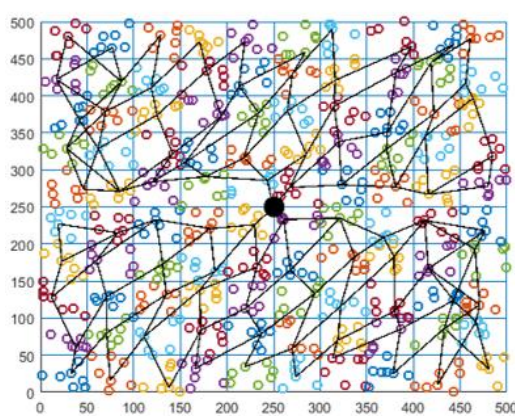


**Figure 5.11(f)** Throughput

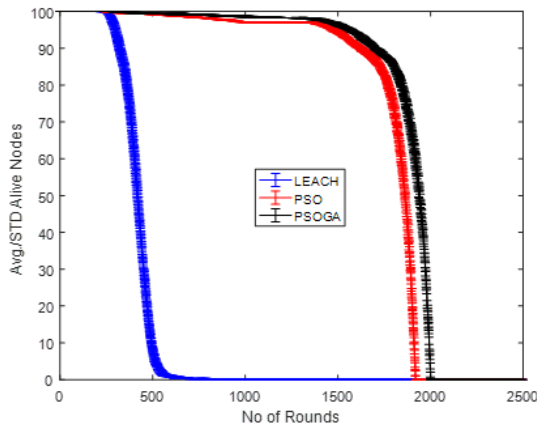
**Figure 5.11:** Results of Case Study 3: 4×4, 200 Nodes

#### 5.7.4 Case Study 4: 10×10 grids, 625 nodes

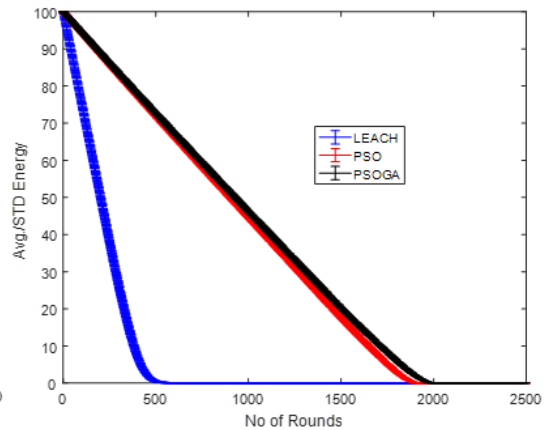
The Figure 5.12 shows the results of Case Study 4 with 10×10 grids, 625 nodes, where the network structure Figure 5.12(a) shows 100 grids with the selected cluster heads marked in numbers and connected by a black line. The results of performance metrics show that with 625 nodes, the packets sent to BS Figure 5.12(b) observes an improvement of 325% and 30.76% as compared to LEACH and PSO respectively. The number of alive nodes is enhanced by 232.22% and 6.26% as compared to LEACH and PSO respectively. In Figure 5.12(c), residual energy is improved by 298.4% and 7.67% with respect to LEACH and PSO respectively as shown in figure 8d. Further, in figure 5.12(e) PSOGA demonstrated the increase of 266.36% and 46.47% in PDR as compared with LEACH and PSO respectively. Similarly, figure 5.12(f) observes an increase in throughput of the network by 46.3% and 6.87% when compared to LEACH and PSO.



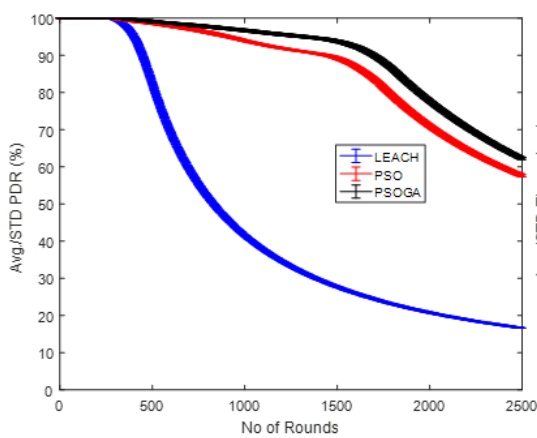
**Figure 5.12(a)** Network structure for Case Study 4 **Figure 5.12(b)** Packets reaching the BS



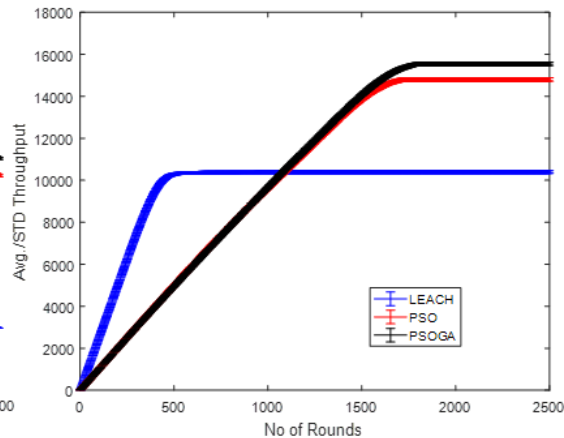
**Figure 5.12 (c)** Total alive nodes



**Figure 5.12 (d)** Total Residual Energy



**Figure 5.12 (e)** PDR



**Figure 5.12 (f)** Throughput

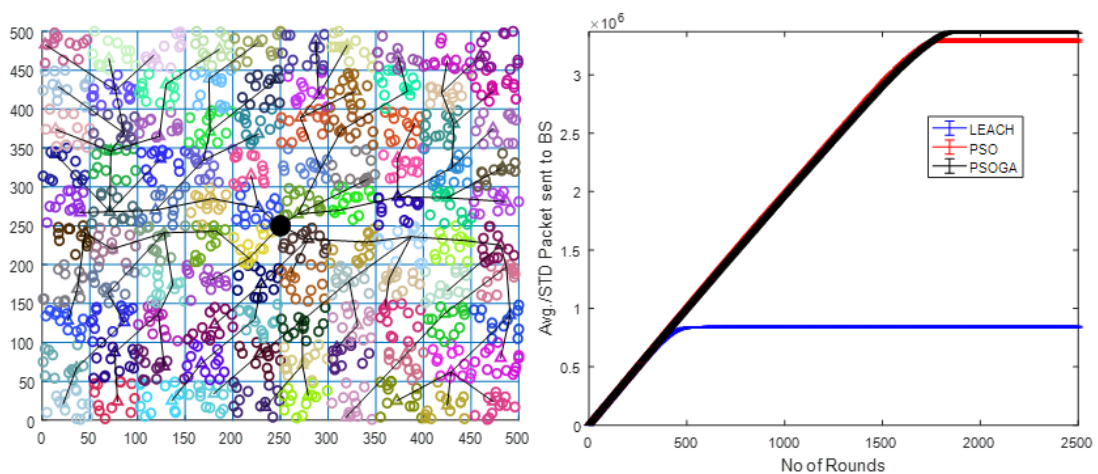
**Figure 5.12:** Results of Case Study 4: 10×10, 625 nodes

In case study 4, with 625 nodes and 100 grids, the performance of the network deteriorates as compared to previous case studies. The number of packets sent to the base station are  $3.1 \times 10^6$ , which is substantially lower than previous case studies. Similarly, the PDR% is also reduced to 60% from the 70% achieved in case study 3. The throughput achieved here is 15,500, much less than 18,000 achieved in case study 3. The drastic re-duction in the performance metrics can be attributed to the structure where, although the number of nodes is higher, yet the grid structure of 10×10 makes the process of path discovery cumbersome and hence reduces the throughput of the network.

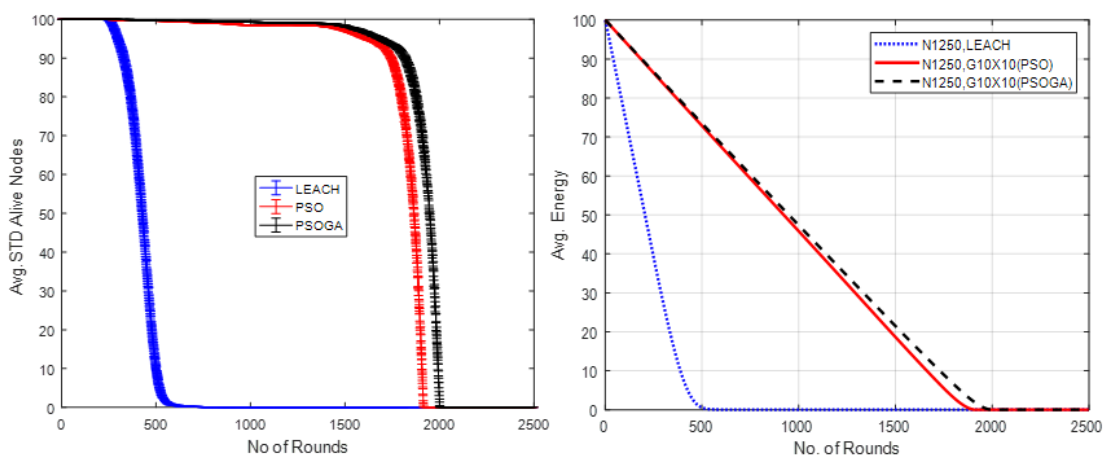
### 5.7.5 Case Study 5: 10×10 grids, 1250 nodes

The Figure 14 shows the results of Case Study 5 with 10×10 grids, 1250 nodes, where the network structure Figure 5.13(a) shows 100 grids with the selected cluster heads

marked in numbers and connected by a black line. The results of performance metrics show that with 1250 nodes, the packets sent to BS Figure 5.13(b) in PSOGA achieves an improvement of 333% and 45.83% respectively as compared to LEACH and PSO. Further, Figure 5.13(c) illustrates that increase in alive nodes by 236.7% and 5.89% when compared to LEACH and PSO. PSOGA shows a significant improvement in residual energy by 301% and 7.9% compared with LEACH and PSO respectively Figure 5.13(d). PSOGA also shows substantial improvement in PDR by 274.7% compared to LEACH and 46.92% compared to PSO Figure 5.13(e) and throughput of the network in PSOGA increases by 54.82% and 6.98% as compared to LEACH and PSO Figure 5.13(f) respectively.

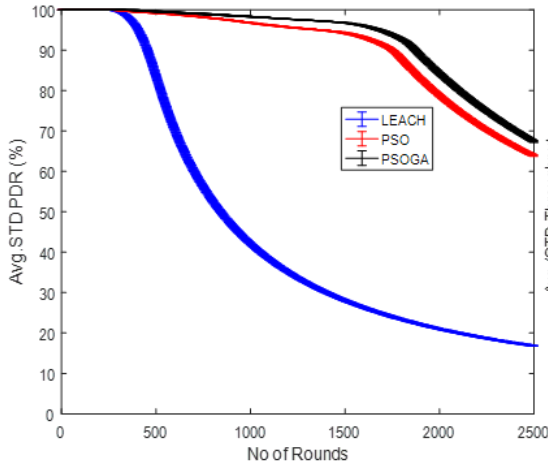


**Figure 5.13(a)** Network structure for Case Study 5 **Figure 14(b)** Packets reaching the BS

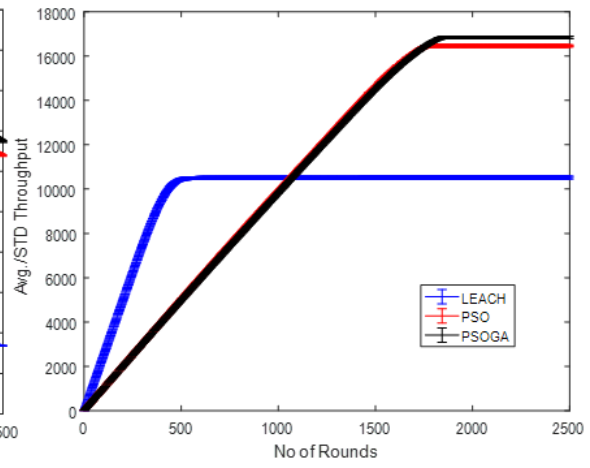


**Figure 5.13 (c)** Total alive nodes

**Figure 5.13 (d)** Total Residual Energy



**Figure 5.13 (e) PDR**



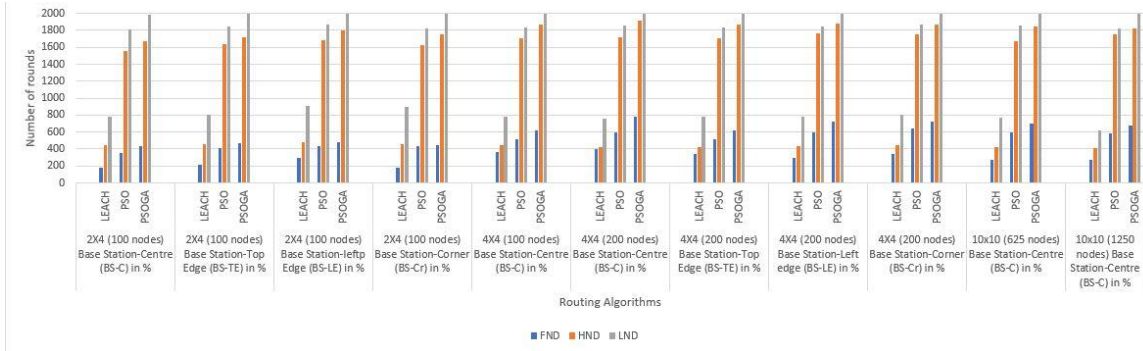
**Figure 5.13 (f) Throughput**

**Figure 5.13:** Results of Case Study 5: 10×10, 1250 nodes

In case study 5, with 1250 nodes and 100 grids, the performance of the network improves as compared to previous case study 4. The number of packets sent to the base station are  $3.2 \times 10^6$ , which is higher than the previous structure. Similarly, the PDR% is also enhanced to 65% from the 60% achieved in case study 4. The throughput achieved here is 17,000, higher than 15,500 achieved in case study 4. The enhancement in the performance metrics can be attributed to the structure where although the number of grids is higher, yet the higher number of nodes i.e., 1250 sustains the network for a longer time and thus enhances the performance metrics of the network.

## 5.8 Comparative Analysis

The results over various node densities and varying network grids have been analysed and the comparative data of the network lifetime is presented in Figure 5.14. The First Node Dead (FND), Half Node Dead (HND) and Last Node dead (LND) are the metrics of comparison between LEACH, PSO and PSOGA. For all the cases, PSOGA shows significant improvement over LEACH for all the metrics. PSOGA also shows improvements over PSO, albeit to a much lesser extent than the improvements of LEACH.



**Figure 5.14:** Overall lifetime of sensor nodes for FND, HND, and LND

## 5.9 Conclusion

This chapter outlines a trust-based PSOGA model to improve network lifetime in an IoT-based WSN environment. In this model, after grid formation, the optimal selection of CH among stationary nodes using a trust model provides reliable data transmission from sensor nodes to cluster head. After forming the first random paths using the zigzag approach, the optimization algorithm assists in determining the optimum routes that provide the efficient path of data packets to the sink node. Metrics such as route score, number of received packets, number of delayed packets, residue energy, power consumption, and total hop counts enable for optimal route selection among random paths. Such routes are reliable enough to carry out packet transmissions while allowing for a higher residual energy. The application of PSOGA ensures faster route selection than the present LEACH mechanism, with the proposed PSOGA obtains increased network lifetime in all five case studies. The number of dead nodes in the network after numerous iterations is far lower than that of the LEACH protocol, demonstrating the effectiveness of the present system.

The authors are currently working on expanding the provided work in the direction of data reduction combined with security to improve network efficiency and privacy. Deep learning techniques can be used in the future to develop bufferless systems that match the speed of input data collecting from multiple IoT devices. In addition to this, further research will consider cross layer approach to increase the network efficiency and lifetime when faced with node failures.

The proposed method appears to have strong potential for deployment in a static WSNs infrastructure. To fully utilise its potential in addressing practical issues like sensor lifetime and geographical conditions, the proposed method needs to be studied in the context of being implemented in a dynamic WSNs system.

