Advanced Zonal Rectangular LEACH (AZR-LEACH):
An Energy Efficient Routing Protocol For Wireless Sensor Networks

by

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DEDICATIONS

This thesis is dedicated to the memory of my son Aaqib Zahoor Khan (2006-2011) who lost his battle against a rare form of brain tumor, medulloblastoma.

I also dedicate this thesis to the memory of every patient who is currently fighting against any kind of cancer or who has passed away due to this disease.

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ABSTRACT

Reducing the energy consumption of available resources is still a problem to be solved in Wireless Sensor Networks (WSNs). Many types of existing routing protocols are developed to save power consumption. In these protocols, cluster-based routing protocols are found to be more energy efficient. A cluster head is selected to aggregate the data received from root nodes and forwards these data to the base station in cluster-based routing. The selection of cluster heads should be efficient to save energy. In our proposed protocol, we use static clustering for the efficient selection of cluster heads. The proposed routing protocol works efficiently in large as well as small areas. For an optimal number of cluster head selection we divide a large sensor field into rectangular clusters. Then these rectangular clusters are further grouped into zones for efficient communication between cluster heads and a base station. We perform MATLAB simulations to observe the network stability, throughput, energy consumption, network lifetime and the number of cluster heads. Our proposed routing protocol outperforms in large areas in comparison with the LEACH, MH-LEACH, and SEP routing protocols.

LIST OF ABBREVIATIONS USED

WSNs	Wireless Sensor Networks
LEACH	Low Energy Adaptive Clustering Hierarchy
BS	Base Station
AZR-LEACH	Advanced Zonal Rectangular LEACH
CH	Cluster Head
ADC	Analog to Digital Converter
DAC	Digital to Analog Converter
TDMA	Time Division Multiple Access
MAC	Medium Access Control
SOSUS	Sound Surveillance System
DARPA	Defense Advance Research Project Agency
MIT	Massachusetts Institute of Technology
DSNs	Distributed Sensor Networks
WSSN	Wireless Self-Sustaining Sensor Network
CPU	Central Processing Unit
RAM	Random Access Memory
WANET	Wireless Ad-hoc Network
MANETs	Mobile Ad-hoc Networks
WMNs	Wireless Mesh Networks
IEEE	Institute of Electrical and Electronics Engineers
WBSNs	Wireless Body Sensor Networks
P2P	Point to Point
Kbps	Kilobits per second
Mbps	Megabits per second
MHz	Mega Hertz
ID	Identification
IP	Internet Protocol
GPS	Global Positioning System
RF	Radio Frequency
ISM	Industrial Scientific and Medical
WINS	Wireless Integrated Network Sensors
UCLA	University of California Los Angeles
WLAN	Wireless Local Area Network
CCR	Corner-Cube Retro-reflector
LAN	Local Area Network
MAN	Metropolitan Area Network
WPANs	Wireless Personal Area Networks
BAN	Body Area Network
FHSS	Frequency Hopping Spread Spectrum
L2CAP	Logical link Control and Adaptation Protocol
LMP	Link Manager Protocol
UWB	Ultra-Wideband
FCC	Federal Communications Commission

mmWave	millimeter Wave
PHY	Physical layer
HR-WPANs	High Rate Wireless Personal Area Networks
LR-WPANs	Low Rate Wireless Personal Area Networks
DSSS	Direct Sequence Spread Spectrum
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
FFD	Full Function Device
RFD	Reduced Function Device
AODV	Ad-hoc On Demand distance Vector
ZDO	ZigBee Device Object
AES	Advanced Encryption Standard
MWE	Multiple Winner Algorithm
SWE	Single Winner Algorithm
MECN	Minimum Energy Communication Network
TBF	Trajectory-Based Forwarding
GAF	Geographic Adaptive Fidelity
GEAR	Geographic and Energy Aware Routing
SPIN	Sensor Protocols for Information via Negotiation
MCFA	Minimum Cost Forwarding Algorithm
GBR	Gradient-based routing
MECN	Minimum Energy Communication Network
CH	Cluster Head
QoS	Quality of Service
RSSI	Received Signal Strength Indication
LEACH-C	LEACH Centralized
sLEACH	Solar-aware LEACH
M-LEACH	Mobile LEACH
LEACH-SC	LEACH Selective Cluster