# Investigation of energy cost of data compression algorithms in WSN for IoT Applications

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M. Mishra, G. S. Gupta, and X. Gui, “Investigation of energy cost of data compression algorithms in WSN for IoT Applications ,” MDPI Sensors Journal (Submitted)

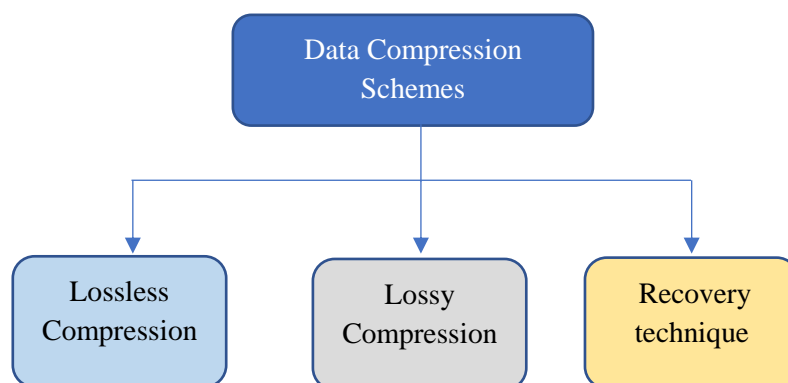
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### 6.1 Outline

Wireless sensor networks (WSN) have developed because of the rapid expansion of both distant technologies and computerised integrated circuits. The Wireless Sensor Network is made up of a variety of sensor nodes and hubs that are able to detect, analyse, and communicate data remotely. The memory, power, and processing power of sensor nodes are highly limited. Many image compression techniques have been proposed to deal with these limitations, but most of them aren't practical on sensor nodes because to issues with memory, power, and processing performance. Considering that Run Length Encoding [155] and Adaptive Huffman Encoding [156] may be run on sensor nodes, they were selected by the writers of this chapter as a means of resolving this problem. In terms of balancing compression ratio and energy usage, both RLE and AHE perform admirably. This chapter proposes and explores additional investigation into a hybrid approach consisting of RLE and AHE dubbed H-RLEAHE for sensor nodes. Five distinct scenarios were simulated, and the results compared to compression techniques employing RLE, AHE, and no compression strategy at all to verify the usefulness of the proposed hybrid algorithm. Based on the collected findings, we can conclude that the suggested method is superior to the state-of-the-art approaches in terms of energy efficiency, network throughput, packet delivery ratio, and residual energy.

Wireless sensor networks have an urgent issue with power consumption that severely limits their useful lifespan [157]. Energy-efficient media access control or routing protocols are only two of the many methods proposed to address this problem [158]. Since most sensor nodes rely on batteries for power, and many WSN applications want to keep tabs on the world around them for an extended period of time, figuring out how to keep sensor nodes running for as long as possible is an important problem to

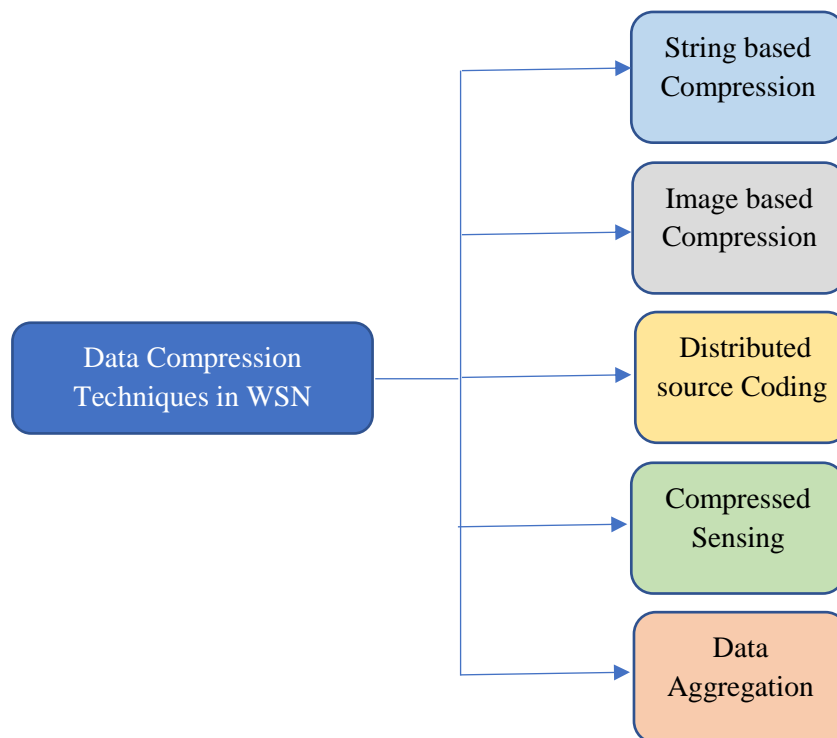
solve. There are two standard approaches to limiting sensor node power consumption. To address this issue, one strategy is to activate a subset of sensor nodes while putting the rest to sleep to save power. To ensure continued network connectivity and full coverage of the monitoring area, a subset of active sensor nodes must be chosen. In other words, the network's continued viability depends on the performance of these active sensor nodes, which must guarantee the same level of performance as when all sensor nodes are online. We can prevent some sensor nodes from using too much energy and so prolong the lifetime of the network by periodically activating various groups of sensor nodes. Such sleep-active techniques, however, may not be used [159-160] in situations when redundancy among nodes is unavailable (as may be the case, for example, during network rollout [161], or sensor failure), such sleep-active mechanisms may not be applied [162]. As transmission is one of the most energy-consuming actions of sensor nodes, reducing the amount of sensing data to be sent is another option [163]. In situations where sensor nodes must continuously update the sink(s) with sensing data, this kind of solution proves invaluable. Internal network compression is necessary to minimise the volume of sensor data. To lessen the load on wireless networks, one of the methods offered is to utilise a data compression algorithm. With this method, the amount of inter-node communication that is normally needed is cut down, saving the network's energy supply. Data compression algorithms may be broken down into three distinct groups based on lossless, lossy and recovery technique with compression [164]. (see Figure 6.1 below for a visual representation of these groups):



**Figure 6.1:** Classification of Data Compression Techniques [164]

A lossless compression is one in which the data are unaltered when decompressed back to their original state [165]. One of the good examples is Huffman coding [166]. When data is compressed, it may lose some information (often less significant details). This class includes the majority of image and video compression formats, including JPEG2000. The last, from a compressed file some data are lost, the recovery tools such as error concealment tools are employed to retrieve the lost data. To put it another way, there is no decompression operation being performed. As an illustration, the average value of a group of numbers may be used to compress the group, but this average value does not provide a direct path back to any of the original values.

Figure 6.2 depicts five broad categories into which the data compression techniques used in WSNs may be sorted.



**Figure 6.2:** Categorization of Data Compression Techniques in WSN [159-167]

A brief description of these techniques is as follows [167]: 1) In string-based compression methods, sensing data is represented as a string of characters, and the techniques used to compress textual data are applied to the sensing data. (2) The image-based compression methods first employ a hierarchical structure for organising WSNs, and then adapt the ideas behind image-based compression solutions for processing sensing data. The Slepian-Wolf theorem is extended by the distributed source coding methods, which allow for the independent encoding of many correlated

data streams at sensor nodes and their combined decoding at the sink. 4) To reduce the size of sensing data, compressed sensing methods use a small number of nonadaptive and randomly generated linear projection samples. 5) In order to cut down on the quantity of data transfers, the data aggregation methods pick a subset of sensor nodes in the network to be responsible for fusing the sensing data from other sensor nodes. The chapter is structured as follows: The context and rationale for choosing these methods are presented in Section 6.2. The fundamentals of compression are covered in Section 6.3. In Section 6.4, we see a practical application of the suggested hybrid paradigm for data compression. The network configuration is discussed in detail in Section 6.5. Various data compression models, including RLE, AHE, Hybrid-RLEAHE (H-RLEAHE), and no compression, are compared and contrasted in Section 6.6. Finally, the chapter wraps up the whole work by suggesting future study directions.

## **6.2 Background and Motivation**

Surveillance, recognition, tracking, localisation, and object identification are just a few of the growing WSN applications that rely on visual capabilities [168]. While most sensor nodes in WSNs run on batteries, this type of application is often utilised for continuous environmental monitoring. The primary goal of extending the life of sensors necessitates conserving the power of those batteries. Most power is used up during transmission in sensor nodes [169]. Energy may be saved by decreasing the quantity of data that must be sent. Compressing the data is one way to do this. There are several uses where the recent development of data compression methods has become crucial.

The development of mechanisms that enable the network to operate for extended periods of time using only the limited amounts of energy stored in or harvested by wireless sensor nodes is one of the greatest challenges in the construction of large-scale wireless sensor networks (WSNs) with practical applicability [170]. Since data transfer is typically the primary cause of a network's depleted energy reserves, methods to limit the quantity of data communicated by the sensor nodes are of major importance. The proposed effort is motivated primarily by the need to lessen the amount of network traffic by compressing data at its source.

Despite the incredible progress in the processing capabilities of embedded devices, most known algorithms still cannot be easily translated to wireless sensor nodes due

to the restricted hardware resources available, especially programme and data memory [171]. It is true that many of the time-tested compression methods could be run on contemporary wireless sensor nodes, but doing so would leave little computing power for the nodes to do other duties, such as sensing and communication. What's more, these nodes would have much fewer chances to enter deep sleep states and achieve the energy efficiency that necessitated the deployment of a compression technique. As a result, many different data compression techniques tailored to WSNs have been developed in recent years. The unifying denominator among these approaches is that they all leverage the correlation of the data obtained by the sensor nodes in order to get high compression ratios with computationally affordable techniques.

Run-Length Encoding (RLE), Huffman encoding, Golomb-Rice encoding, Lempel-Ziv-Welch (LZW), and wavelet compression are among the most well-known compression techniques [172]. Sensors may take in information in a variety of media types, such as text, photos, videos, and audio [173]. It's possible that various compression techniques will need to be applied to various forms of telemetry data. Discrete Fourier transforms (DFTs), LZW, and Flate algorithms, and JPEG coding were employed by Kattan et al [174] to compress textual material. Two practically lossless compression algorithms have been published [175] for telemetry data collected by hyperspectral sensors aboard a satellite. David et al [176] created a distributed compression framework that makes use of both source and channel coding.

This technique uses quantized and correlated side information to minimise the need for communication between nodes during the compression process. The technique for reconstructing noisy random projections from the data is presented, as well as a distributed architecture for matched source-channel communication, by Qian et al. [177]. Despite claims of universality, there are in fact trade-offs between power, distortion, and delay [178]. There is also no consideration of how the data are related to one another. Logeswaran et al. [179] and Rong et al. [180], suggested a grid-independent architecture for distributed wavelet analysis. The spatial link has not been well investigated, and it is unclear how to choose the optimal path for compression. Using a two-stage Lempel-Ziv lossless data compression technique [181]. Telemetry data is compressed from sensors aboard satellite launch vehicles. A modified version of the Rice compression algorithm [182] is used to compress data from a launch vehicle with a compression ratio of 2:1. Combining several data compression methods yields

a high compression ratio [183]. Correct hardware implementation of data compression is also crucial for enhancing compression performance [184-185]. Kao et al. offered a modularized approach to strike a compromise between hardware costs and a workable compression ratio [186]. Two-stage hardware architecture, as proposed by Hashempour et al. [187] is expected to improve compression and decompression times.

However, in most cases, WSNs are set up to keep tabs on some sort of target phenomena. In order to achieve compression ratios greater than those attained by state-of-the-art techniques, the authors of this study suggest a hybrid approach that combines Run length encoding with standard Huffman encoding.

An emerging use for WSNs is the use of their visual skills to keep an eye on things and identify, track, and locate specific items. For the most part, WSNs are used to keep tabs on the environment over the course of a lengthy period of time, and their sensor nodes often run on batteries. That's why it's so important to limit the use of those batteries to power sensors for as long as possible. Sensor nodes expend the bulk of their energy during transmission. Sending less data can help conserve power. Data compression is a viable option for doing this. The use of data compression techniques has increased in significance across a variety of contexts, especially in multimedia contexts.

The development of mechanisms that allow the network to operate for extended periods of time using only the limited amounts of energy that can be stored or harvested by wireless sensor nodes is one of the greatest challenges for large-scale wireless sensor networks (WSNs) with practical applicability [188]. Since data transmission between sensor nodes is a significant consumer of the network's resources, methods to reduce the amount of data transmitted between nodes are of paramount relevance. The fundamental objective of this research is to reduce network traffic through the use of local data compression before transmission.

Data compression is not new, but most current algorithms have difficulty being adapted to wireless sensor nodes due to the limited hardware resources, especially the programme and data memory [189]. Many of the time-honored compression techniques might be performed by today's wireless sensor nodes, but doing so would leave those nodes with fewer resources to devote to other tasks, such as sensing and

communication. These nodes were less likely to enter deep sleep after adopting a compression strategy, a feature crucial to optimising power consumption. A number of data compression methods tailored to WSNs have been introduced recently. Many computationally inexpensive ways to achieving high compression ratios rely on correlation of data acquired by sensor nodes.

However, WSNs are frequently employed to keep an eye on a single, carefully selected event. Through the combination of run length encoding and fundamental Huffman encoding, this study was able to achieve compression ratios that were higher than those obtained by the most advanced methods now in use.

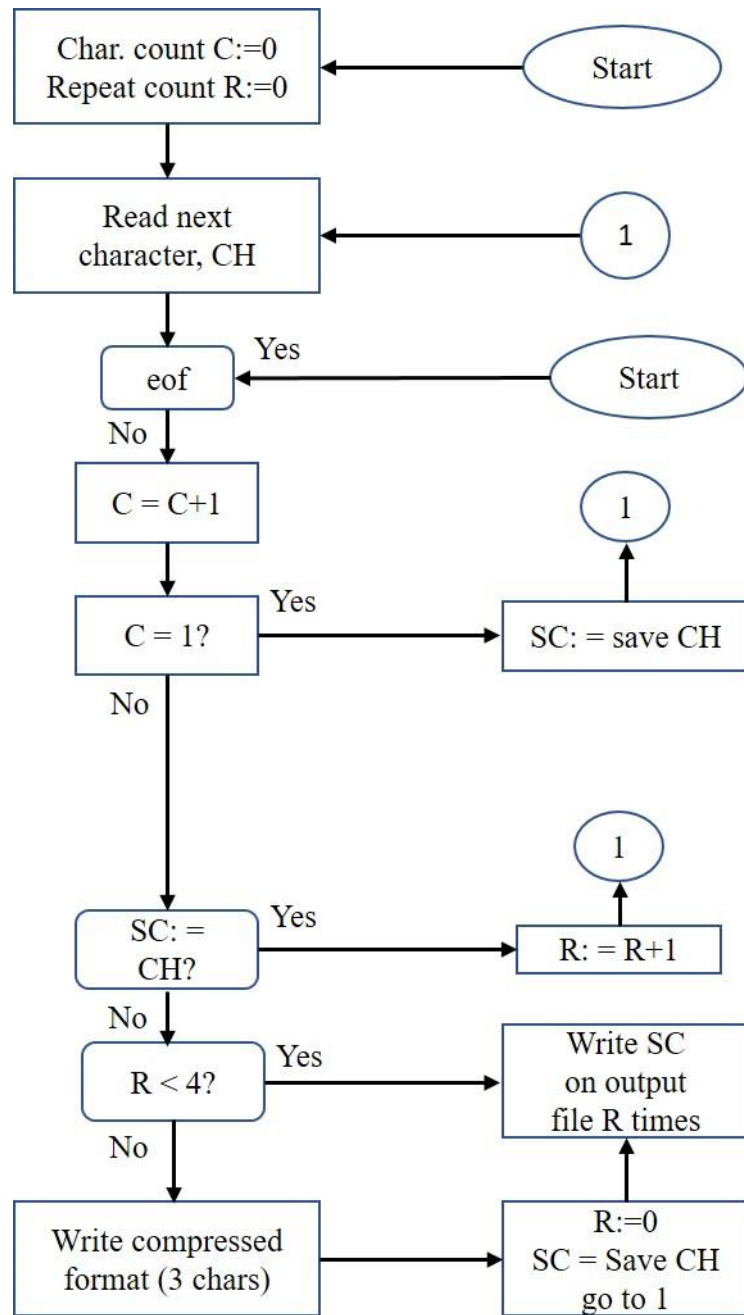
The suggested method's primary goal is to maximise compression while minimising power consumption, which is a problem that both RLE and AHE have in the context of a WSN situation. The primary issue with RLE is that its compression outcomes are data-source dependent. Adaptive Huffman coding is a more time-consuming method of compression since neither the sender nor the receiver has any prior knowledge of the source sequence's statistical properties. The proposed H-RLEAHE first compresses the data using the RLE approach, taking into account the statistics of the original data sources. Additionally, the AHE algorithm is fed the compressed data. The BS receives the compressed data and then uses the decompression method on it. In contrast to AHE, which guarantees a greater compression ratio without needing to know the data sources in advance, RLE relies on the correlation of data at the data sources in order to function.

### **6.3 Data compression Techniques for WSN**

In the next section, we'll go over the basics of the two main algorithms, RLE and AHE.

#### **6.3.1 RLE (Run Length Encoding)**

In the realm of compression algorithms, Run Length Encoding (RLE) is one of the simplest forms. This technique is based on the following basic principle, as presented in [190], if data item  $\mathbf{d}$  appears  $\mathbf{n}$  times in a row in the input stream, we replace all  $\mathbf{n}$  occurrences with the single pair  $(\mathbf{n}, \mathbf{d})$ . The fundamental RLE method is shown in graphical form in Figure 6.3 [191]. However, RLE's findings are data-dependent due to its dependence on the same sequential input stream.



**Figure 6.3:** The flowchart of the RLE Algorithm [165-191]

### 6.3.2 Adaptive Huffman Algorithm

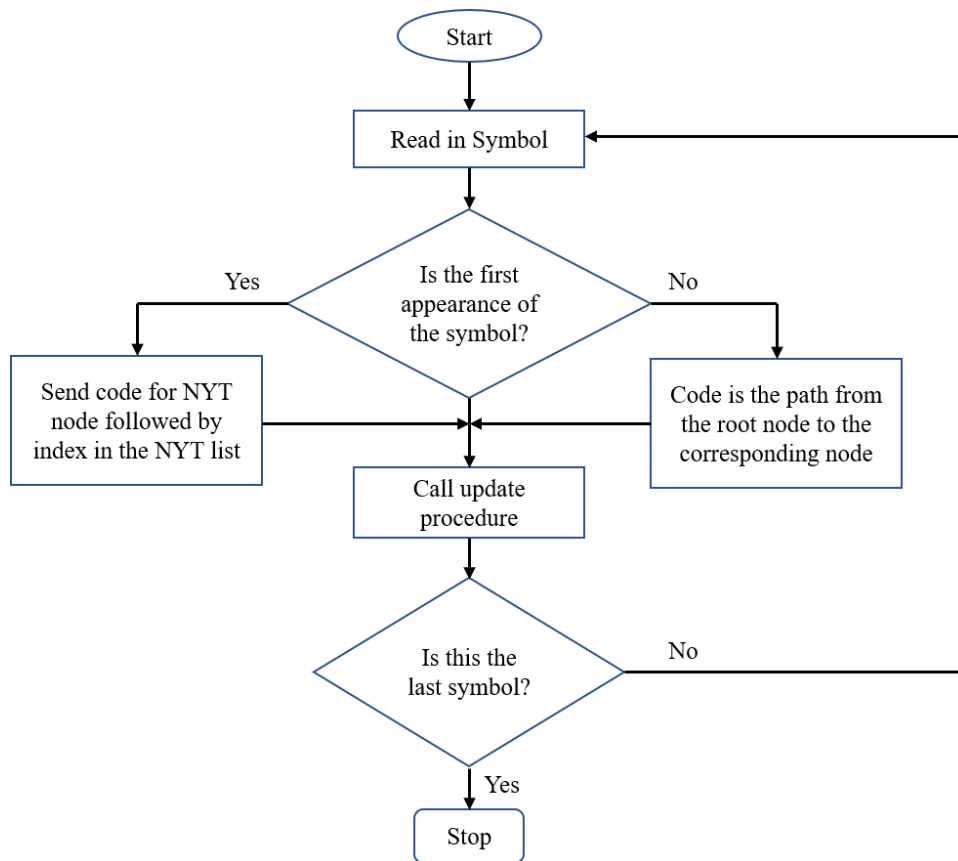
Knowledge of the source sequence's probability is required for the Huffman coding algorithm. If we don't have these statistics, then Huffman encoding must be done in two stages: first we obtain the data, and then we encode the source. Researchers working in isolation have developed adaptive algorithms that can construct the Huffman code based on the statistics of the symbols that have previously been observed [192]. Theoretically, if we wanted to encode the  $(k+1)$ -th symbol using the statistics of the first  $k$  symbols,

we could recompute the code using the Huffman coding procedure each time a symbol is transmitted. However, this would not be a very practical approach due to the large amount of computation involved—hence, the adaptive Huffman coding procedure is required.

In the adaptive Huffman coding procedure, neither transmitter nor receiver knows anything about the statistics of the source sequence at the start of transmission. The tree at both the transmitter and the receiver consists of a single node that corresponds to all symbols not yet transmitted (NYT) and has a weight of zero [193]. Adaptive Huffman encoding relies on knowing the probability of the starting sequence. In the absence of such information, the file in question will need to be compressed not once, but twice: once to save the obtained data, and once to save the encoded source code. At the outset of each given communication, neither the sender nor the receiver has any knowledge of the source sequence. Using adaptive Huffman coding, this is reduced to a single step. In both the sender's and receiver's trees, all symbols that have not yet been transmitted (NYT) are represented by a single node with no weight. The tree is dynamically modified when new symbols are added during transmission. Both endpoints of this signal originate from the same node. Both the sender and the receiver must perform the update procedure. This guarantees synchronicity between the encoding and decoding phases [194].

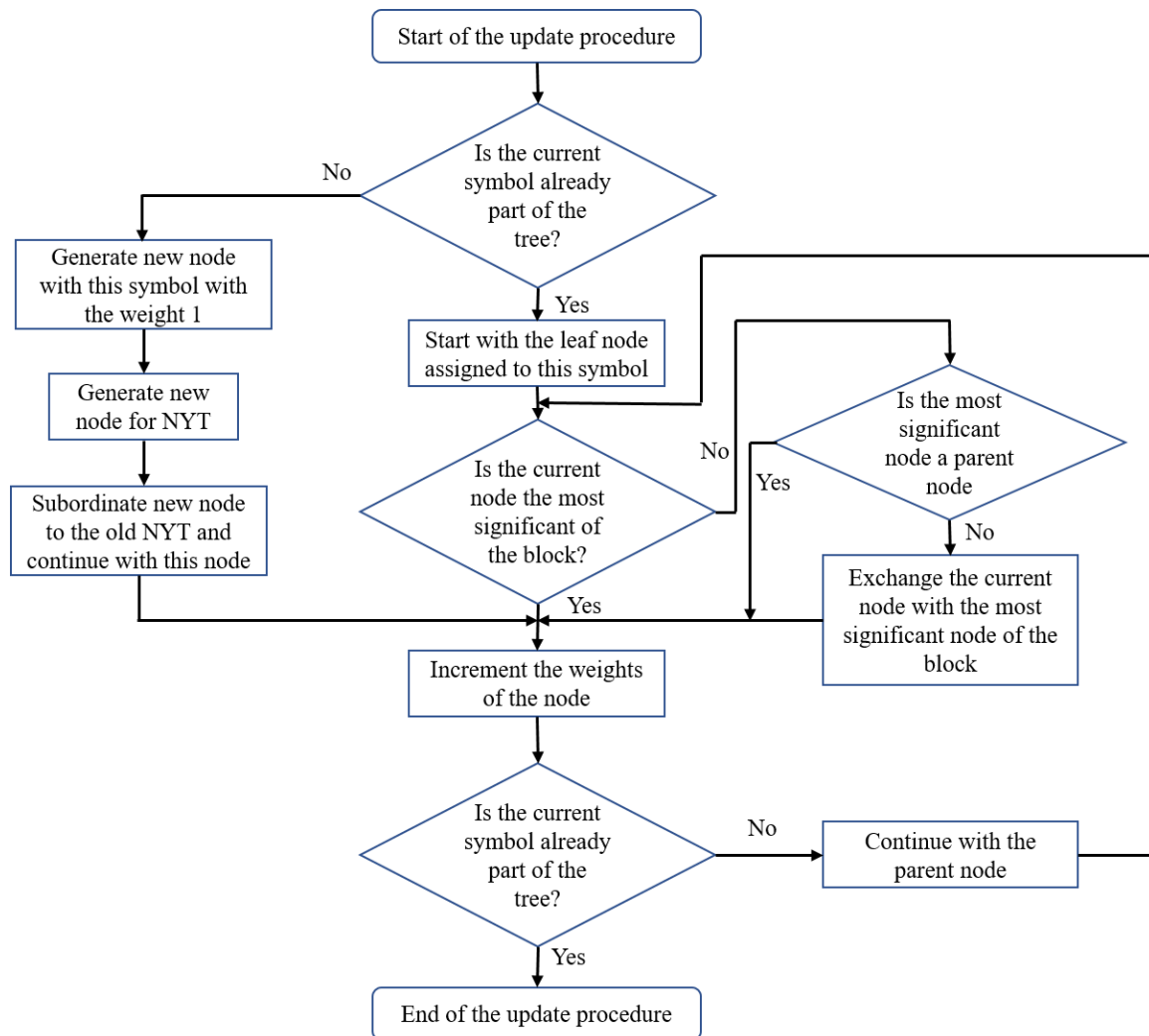
1) Encoding Procedure: The flowchart for the encoding procedure is shown in Figure 6.4.

Initially, the tree at both the encoder and decoder consists of a single node, the NYT node. Therefore, the codeword for the very first symbol that appears is a previously agreed-upon fixed code. After the very first symbol, whenever we have to encode a symbol that is being encountered for the first time, we send the code for the NYT node, followed by the previously agreed-upon fixed code for the symbol. The code for the NYT node is obtained by traversing the Huffman tree from the root to the NYT node. This alerts the receiver to the fact that the symbol whose code follows does not as yet have a node in the Huffman tree. If a symbol to be encoded has a corresponding node in the tree, then the code for the symbol is generated by traversing the tree from the root to the external node corresponding to the symbol.



**Figure 6.4:** The flowchart of the encoding procedure [195]

- 2) Update procedure The nodes must be organised in a specific sequence before the update procedure can be carried out. This hierarchy is preserved using node identifiers. The updating procedure is shown in Figure 6.5.



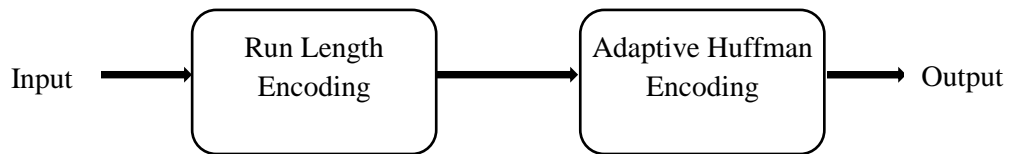
**Figure 6.5:** The update procedure of the AHE Algorithm [195]

#### 6.4 Hybrid model for Run Length Encoding with Adaptive Huffman Encoding

It is now clear that the classic Huffman method requires the availability of a probability distribution in order to produce the Huffman code. As an added downside, it may not work well in situations where the input symbol probabilities change over time [196]. In order to overcome Huffman coding's drawbacks, researchers developed an alternative method of forming Huffman trees, called Adaptive Huffman coding. Adaptive Huffman codes require a tree with a starting point of 0 and a counter for each symbol. The produced codes are superior to the Huffman code since the tree is generated on the fly. This is because the adaptive Huffman tree is generated on the fly, allowing for a single pass of the input text.

More importantly, for data with repeating symbols, RLE is one of the simplest compression methods and performs exceptionally well. However, its worst-case output size might be twice as large as its input, which is a major drawback of RLE. Therefore,

the study team proposes a strategy that combines RLE and AHA to overcome this constraint (see Figure. 6.5).



**Figure 6.6:** The flowchart of Hybrid Model

#### 6.4.1 Hybrid Algorithm

The H-RLEAHE algorithm contains two stages. In the initial stage of the encoding process, the data item  $d$  is replaced with the single pair  $nd$  if it appears  $n$  times in a row in the input stream. The H-RLEAHE is shown graphically in Figure 6.4. However, RLE's output is data-dependent due to its need on a continuous input stream. The ST file is downloaded via RLE. For the second phase, the tree at both the transmitter and the receiver consists of a single node that corresponds to all symbols not yet transmitted (NYT) and has a weight of zero. As transmission advances, nodes matching to symbols transferred will be added to the tree, and the tree is redesigned using an update mechanism. Before the beginning of transmission, a predetermined code for each symbol is agreed upon between transmitter and receiver. A symbol's fixed code is communicated after the NYT node's code has been sent the first time it appears. When this happens, a node is formed for the symbol, and it is removed from the NYT. The tree structure used by the sender and the recipient is identical. Both the transmitter and the receiver follow the same update method. Therefore, the encoding and decoding operations stay synchronised. The update technique requires that the nodes be in a set sequence. Numbering the nodes keeps them in their proper sequence. The tree's root is given the highest node number, while the NYT node is given the lowest. From the NYT leaf node down to the tree's trunk, the corresponding nodes are numbered from left to right, and from the lowest to highest level in the tree. The set of nodes with the same weight makes up a block.

### 6.4.2 Proposed Hybrid Algorithm

The proposed algorithm works in two phases: Initially the data is compressed using RLE algorithm, then in second phase, AHE algorithm is applied on the compressed data received from RLE. The parameters used in the proposed H-RLEAHE algorithm is given in the table 6.1. Further, the compression technique using the proposed algorithm and decompression is discussed thereafter.

**Table 6.1.** Parameters used in the proposed H-RLEAHE algorithm

Parameter	Description
$D_{in}$	A sequence of sensor data
$P_k$	Packet size
NYT	Not Yet Transmitted
$R_{code}$	Repeat count in RLE
Length	Length of the stream
Unique	Unique data in the stream
Final stream	Output stream packet
Loc	Location of the Pointer
Info()	Information about the node

The algorithm for the proposed model is given below:

#### **Algorithm 1:** Proposed H-RLEAHE Compression Algorithm

```

1. Input
   Packet Size =  $P_k$ 
   Input Data =  $D_{in}$  : A sequence of sensor data of length  $P_k$ 
2. Start:
3. Index = 1
4.  $R_{Code}(Index) = D_{in}(index)$ 
5.  $Info(Index) = 1$ 
6. for  $i = 2$  to  $P_k$  :
   if  $D_{in}(i-1) == D_{in}(i)$  :
      $Info(Index) = Info(Index) + 1$ 
   else :
      $Index = Index + 1$ 
      $R_{Code}(Index) = D_{in}(i)$ 
      $Info(Index) = 1$ 
   End if
   End for
7.  $NYT = unique(R_{Code})$ 
8.  $N = length(R_{Code})$ 
9.  $Loc = 1$ 
10. for  $i = 1$  to  $N$ 
     $Temp = R_{Code}(i)$ 
    If  $(NYT == Temp)$ 
       $Old\_Code = NYT\_Code(NYTlocation - 1)$ 
       $New\_Node = Weight\_Increment$  for  $Temp, OldCode$ 
    else

```

```

        Code=NYT_Code()
        Number=get_Number(Code)
11. Step:A
    if max(Number) in Block
        New_Node=Weight_Increment()
    else
        switch_Node to max Numbered Node
        New_Node=Weight_Increment()
    end
12. end
13. if New_Node in Root Node:
    Final_Stream(Loc)=New_Node
    Loc++
    exit()
    else
        Go to parent node in step A
    end
14. end
15. Output: Final_Stream

```

In the proposed algorithm, in step 1, data packet is initialized in bits. From step 2 to step 5, RLE algorithm is initialized. In step 6 for loop is initialized and checks if the character at current index is the same as the character at next index. If the characters are the same, the count increment to 1. If not the count and character are concatenated. Step 10 check for unique code and matches and store it in the location. In step 11, Adaptive Huffman encoding is applied. The algorithm for decompression is given below.

**Algorithm 2:** Proposed H-RLEAHE Decompression Algorithm

```

1. loop=1
2. While (loop<length(Final_Stream))
    Temp= Final_Stream(loop)
    If (Temp ==NYT)
        Val=Freq_increment(Temp)
        Update(Tree)
    else
        Readbits_(NewNYT)
        Val=Get_NYT()

        Add_NYT to tree
    end
3. AHcode(Loc)=Val
4. loop++
5. end
6. Final_Data=empty array
7. Count, AHcode =SeperateCountData(AHcode)

```

```

8. For i 1 to length(AHcode)
9.     Final_Data(i)= AHcode(i)*ones(Count(i))
10. End
11. Decompressed_Data=Final_Data

```

## 6.5 Performance measures

The following measures are applied to analyses the performance of different data compression algorithms.

- a) Compression Ratio (CR): The data compression ratio is defined as the ratio of the uncompressed data size, in bits,  $b_{uc}$  and compressed size, in bits,  $b_c$ . is written as shown in equation (6.1) [197]

$$CR = \frac{b_{uc}}{b_c} \quad (6.1)$$

- b) Compression Time (CT): The time it takes to compress the original data. [197]  
c) Energy consumed during data compression or CPU cost: This analyses the energy used when compressing data.  
d) Transmission cost: The amount of energy consumed to transmit compressed data

### 6.5.1 Analysis of RLE, AHE, H-RLEAHE and H-AHERLE algorithm

In this section we have used real world data [198] to analyze the compression ratio of different algorithms with data varying size. Again, suppose the length of original data is  $L$  and the length of compressed data is  $K$ . Hence, we have formulated the energy consumption of different algorithms and used the MSP430 microcontroller. The hardware powered with a 16-bit CPU developed to support resource limited systems. The supply voltage is  $V_{CC} = 3.3V$ , the clock rate is  $F_{CLK} = 3.3MHz$ , and the current consumption of the complete TIMSP430 system during the active mode is  $I_{MSP430} = 1.85mA$  Hence, the power consumption of the TIMSP430 micro-controller per clock cycle is given by equation (6.2). The energy consumed for transmitting and receiving one bit of data is given by equation (6.3) [199-200].

$$E_{CLK} = V_{CC} \times I_{MSP430} / F_{CLK} = 1.85nJ \quad (6.2)$$

$$S_{bit} = V_{CC} * I_{TX} / D_r = 230nJ \quad (6.3)$$

where  $V_{CC} = 3.3V$ ,  $I_{TX} = 17.4mA$  and  $D_r = 250$  kbps

Table 6.2 shows how basic CPU activity cycles may be utilised to indicate the energy required to transport data while using compression.

**Table 6.2:** CPU cycles for the TIMSP430 microocntroller [200]

Operations	# of CPU cycles
Addition	184
Subtraction	177
Multiplication	395
Division	405
Comparison	37

Finally, we use the design components to figure out the computational complexity (in number of clock cycles) of different data compression algorithms for compressing the input data using the  $EC_{\text{algo}}(L1, K)$ .

where  $EC_{\text{algo}}$  is the energy consumption of algorithm,  $L1$  is the actual input data and  $K$  is the compressed data.

We have used actual data input of 1500 bits and the data compressed for difference algorithms is mentioned below. Further, we have evaluated the CPU and transmission cost.

- a) CPU cost for RLE is formulated as in equation (6.4)

$$EC_{RLE} = \left( (2 * 184) + (1 * 37) \right) * L1 * 1.85e - 9; \quad (6.4)$$

where  $L1$  is the compressed data of RLE & compressed bits is 70 bits , CPU cost is 0.00018731 J and transmission cost is  $S_{bit} * 70 \text{ bits}$  is 1.61 e-05 J. RLE algorithm uses two addition operators and one compariosn operator.

- b) CPU cost for AHE is formulated as in equation (6.5)

$$EC_{AHE} = \left( (9 * 184) + (4 * 177) + (1 * 395) + (1 * 405) + (14 * 37) \right) * L1 * 1.85e - 9; \quad (6.5)$$

where  $L$  is the compressed data of AHE & compressed data is 330bits, CPU cost is 0.0017029 J and transmission cost is  $S_{bit} * 330 \text{ bits}$  is 7.59e-05 J. In equation (5) there are 9 addition operators 4 subtratctions, 1 multiplication, 1 division and 14 comaprison operators.

- e) CPU cost for H-RLEAHE is formulated as in equation (6.6)

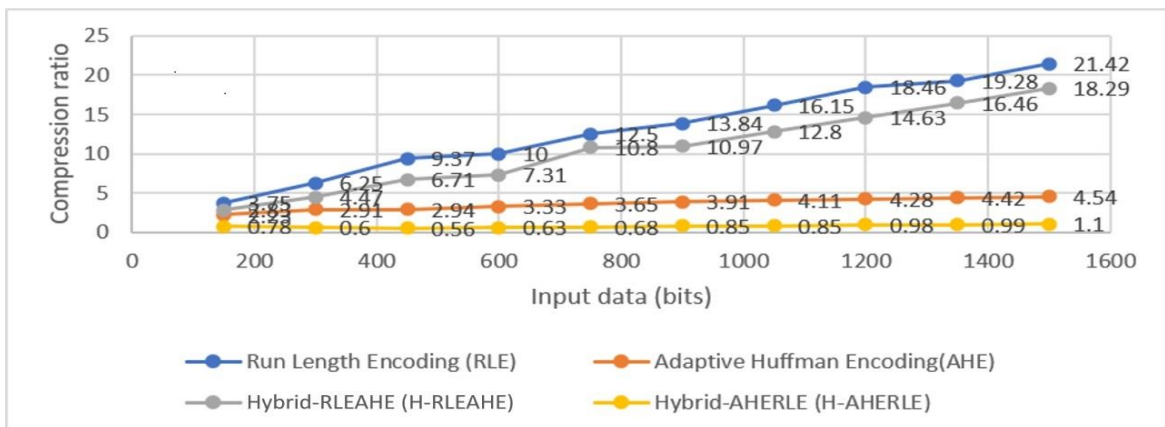
$$EC_{H-RLEAHE} = \left( ((2 * 184) + (1 * 37)) * L1 + ((9 * 184) + (4 * 177) + (1 * 395) + (1 * 405) + (14 * 37)) * K_{H1} \right) * 1.85e - 9; \quad (6.6)$$

where L1 is the compressed data of RLE, the  $K_{H1}$  is the compressed data of H-RLEAHE and data compressed is 82, CPU cost is 0.00025543 J and transmission cost is  $S_{bit} * 82$  bits is 1.886e-05 J. From equation 6 we can observe that there are two addition operators, one comparison, 23 addition operators, 4 subtractions, 1 division and multiplication and 1 comparison operators.

f) CPU cost for H-AHERLE is formulated as in equation (6.7)

$$EC_{H-AHERLE} = \left( ((9 * 184) + (4 * 177) + (1 * 395) + (1 * 405) + (14 * 37)) * L1 + ((2 * 184) + (1 * 37)) * K_{H2} \right) * 1.85e - 9; \quad (6.7)$$

where L1 is the compressed data of AHE,  $K_{H2}$  is the compressed data of H-AHERLE and data compressed is 1360, CPU cost is 0.0019502 J and transmission cost is  $S_{bit} * 1360$  bits is 0.0003128 J. Operators used in equation 7 is 23 additions, 4 subtractions, 1 multiplication and division, and 1 comparison. It can be clearly seen that the data compression ratio, transmission cost and CPU cost for RLE is better than the other data compression algorithms. Hence based on the above equations we have analysed the compression ratio of different algorithms with varying data size from 0 to 1500 bits as shown in Figure 7. It can be clearly seen that the compression ratio of RLE is better than Hybrid-RLEAHE, AHE and Hybrid-AHERLE. For instance, the compression ratio for 1500 bits for RLE is 21.42, H-AHERLE is 18.29, AHE is 4.54 and H-AHERLE is 1.1. Hence from the analysis and compression ratio results we have considered only RLE, AHE and H-RLEAHE in our further studies.



**Figure 6.7:** Compression ratio with data varying size in bits

## 6.6 Network Setup and Scenario Analysis

As discussed in previous chapter, following are the different network parameters setup that have been used during simulation of proposed methodology as shown in Table 6.3.

This section, the study considers a two-dimensional network model [201] with sensor nodes, considering the assumptions given below:

- All sensor nodes are considered stationary.
- Study assumes one BS where the data collected from source IoT nodes are destined for.
- Homogeneous SNs with similar processing and communication capability. Also, it considers that SNs are deployed with the same initial energy.
- SNs deployed randomly are always located with its x and y coordinates in the topological area.
- The distance between the two neighbouring SNs is evaluated using Euclidean distance.

**Table 6.3:** Network parameter setup

<b>Base station location</b>	2x4, 100 nodes (Centre, left edge, top edge and corner) 4x4, 100 nodes 4x4, 200 nodes (Centre, left edge, top edge and corner) 10x10, 625 nodes 10x10, 1250 nodes
<b>Number of Rounds</b>	1500 rounds

## 6.7 Results and Discussion

The study is further tested in different scenarios with varying network area, number of grids/clusters, and total number of nodes as shown in Table 6.4., where the number of grids varies at different cases and ranges between 8 and 100 with node population ranging from 100 to 1250 based on the size of the network area. The hybrid routing protocol and its network configuration form the base for the scenarios' routing [202].The details of these scenarios are given in Table 3.

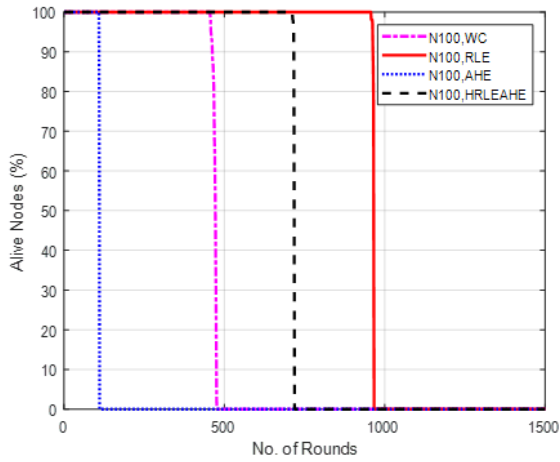
**Table 6.4:** Different network setups for simulation

Case Study	Network Area	Number of Grids	Total Number of Nodes
1	100 m × 100 m	2×4	100
2	100 m × 100 m	4×4	100
3	200 m × 200 m	4×4	200
4	500 m × 500 m	10×10	650
5	500 m × 500 m	10×10	1250

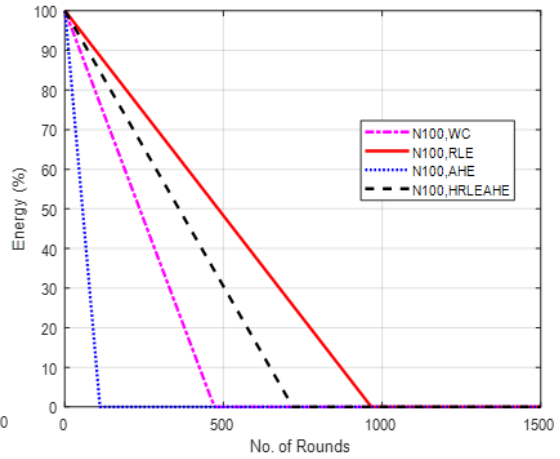
The entire setup is in an area with the base station located at various locations as shown in Table 6.3. The conventional data compression algorithm RLE and AHE is compared with H-RLEAHM and without compression with the parametric settings given in Table 6.3 and the grid formation is shown in Table 6.4. The performance evaluation is done based on total number of packets reaching BS, total number of alive nodes, residual energy of the network, packet delivery ratio (PDR), and throughput of the network. Packet Delivery Ratio (PDR) indicates the ratio of packets that the sink or destination receives to the entire number of packets sent by source. Following subsections demonstrate the performance evaluation based on different grid configurations and network settings..

### 6.7.1 Case Study 1-1: 2x4 grids, 100 nodes, BS at Center

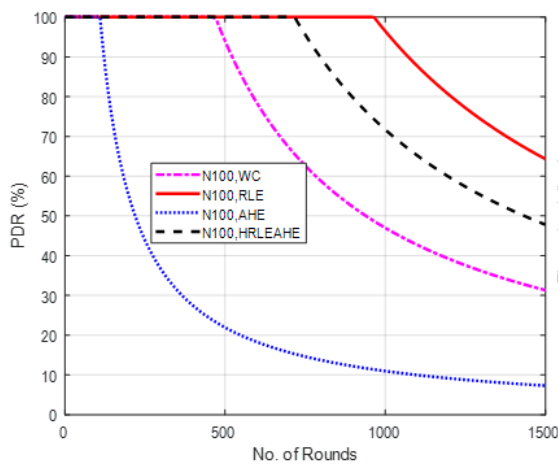
Figure 6.8 shows the results of Case Study 1: 2×4 grids, 100 Nodes, where the base station is placed at the center. The comparative results of performance metrics Figure 6.8(a) show that with 100 nodes, the network remains alive up to 118 (AHE), 484 (without compression), 740 (H-RLEAHE) and 982 (RLE) rounds, respectively. Compared to RLE, the network lifetime reduces by 87.98%, 50.71% and 24.64% respectively for AHE, WC and H-RLEAHE. The increase in the number of rounds for which the network remains alive can be safely attributed to the lesser data to be communicated to the BS as the compression techniques reduce the data significantly. The visualization of average energy in the nodes can be seen from Figure 6.8(b), validating the higher energy in the nodes in the RLE method vis-à-vis other strategies. Further, packet delivery ratio also demonstrates an improvement as shown in Figure 6.8(c). Similarly, Figure 6.8(d) demonstrates an improvement in throughput by sending packets up to 982 rounds. The average packets sent to BS/round is also increased significantly as shown in Figure 6.8(e).



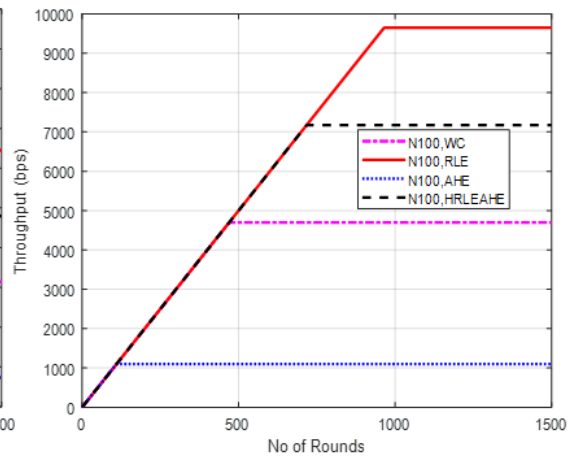
**Figure 6.8(a)** Alive Nodes in Case Study 1-1



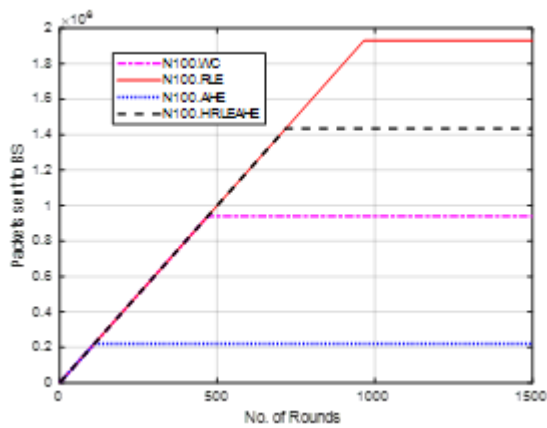
**Figure 6.8(b)** Energy in Case Study 1-1



**Figure 6.8(c)** PDR in Case Study 1-1



**Figure 6.8(d)** Throughput in Case Study 1-1



**Figure 6.8(e)** Packets sent to BS in Case Study 1-1

**Figure 6.8:** Results of Case Study 1-1 :  $2 \times 4$ , 100 Nodes, BS at Center

### 6.7.2 Case Study 1-2: 2x4 grids, 100 nodes, BS at top edge

This scenario demonstrated in Figure 6.9 considers placement of BS at top edge. Here, the alive nodes show that with 100 nodes, the network remains alive up to 111 (AHE), 480 (without compression), 733 (H-RLEAHE) and 968 (RLE) rounds respectively. Compared to RLE, the network lifetime reduces by 88.53%, 50.41% and 24.27% respectively for AHE, WC and H-RLEAHE. Also, the throughput reduces for AHE by 88.25%, without compression by 51.28% and for H-RLEAHE it reduces by 25.64% compared to RLE.

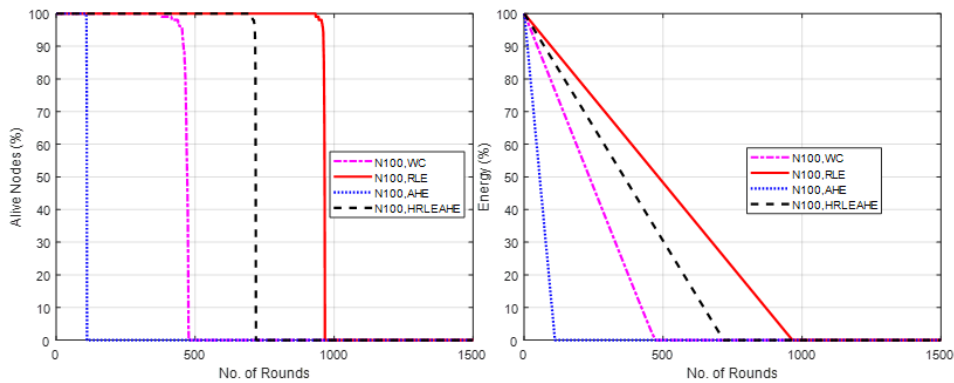


Figure 6.9(a) Alive Nodes in Case Study 1-2

Figure 6.9(b) Energy in Case Study 1-2

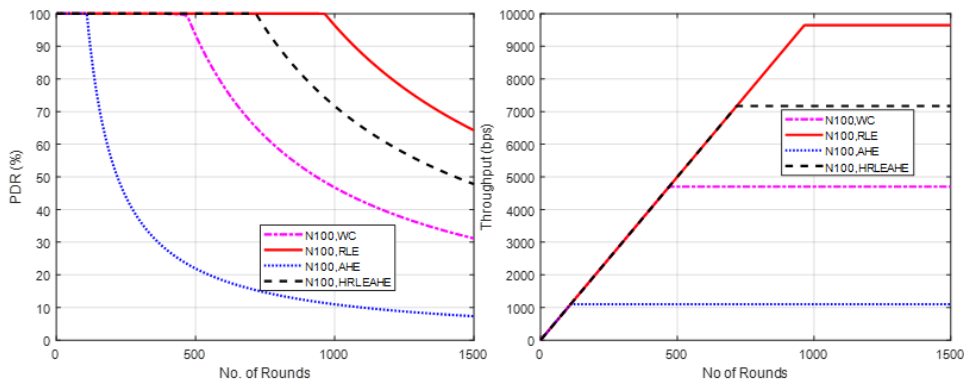


Figure 6.9(c) PDR in Case Study 1-2

Figure 6.9(d) Throughput in Case Study 1-2

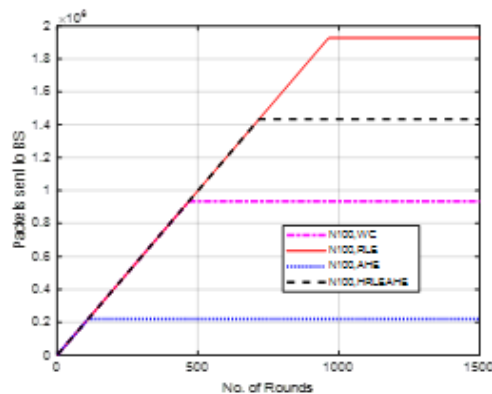
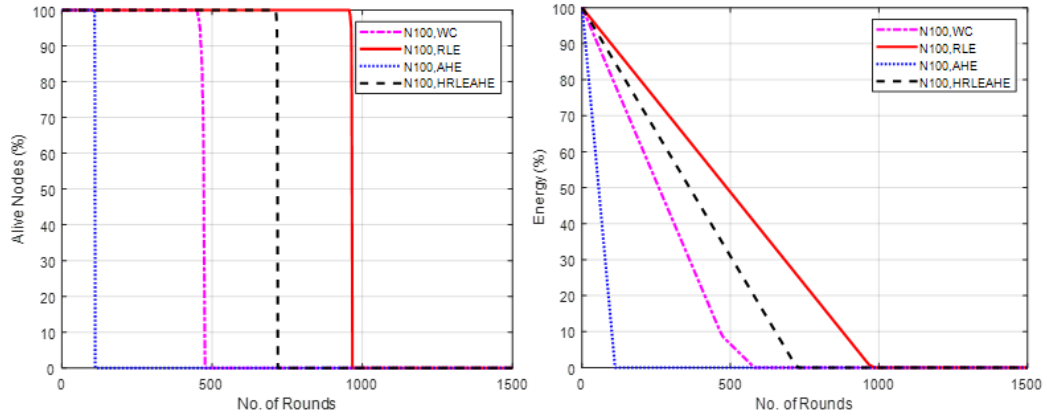


Figure 6.9(e) Packets sent to BS in Case Study 1-2

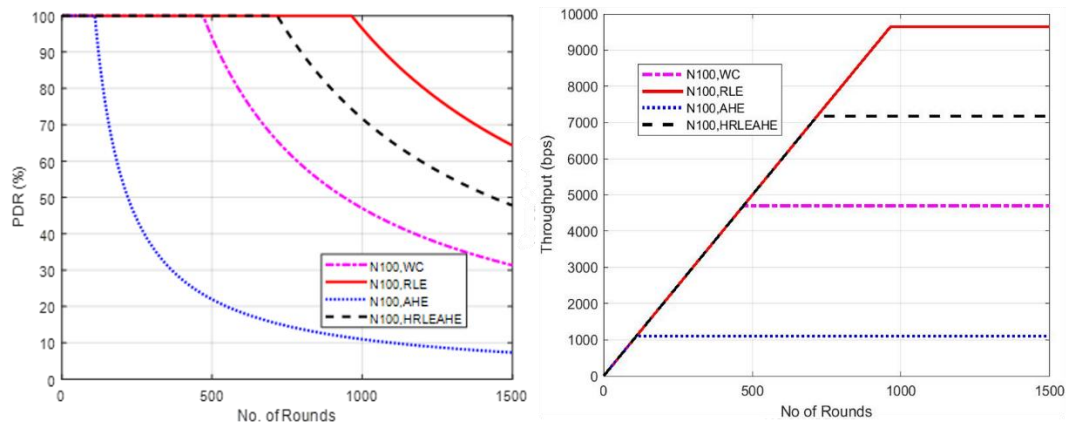
Figure 6.9: Results of Case Study 1-2: 2x4, 100 Nodes, BS at Top edge

### 6.7.3 Case Study 1-3: 2x4 grids, 100 nodes, BS at left edge

The scenario demonstrated in Figure 6.10 considers placement of BS at left edge. Here, the alive nodes for AHE, without compression and H-RLEAHE techniques reduces by 88.56%, 49.84% and 24.51% rounds respectively compared to RLE. Also, the throughput for AHE, without compression and H-RLEAHE technique is reduced by 88.36%, 50.67% and 25.10% respectively compared to RLE.

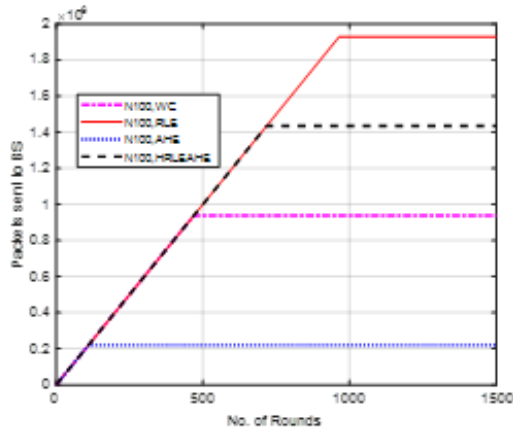


**Figure 6.10(a)** Alive Nodes in Case Study1- 3 **Figure 6.10(b)** Energy in Case Study1- 3



**Figure 6.10(c)** PDR in Case Study 1-3

**Figure 6.10 (d)** Throughput in Case Study 1-3

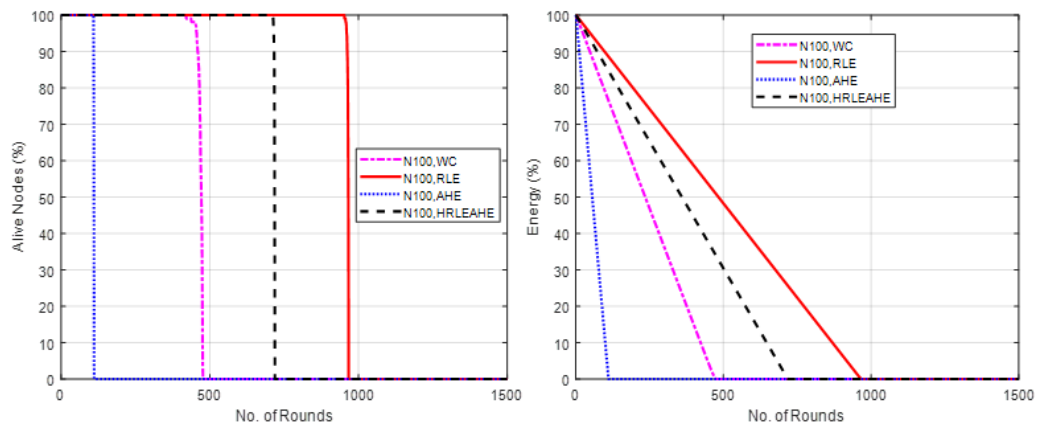


**Figure 6.10(e)** Packets sent to BS in Case Study 1-3

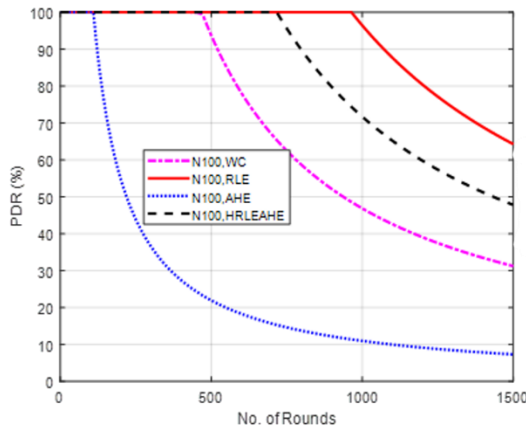
**Figure 6.10:** Results of Case Study 1-3: 2x4, 100 Nodes, BS at left edge

#### 6.7.4 Case Study 1-4: 2x4 grids, 100 nodes, BS at Corner

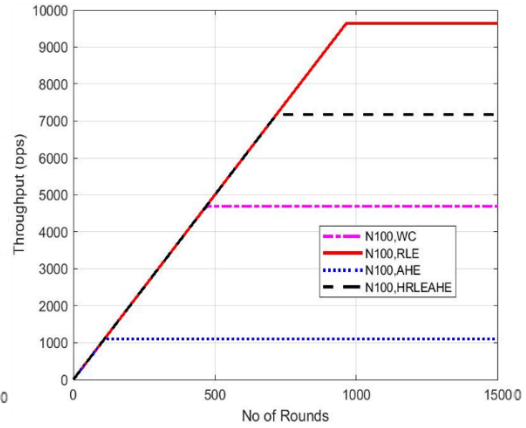
The scenario demonstrated in Figure 6.11 places BS at a corner. Here, the network lifetime for AHE, without compression and H-RLEAHE techniques reduces by 88.02%, 48.63% and 21.81% respectively compared to RLE. Also, the throughput for AHE, without compression and H-RLEAHE technique is 88.01%, 50.82% and 24.89% respectively compared to RLE.



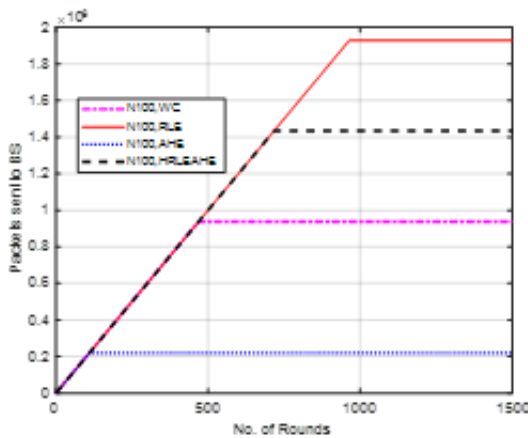
**Figure 6.11(a)** Alive Nodes in Case Study1-4 **Figure 6.11(b)** Energy in Case Study 1-4



**Figure 6.11(c)** PDR in Case Study 1-4



**Figure 6.11(d)** Throughput in Case Study 1-4



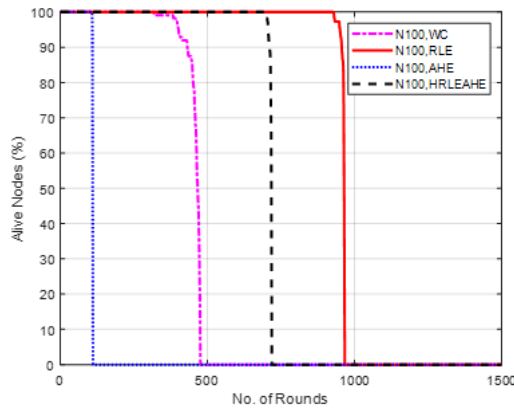
**Figure 6.11(e)** Packets sent to BS in Case Study 1-4

**Figure 6.11:** Results of Case Study 1-4:  $2 \times 4$ , 100 Nodes, BS at corner

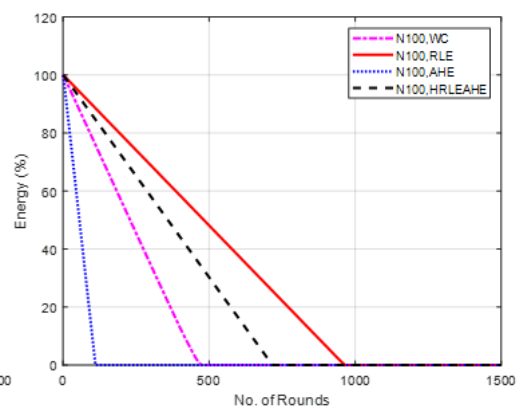
### 6.7.5 Case Study 2: $4 \times 4$ grids, 100 nodes, BS at center

Figure 6.12 shows the results of Case Study 2:  $4 \times 4$  grids, 100 nodes, where the network structure is divided into 16 grids with the different cluster heads deployed at random locations and connected to the BS at the center. The results of alive nodes in figure 6.12 (a) shows that with 100 nodes, the network remains alive up to 111 (AHE), 475 (without compression), 719 (H-RLEAHE) and 964 (RLE) rounds respectively. Compared to RLE, the network lifetime reduces by 88.48%, 50.62% and 25.41% respectively for AHE, WC and H-RLEAHE. Further, RLE demonstrates an overall increase in the average energy of the network as shown in figure 6.12(b). The results in Figure 6.12(c) illustrates that packet delivery ratio is higher in RLE as compared to other techniques. Similarly, the total throughput in the network is improved in the RLE as can be visualized in Figure 6.12(d). Finally, packets sent to the BS is also increased

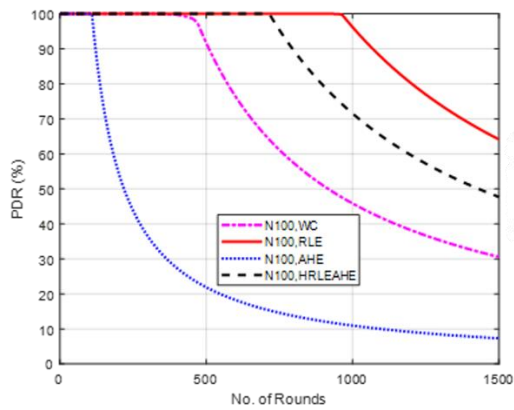
for more number of rounds in RLE as compared to AHE, no compression and H-RLEAHE respectively as shown in Figure 6.12(e).



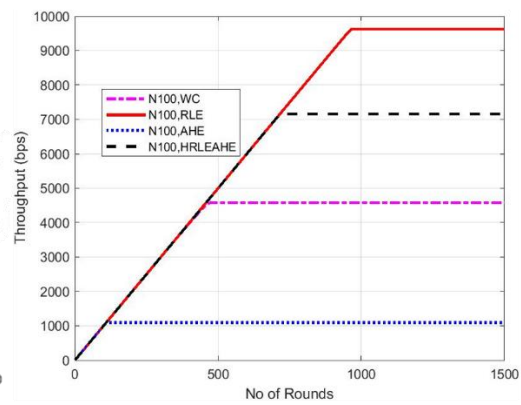
**Figure 6.12(a)** Alive Nodes for Case Study 2



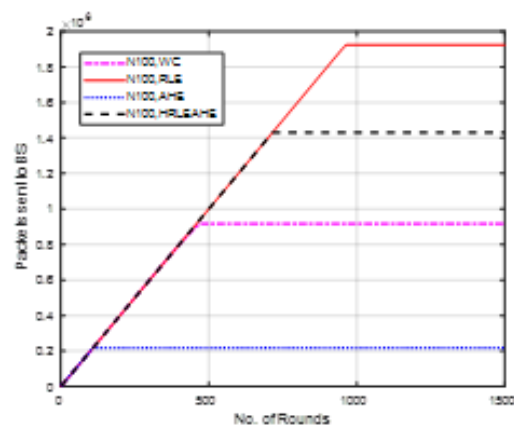
**Figure 6.12(b)** Energy for Case Study 2



**Figure 6.12(c)** PDR for Case Study 2



**Figure 6.12(d)** Throughput for Case Study 2



**Figure 6.12(e)** Packets sent to BS for Case Study 2

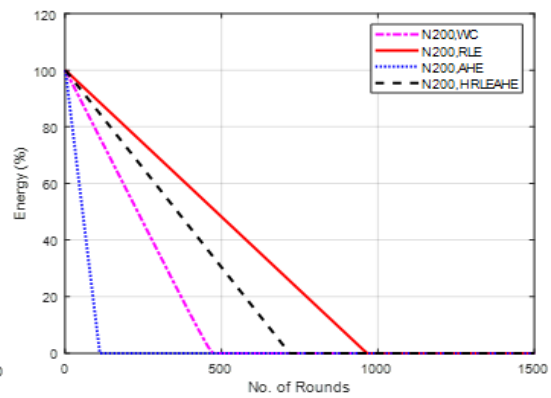
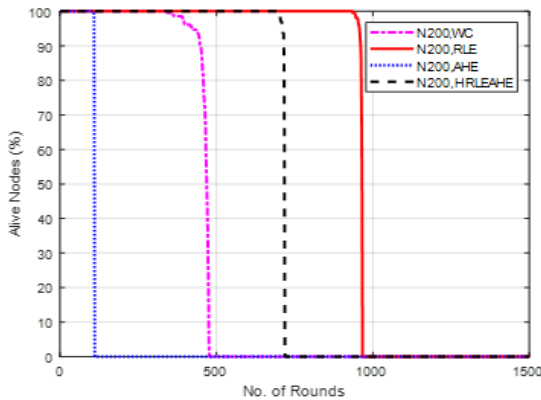
**Figure 6.12:** Results of Case Study 2: 4x4, 100 Nodes, BS at Center

Comparing Case study 1: 2x4 grids, 100 nodes to this, it is clear that while the total number of nodes in both cases is the same, there is a significant distinction in the grid

layout. The network performs better in terms of the examined parameters when it is constructed with a 4x4 grid. For example, data compression extends network life by 980 rounds as compared to no data compression. Additionally, the network's topology has shown some improvement in other metrics.

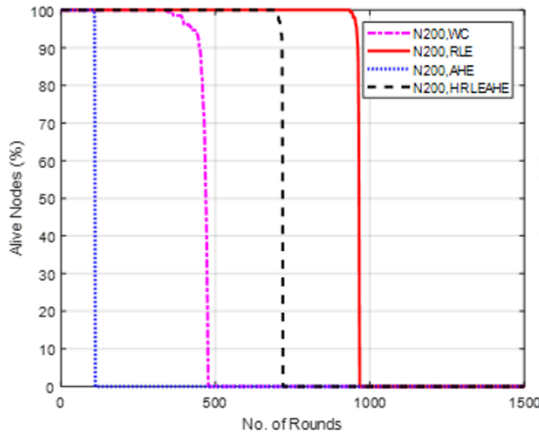
### 6.7.6 Case Study 3-1: 4x4, 200 Nodes, BS at center

Results from Case Study 3-1: 4x4 grids, 200 nodes with the BS at the centre of the network are shown in Figure 6.13. For RLE compression technique the network is alive for 968 rounds compared to 118 rounds, 478 rounds and 722 rounds for AHE, no compression and H-RLEAHE respectively. This shows that network lifetime for AHE, without compression (WC) and H-RLEAHE reduces by 87.80%, 50.61% and 25.41% respectively compared to RLE. Further, the average energy in the network is improved as the compression technique reduces the data leading to lesser transmission of data and thereby more energy in the network (Figure 6.13(b)). Figure 6.13(c) and Figure 6.13(d) also demonstrate similar trends with respect to PDR and throughput. Figure 6.13(e) further demonstrates the efficacy of RLE in terms of average packets sent to the BS compared to AHE, no compression and H-RLEAHE techniques respectively.

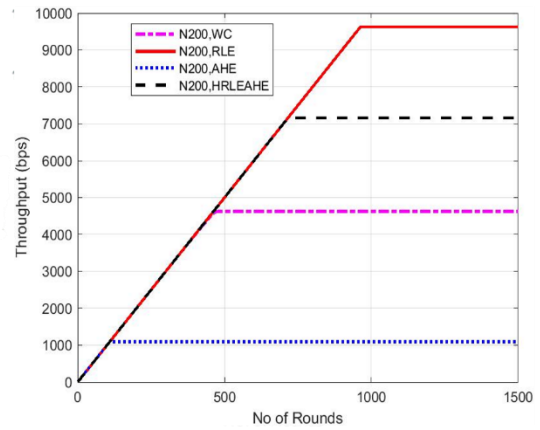


**Figure 6.13(a)** Alive Nodes for Case Study 3-1

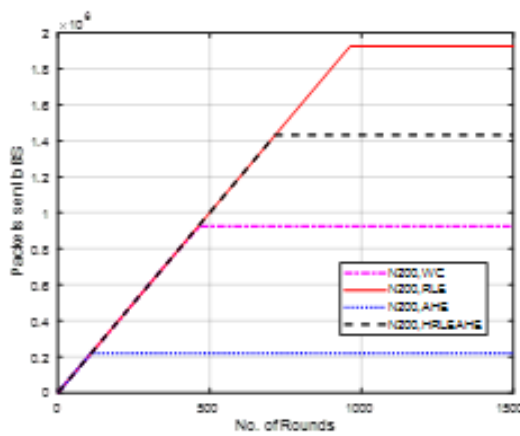
**Figure 6.13(b)** Energy for Case Study 3-1



**Figure 6.13(c)** PDR for Case Study 3-1



**Figure 6.13(d)** Throughput for Case Study 3-1



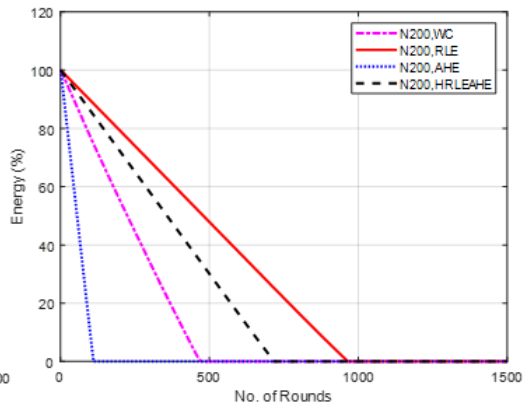
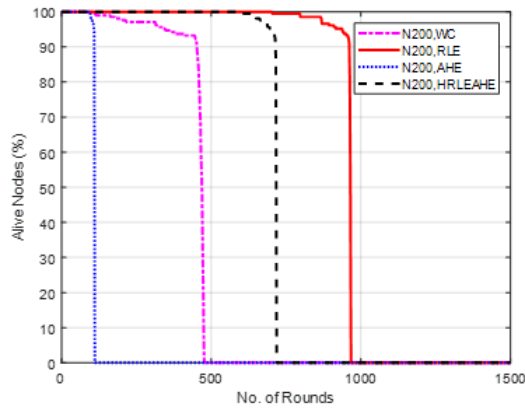
**Figure 6.13(e)** Packets sent to BS for Case Study 3-1

**Figure 6.13:** Results of Case Study 3: 4x4, 200 Nodes, BS at Centre

To draw the comparison of performance metrics with respect to the case study 2, where the number of grids is same i.e., 16 but the number of nodes is higher i.e., 200 nodes, the network remains alive for 58000 rounds vis-à-vis 2000 rounds. Moreover, from fig. 6.11(c) to 6.11(e), minimal improvement in other parameters is witnessed.

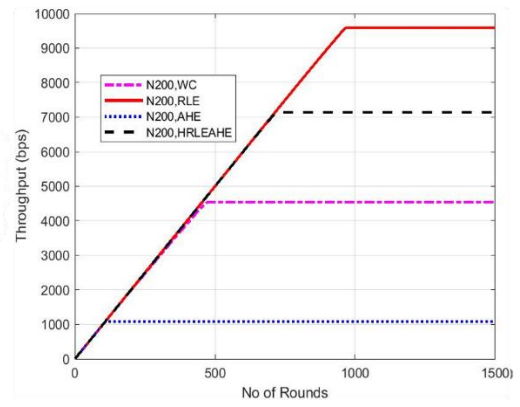
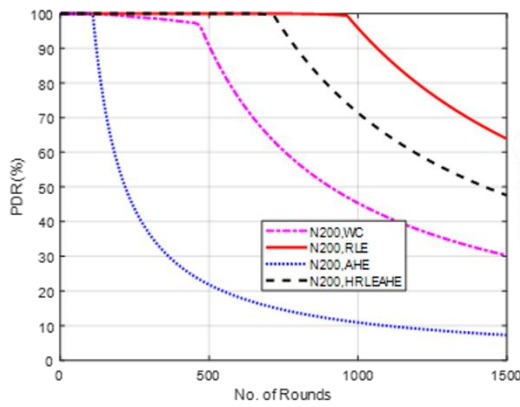
### 6.7.7 Case Study 3-2: 4x4, 200 Nodes, BS at top edge

The scenario demonstrated in Fig. 6.14 places BS at top edge. Here, the network stays alive for 111(AHE), 474 (without compression), 722 (H-RLEAHE), and 971 (RLE) rounds. The network lifetime reduces by 88.56%, 51.18% and 25.64% for AHE, WC and H-RLEAHE respectively compared to RLE. Also, the throughput for AHE, without compression and H-RLEAHE technique reduces by 87.95%, 51.69% and 25.95% respectively compared to RLE.



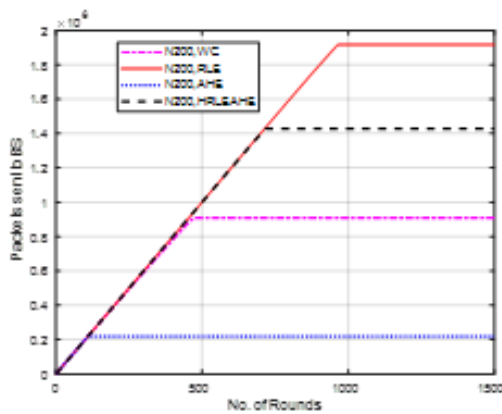
**Figure 6.14(a)** Alive Nodes for Case Study 3-2

**Figure 6.14(b)** Energy for Case Study 3-2



**Figure 6.14(c)** PDR for Case Study 3-2

**Figure 6.14(d)** Throughput for Case Study 3-2



**Figure 6.14(e)** Packets sent to BS for Case Study 3-2

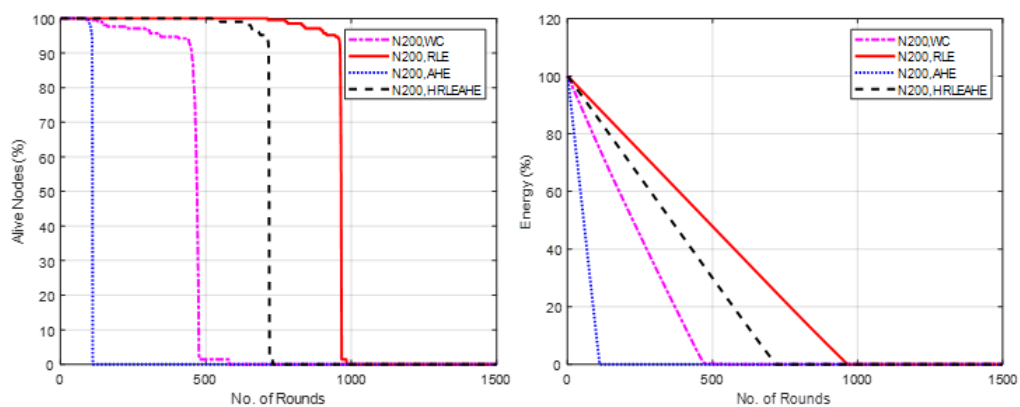
**Figure 6.14:** Results of Case Study 3-2: 4x4, 200 Nodes, BS at top edge

The scenario demonstrated in Fig. 6.14 places BS at top edge. Here, the alive nodes for H-RLEAHE, AHE and without compression techniques remain up to 17.03%, 367.59% and 1963.63% rounds respectively advocating the supremacy of proposed

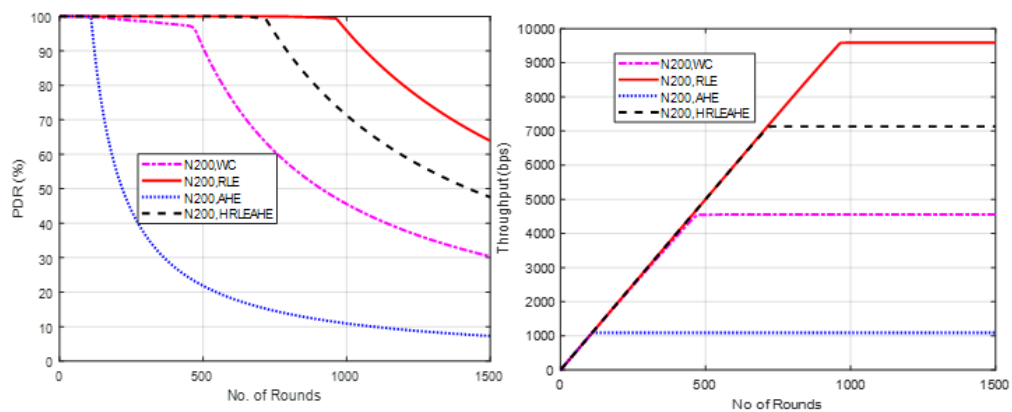
model. Also, the throughput for H-RLEAHE, AHE and without compression technique is 21.91%, 378.30% and 2148.79% respectively

### 6.7.8 Case Study 3-3: 4x4, 200 Nodes, BS at Left edge

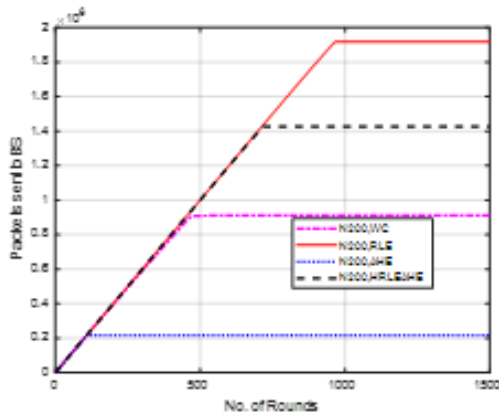
The scenario demonstrated in Figure 6.15 places BS at the left edge. Here, the network lifetime for AHE, without compression and H-RLEAHE techniques reduces by 87.89%, 50.05% and 25.12% respectively when compared to RLE. Also, the throughput for AHE, without compression and H-RLEAHE model is reduced by 88.33%, 51.97% and 25.10% respectively compared to RLE.



**Figure 6.15(a)** Alive Nodes for Case Study 3-3      **Figure 6.15(b)** Energy for Case Study 3-3



**Figure 6.15(c)** PDR for Case Study 3-3      **Figure 6.15(d)** Throughput for Case Study 3-3

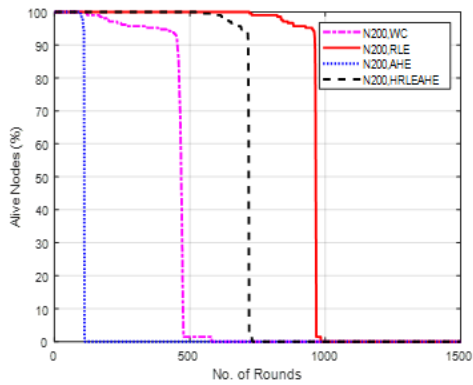


**Figure 6.15(e)** Packets sent to BS for Case Study 3-3

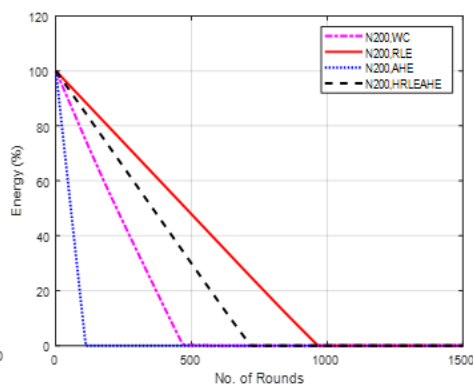
**Figure 6.15:** Results of Case Study 3-3: 4x4, 200 Nodes, BS at left edge

### 6.7.9 Case Study 3-4: 4x4, 200 Nodes, BS at Corner

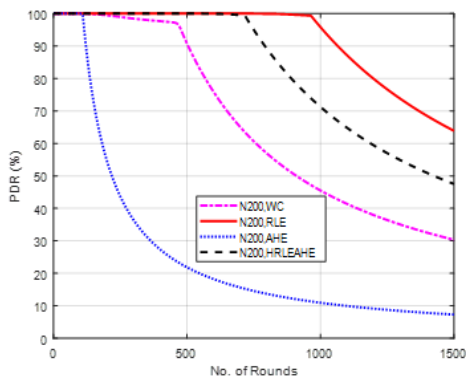
The scenario demonstrated in Figure. 6.16 places BS at a corner. Here, the network lifetime for AHE, without compression and H-RLEAHE techniques reduces by 87.80%, 51.01% and 25.80% respectively compared to RLE. Also, the throughput for AHE, without compression and H-RLEAHE techniques reduces by 87.86%, 52.48% and 25.20% respectively compared to RLE.



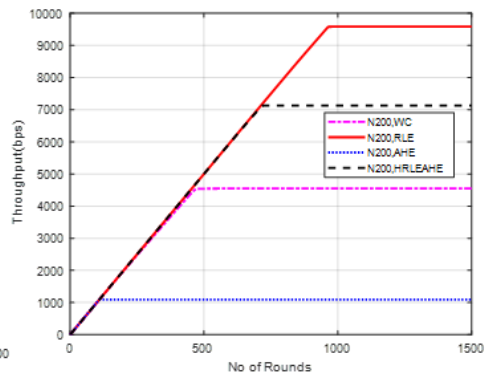
**Figure 6.16(a)** Alive Nodes for Case Study 3-4



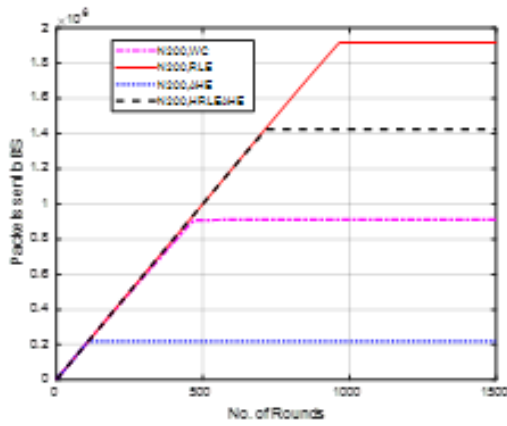
**Figure 6.16(b)** Energy for Case Study 3-4



**Figure 6.16(c)** PDR for Case Study 3-4



**Figure 6.16(d)** Throughput for Case Study 3-4

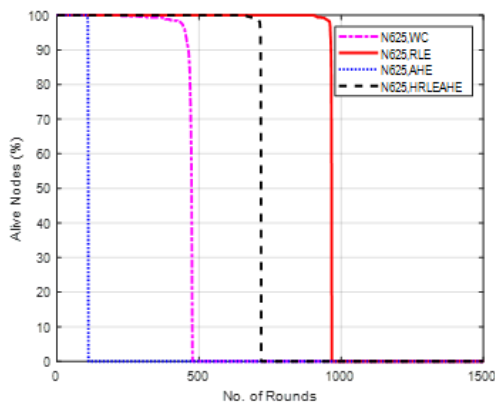


**Figure 6.16(e)** Packets sent to BS for Case Study 3-4

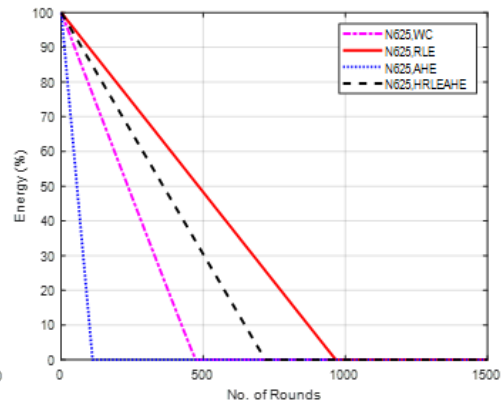
**Figure 6.16:** Results of Case Study 3: 4x4, 200 Nodes, BS at corner

### 6.7.10 Case Study 4: 10x10, 650 Nodes, BS at center

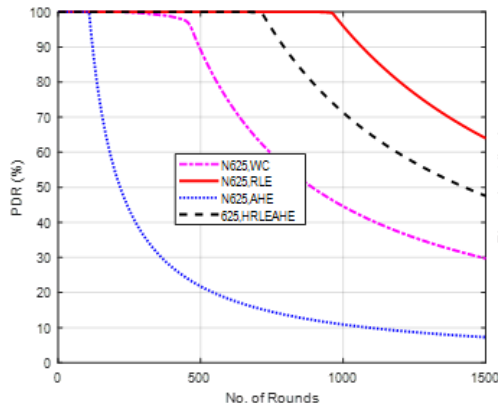
Figure 6.17 illustrates the findings of Case Study 4, which was conducted with a grid size of 10x10 and 650 nodes. The network topology consisted of 100 grids, and the BS was situated in the center. The results of performance metrics show that the network remains alive for 111 (AHE), 478 (without compression), 722 (H-RLEAHE) and 967 (RLE) rounds respectively as shown in Figure 17(a). Compared to RLE, the network lifetime reduces by 88.52%, 50.56% and 25.33% respectively for AHE, without compression and H-RLEAHE. The average energy in the network is depicted in Figure 6.17(b) for the RLE, H-RLEAHE, no compression and AHE technique respectively. In Figure 6.17 (c), the simulation for PDR is demonstrated which shows trivial improvement as compared to previous case studies. Further, in figures 6.17(d) and 6.17(e) RLE demonstrated the increase in residual energy and throughput of the network compared to AHE, no compression and H-RLEAHE.



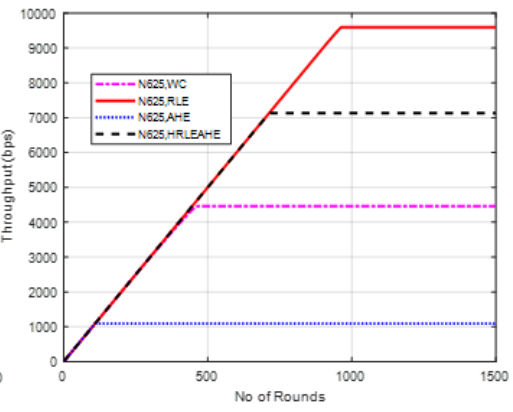
**Figure 6.17(a)** Alive Nodes for Case Study 4



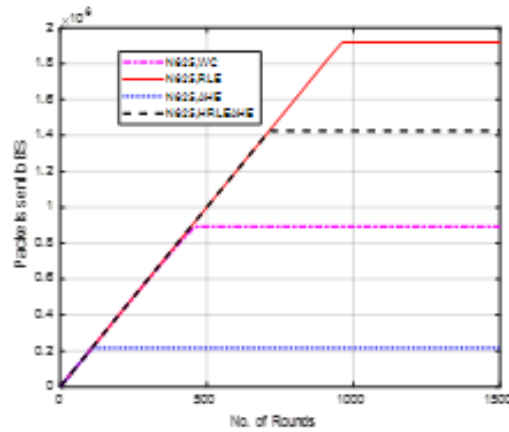
**Figure 6.17(b)** Energy for Case Study 4



**Figure 6.17(c)** PDR for Case Study 4



**Figure 6.17(d)** Throughput for Case Study 4



**Figure 6.17(e)** Packets sent to BS for Case Study 4

**Figure 6.17:** Results of Case Study 4: 10x10, 650 nodes

In case study 4, with 650 nodes and 100 grids, the performance of the network remains comparable to previous case studies.

### 6.7.11 Case Study 5: 10x10, 1250 Nodes, BS at center

The findings of Case Study 5 with 10x10 grids and 1250 nodes are shown in Figure 6.18. The network topology consists of 100 grids, and the BS is located at the center. Here the network remains alive for 111 (AHE), 484 (without compression), 726 (H-RLEAHE) and 972 (RLE) rounds respectively. Compared to RLE, the network lifetime reduces by 88.58%, 50.20% and 25.30% respectively for AHE, WC and H-RLEAHE

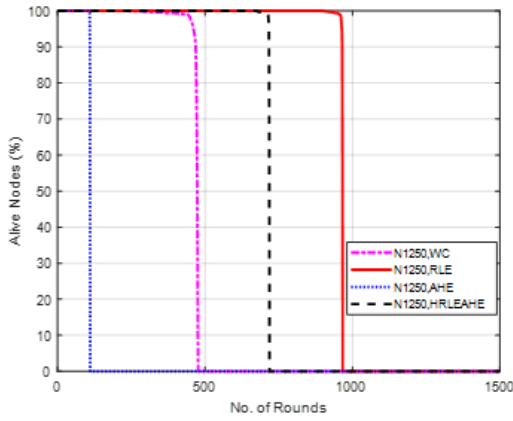


Figure 6.18(a) Alive Nodes for Case Study 5

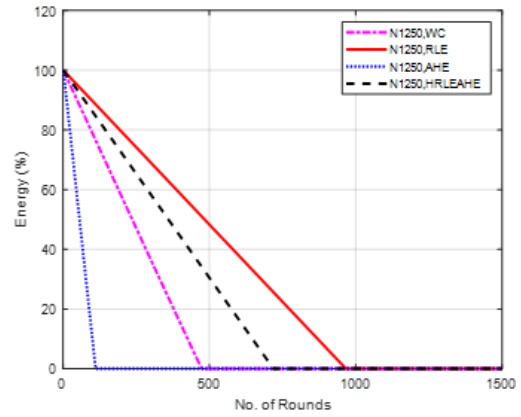


Figure 6.18(b) Energy for Case Study 5

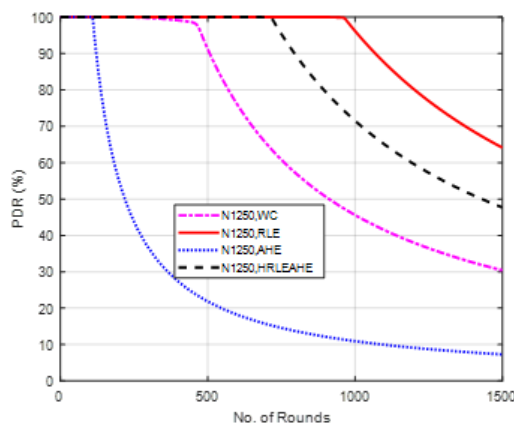


Figure 6.18(c) PDR for Case Study 5

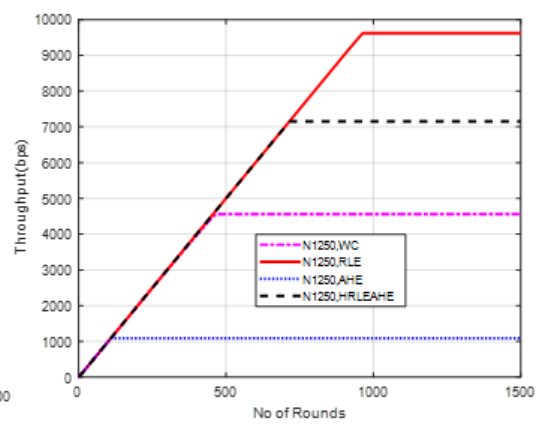


Figure 6.18(d) Throughput for Case Study 5

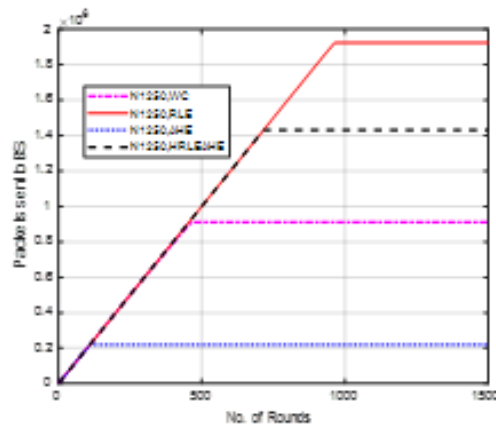


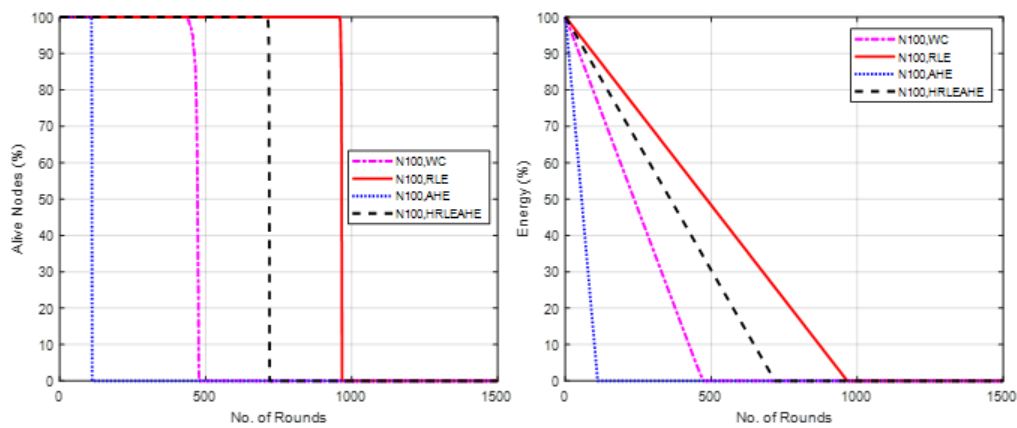
Figure 6.18(e) Packets sent to BS for Case Study 5

Figure 6.18: Results of Case Study 5: 10×10, 1250 nodes

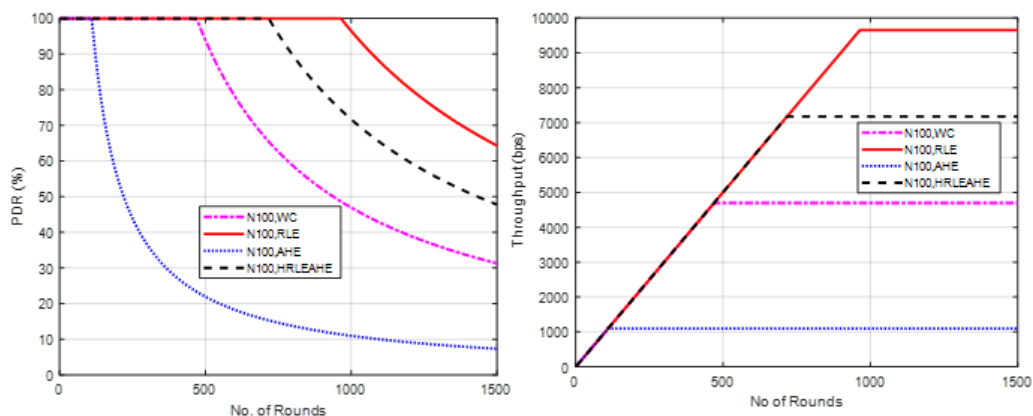
### 6.7.12 Study of Data Compression with Elliptic Curve Cryptography (ECC) for 2x4, 100 nodes, BS at the Center

As mentioned earlier, the author also considered using Elliptic Curve Cryptography (ECC) that can be considered as one of the techniques.

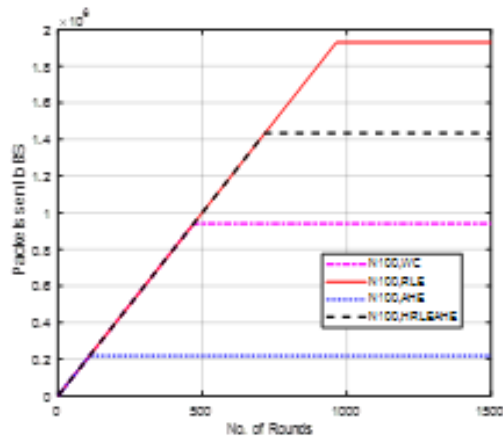
The detailed description of ECC is given by authors in [203-204]. To complete the study and evaluate the efficacy of the data compression algorithm, added with ECC for 2x4, 100 nodes and BS at the centre. This case study illustrates how the compression method performs when the base station is situated on the edge of a 2x4 configuration with 100 nodes. The RLE shows a significant increase in different performance indicators in this scenario. Figure 6.19 (a) shows that the network remains alive for 111 (AHE), 477 (without compression), 719 (H-RLEAHE) and 967 (RLE) rounds respectively. Compared to RLE, the network lifetime reduces by 88.52%, 50.67% and 25.64% respectively for AHE, WC and H-RLEAHE. As shown in Figure 6.19(b), 6.19 (c), 6.19 (d) and 6.19 (e), RLE achieves an improvement in all the other performance metrics.



**Figure 6.19(a)** Alive Nodes for Case Study 6 **Figure 6.19(b)** Energy for Case Study 6



**Figure 6.19(c)** PDR for Case Study 6 **Figure 6.19(d)** Throughput for Case Study 6

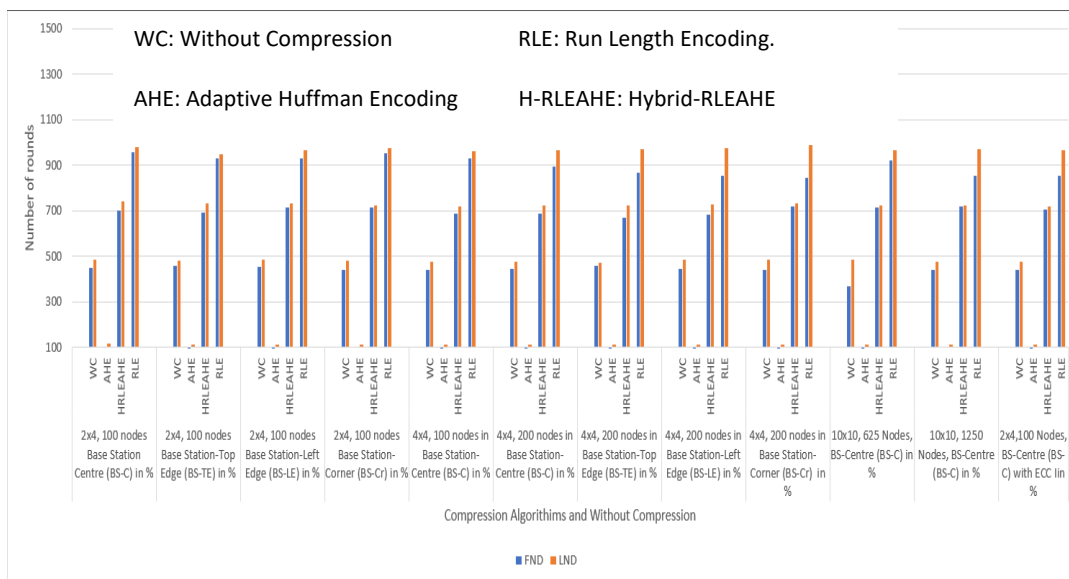


**Figure 6.19(e)** Packets sent to BS for Case Study 6

**Figure 6.19:** Results of BS at edge, 2x4 100 nodes

### 6.8. Comparative analysis with respect to alive nodes

In order to have a comparative analysis of various scenarios with respect to alive nodes, a graph is illustrated in Figure. 6.20.



**Figure 6.20:** Comparative analysis of various Scenarios

From the graphical representation, it is evident that RLE data compression technique outperforms the other models (Without compression, AHE and H-RLEAHE ) for all the scenarios. This strengthens the effectiveness and efficiency of RLE data compression model thus advocating its widespread deployment.

## 6.9 Conclusion

In this chapter, we presented an investigative analysis of the energy cost of data compression techniques in WSN for IoT applications. The study includes the efficiency of existing compression techniques like Run Length Encoding (RLE) and Adaptive Huffman Encoding for saving energy and hence improving the lifetime of WSNs. Other measures, such as Packet Delivery Ratio (PDR) and throughput, have been examined for the various compression algorithms while considering energy costs.

While RLE and AHE compression algorithms have distinct advantages and disadvantages, both have certain drawbacks. This motivated the authors to develop and test the H-RLEAHE hybrid model, which combines RLE and AHE. After obtaining the compressed data via RLE, adaptive Huffman encoding is used to further compress it. The use of RLE ensures that data correlation is taken into account, which AHE does not. Analysis shows that AHE requires more energy for compression.

The simulation was performed for various situations in which the total number of sensor nodes, number of grids, and position of the base station were varied. Compressing the data before transmitting, using any technique, increases the network lifetime when compared to uncompressed data. This is in spite of the extra energy cost of the compression algorithm itself, establishing the efficacy of compression.

The performance metrics for the proposed hybrid model are considerably improved over AHE, while RLE delivers the best performance for all metrics measured. The authors compare run length encoding and adaptive Huffman compression methods. Comparing the energy cost of compression and the energy saved during transmission, it suggests that devices can reduce overall energy consumption for certain applications. [205]

The present era of IoT has created new challenges for WSNs. Devices of all types and with varying resources, which are typically constrained, are networked and share essential data. This dominant device connectivity technology has prompted designers to create hybrid algorithms that make use of restricted device resources to meet essential needs such as real-time response, high compression ratio, and data transmission efficiency [206]. As a result, the purpose of this research is to provide a

hybrid data compression methodology that combines two popular lossless compression methods, Run-Length Encoding and Adaptive Huffman Encoding. This hybrid method is especially effective for reducing the amount of data that must be delivered in bio-medical applications [207].

Aside from data transmission efficiency, the protection and security of these IoT-based sensor applications from malicious adversary are also important. The research is completed by adding data encryption and assessing its effects on energy costs and network lifetime. This is critical for practical WSNs as sensed data must be encrypted before compression and transmission. ECC is evaluated in terms of security, and simulation findings suggest that it does not add any substantial overheads that can cause network lifetime to increase. However, the effect is likely to be large if more complicated encryption techniques, such as Elliptic Curve Digital Signature (ECDSA) and Elliptic Curve Diffie-Hellman (ECDH) [208], are employed. This would form part of future investigative research

In order to improve the network's efficiency even further, future work can potentially expand in the direction of data aggregation [209]. Data packets are combined using various routing methods in data aggregation. This is accomplished by modifying some extracted features and statistics of data sets gathered from sensor nodes, such as the minimum, maximum, and/or mean, and then sending them to the sink. A routing method and data compression techniques are required for efficient data aggregation.

Transferring all of the received data to the base station is expensive due to the vast volume of data collected over time. Transferring less data is possible because to data compression and aggregation methods. It is difficult to find literature on the topic of developing a variety of compression and aggregation technique for event-based or continuous data collecting network. Security mechanisms in a WSN need to keep an eye out for, identify, and counteract assaults without disrupting network availability. The both network layer and the data-link layer have seen numerous proposed secure protocols. Any part of the protocol stack can be attacked maliciously. Investigating secure monitoring at various protocol layers is a worthy effort. A further difficult area of study is cross-layer secure monitoring.

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### Summary, Conclusion and Future Work

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#### 7.1. Summary and Conclusion

This thesis discusses the advancement in the domain of sensor technology that has significantly impacted the manner in which we live. Owing to the revolutionary advancements in recent times, WSN has become a vital technology in the context of communication systems. WSN, a network of a huge number of geographically distributed autonomous sensor devices (called nodes), primarily focuses on sensing the data, processing it and communicating the same to base station (BS) through wireless links. Thus WSN mainly has assembly of sensor nodes, BS for gathering information, Wireless network for communication among the nodes and the BS and computing resources at BS for handling queries and data mining. The advancement and widespread deployment of WSN has several associated challenges and issues owing to constrained devices in terms of computational capability and storage. Some of the prime challenges are data aggregation, compression techniques, energy efficiency, self-organization, dynamic network topology, and battery life of the nodes.

As the nodes have limited energy, they have a very short transmission range and hence require multiple hops in order to communicate with other nodes. Additionally, the lifetime of a node determines the lifetime of a network and hence becomes a prime area attracting several researchers. Primarily, the extremely energy constrained nature of WSN implies that their design and operation be done in an energy-aware manner, enabling the system to make trade-offs between performance and energy consumption. In this thesis, several energy efficient protocols are proposed for enhancing the network lifetime, studied, and analysed. The prime objective of the thesis is to propose a trust based cluster head selection using the K-Means algorithm. The proposed algorithm selects a cluster head based on a trust factor that ensures all nodes are trustworthy and authentic during communication. The trust is calculated using parameters such as the residual energy and the distance between the nodes, along with the use of the K-means clustering algorithm. Usage of Zig-Zag strategy for data aggregation reduces congestion, leading to reduction in routing overhead and packet loss.

The focus of this research is to maximize lifetime and energy efficiency while maintaining a desired level of other performance metrics of WSN. Also, an improved strategy called hybrid based reliable routing algorithm handles this problem of energy efficiency and thus this research is going to be quite beneficial for the society.

The thesis has been organized into various chapters. Chapter 1 introduces the topic of research and discusses the motivation of the researcher for undertaking this research. Chapter 2 discusses the various Performance Modeling of WSN. Various performance evaluation parameters have been presented in Chapter 2 viz. Network Lifetime, number of packets reaching the BS, total residual energy of the network, Packet Delivery Ratio, total alive nodes per simulation round, Throughput, and packet sent to BS. The chapter also discusses various models namely traffic model, energy consumption model, and network model. In order to establish the effectiveness of the proposed research, some of the metrics have been considered such as Packets reaching the Base Station, Total alive nodes per simulation round, Total Residual Energy of network, Packet Delivery Ratio (PDR), and Throughput. Simulation of the proposed algorithms is carried out in MATLAB.

The related work has been presented in Chapter 3. Related work has been organized into various sections viz. bio-inspired algorithms for clustering and routing protocols. The various data compression techniques have also been elaborated in the chapter in order to present this thesis in a self-contained manner. Further, various data compression techniques and state-of art techniques are discussed at length. Elaborate literature survey enabled us to find some research gaps as follows:

1. When the number of clusters is unknown, scalability is important for optimal WSN performance.
2. Robustness of the lossless data compression) and other practical data compression algorithms.
3. The practicality of various data compression techniques.
4. Need for developing more robust data compression techniques applicable for both dense and sparse networks.

In Chapter 4, we proposed a Trust-Based Cluster Head Selection algorithm that uses K-Means Algorithm. Cluster head is selected based on a new factor called trust which is calculated using parameters like residual energy, distance among nodes etc. The proposed algorithm aims to conserve the energy of nodes in the network thus elongating

the lifetime of the network. It also maintains that CH will not get compromised upon its deployment in the environment owing to intrusion or change in physical nodes. Further, the proposed algorithm is simulated in order to establish its validity. The experiment demonstrated that the proposed CH selection approach overcomes the limitations of the traditional LEACH approach.

The concept of direct trust evaluation and the K-means clustering scheme are utilized in the proposed algorithm. The network is divided into grids where each grid has equal number of nodes and the node with highest the fitness value is used as the CH. After implementation of the proposed algorithm, the observed results are found to be promising and thus enhance the performance and lifetime of the network in comparison to traditional LEACH method.

Thereafter, research continues in the direction of improving network lifetime through Energy-efficient Hybrid Routing Protocol discussed in chapter 5. The routing is a challenging task as selection of an optimal path highly depends on the various network parameters viz. channel characteristics, network type and performance metrics. Among various associated challenges with routing protocol, optimization of network lifetime is a vital issue in WSN. In order to optimize the network lifetime, researchers have been focusing on various parameters viz. hop count, path reliability, and energy consumption etc. In Chapter 5, we attempt to improve routing protocol through optimization of network lifetime, by using different factors such as residual energy, hop count and reliable path. The performance of the proposed approach is validated in terms of various metrics such as packet delivery, throughput, and energy consumption etc.

The proposed algorithm initiates the formation of the grids and thereafter optimal selection of CH is done using a trust model. It initially forms zigzag paths and thereafter uses optimization algorithm to determine the best routes that offer the quickest delivery of data packets to the sink node. For the same, various factors such as route score, number of received packet, number of delayed packets, residue energy, power consumed, and total hop counts are considered. It is validated in simulation that the proposed algorithm is reliable to carry out the packet transmission allowing higher residual energy. Further, usage of PSOGA ensures the faster selection of routes than the existing LEACH mechanism. Also, the proposed PSOGA achieves enhanced network lifetime in all five different scenarios considered in the study thus establishing supremacy of the proposed model.

The thesis rigourously investigates the algorithms for data compression. The motive behind undertaking this study is the constrained behaviour of sensor nodes in terms of memory and energy. As a result, several researchers have proposed various data compression algorithms in order to conserve energy. In the thesis, we have discussed the well accepted data compression algorithms viz. RLE, AHE and a hybrid extension of these referred to as H-RLEAHE and H-AHERLE. Simulations and analysis are also carried out on real data with actual hardware parameters in order to establish the validity of these algorithms.

## **7.2. Future Work**

While the presented research has proposed several algorithms to improve network lifetime, still there exists scope for extension of the current work. The current work can be extended towards selection of cluster head for static and mobile Base Station which is located far away from the sensing field.

During simulation of the algorithm for CH selection, it is evident that it works towards energy conservation in addition to achieving several other objectives. However existing clustering techniques are unable to support mobile and heterogeneous network infrastructures. Now considering that several applications necessitate such a network, work can be extended to address the issues of heterogeneity and mobility.

In the current research, energy-aware QoS clustering and routing is paid considerable attention which brings stringent requirements in terms of bandwidth. Hence, the proposed algorithm aims to utilize the energy-efficient paths. The work can be carried forward by considering the sensor hardware as an influential factor for the design of routing protocols.

Furthermore, the research work can be extended to provide end-to-end security, privacy homomorphism based secure data aggregation protocols for data compression algorithm.

This work has been proposed with static nodes and BS at centre. Furthermore this study has the limitation of mobile nodes and mobile base station. Where BS will be away from the sensing field.

The proposed method appears to have strong potential for deployment in a static WSNs infrastructure. To fully utilise its potential in addressing practical issues like sensor

lifetime and geographical conditions, the proposed method needs to be studied in the context of being implemented in a dynamic WSNs system.

Transferring all of the received data to the base station is expensive due to the vast volume of data collected over time. Transferring less data is possible because to data compression and aggregation methods. It is difficult to find literature on the topic of developing a variety of compression and aggregation technique for event-based or continuous data collecting network. Security mechanisms in a WSN need to keep an eye out for, identify, and counteract assaults without disrupting network availability. The both network layer and the data-link layer have seen numerous proposed secure protocols. Any part of the protocol stack can be attacked maliciously. Investigating secure monitoring at various protocol layers is a worthy effort. A further difficult area of study is cross-layer secure monitoring.

### **7.2.1 Hardware Implementation**

This research is limited by the lack of real-field power consumption data for several sensor nodes. Ultra-low power approaches in wireless sensor nodes should be studied further. Miniaturization of sensor nodes is another potential future research direction. In addition, sensor node security concerns must not be ignored. We also suggest that the sensor nodes undergo extensive experimental performance evaluations.

In this thesis, the authors used MSP430 microcontrollers to examine data compression. The system design provided in this paper can be expanded in a variety of ways as future work. For example, additional sensing modalities can be incorporated on sensor nodes to satisfy the needs of various monitoring applications. Furthermore, the web interface can be further extended to include more capability in data visualisation, management, and analysis, among other aspects, in order to create a better user interface and user experience.

In the future work, to monitor the environment, which frequently remains stable or gradually changes, we will concentrate on its practical application for small and medium-sized environmental monitoring areas.

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## List of Appendices

### Appendix 1: DRC 16 - Chapter\_3

DRC 16



### STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Mukesh Mishra
Name/title of Primary Supervisor:	Dr. Gourab Sen Gupta
In which chapter is the manuscript /published work:	Chapter 3
Please select one of the following three options:	
<input checked="" type="radio"/> The manuscript/published work is published or in press <ul style="list-style-type: none"> <li>Please provide the full reference of the Research Output: M. Mishra, G. S. Gupta and X. Gui, "A Review of and a Proposal for Cross-Layer Design for Efficient Routing and Secure Data Aggregation over WSN," 2017 3rd International Conference on Computational Intelligence and Networks (CINE), 2017, pp. 120-125, doi: 10.1109/CINE.2017.30.</li> </ul>	
<input type="radio"/> The manuscript is currently under review for publication – please indicate: <ul style="list-style-type: none"> <li>The name of the journal:</li> <li>The percentage of the manuscript/published work that was contributed by the candidate: 75.00</li> <li>Describe the contribution that the candidate has made to the manuscript/published work: Research gap and proposal</li> </ul>	
<input type="radio"/> It is intended that the manuscript will be published, but it has not yet been submitted to a journal	
Candidate's Signature:	Mukesh Mishra <small>Digitally signed by Mukesh Mishra Date: 2022.09.01 12:52:36 +1200</small>
Date:	01-Sep-2022
Primary Supervisor's Signature:	Gourab Sen Gupta <small>Digitally signed by Gourab Sen Gupta DN: cn=Gourab Sen Gupta, o=Massey University, ou=School of Food and Agri-tech, email=g.s.gupta@massey.ac.nz Date: 2022.09.01 15:31:36 +1200</small>
Date:	3-Sep-2022

This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis.

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## STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Mukesh Mishra
Name/title of Primary Supervisor:	Dr. Gourab Sen Gupta
In which chapter is the manuscript /published work:	Chapter 4
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