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CHAPTER 1 INTRODUCTION

In recent years, researchers have been attracted by Wireless Sensor Networks (WSNs) due to their potential use in a wide variety of applications. Initially WSNs were used only in the battlefields for military purposes but now their use is extended for monitoring and controlling the different processes in many other civilian areas. A WSN contains different types of autonomous sensor nodes that are used to sense and transfer the data wirelessly to the base station or the next receiver node. Typically hundreds or thousands of low cost sensors are used in WSNs [1]. The technology advancements made it possible to reduce the cost and the size of the electronic devices. A wide range of sensors are available to monitor the different ambient conditions such as temperature, pressure, humidity, movement, and lightening conditions [2]. Low cost and smaller size of sensor nodes does not allow the use of the large battery source. The required lower energy consumption restricts the sensor to use the limited resources such as less memory capacity, low transmit power, and less processing computations. Other than data communication, a periodic routing protocol transmission is required to update the sensor's routing table. The selection of a proper routing protocol can help to prevent the excessive use of routing updates. The goal of this research is to find an energy efficient routing protocol for Wireless Sensor Networks. Our proposed algorithm aims to provide a higher throughput, a fewer number of dead nodes, and overall lower energy consumption compared to other protocols. The remaining part of this chapter is organized as follows: An overview of WSNs is discussed in Section 1.1; the scope of our project and the motivation for it are given in Sections 1.2 and 1.3 respectively; Section 1.4 describes the problem statement and the thesis outline is presented in Section 1.5.

1.1. OVERVIEW

A state-of-the-art technology Wireless Sensor Networks (WSNs) is used to collect the data from inaccessible locations. A large number of low cost and tiny sensor nodes interact with physical phenomena of the deployed environment. These sensor nodes gather information from a remote area and then transmit it to the base station. Different parts of sensor nodes can be classified in six major units [3]:

1. Communication Unit
2. Processing Unit
3. Sensing Unit
4. ADC/DAC Converters
5. Power Supply
6. Temporary Storage Unit

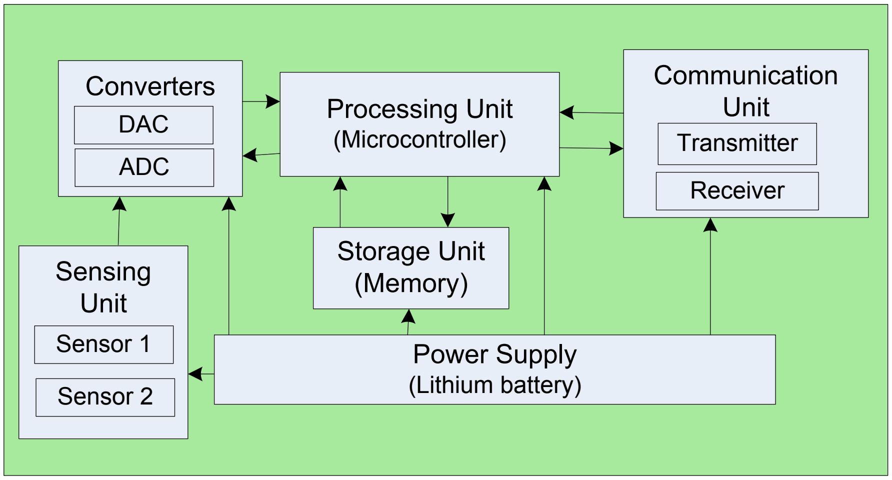

Figure 1-1: Typical Wireless Sensor Node Architecture

The general architecture of a sensor node is shown in Figure 1-1. The sensors in the sensing unit interact physically with the deployed environment. The sensed data is transferred to the ADC/DAC converters for analog to digital conversion. The micro-controller in processing unit receives this digital data and does the required processing by using the temporary storage. The processed data are then moved to the transmitter of the communication unit for transmission towards the cluster head or base station. On the other hand, the data from the cluster head or base station is received by the receiver and then transferred to the processor for further processing. The energy source used in sensor node is a lithium battery. The tiny size of the sensor node only allows for a very small size of battery. The communication and processing units are the two main parts where most of the energy consumption occurs. The life of sensor node depends on the battery life. The node dies immediately when its battery charge vanishes.

The sensor nodes used in WSNs are placed randomly in a deployed field. The sensed information and aggregated data delivery is necessary for efficient communication between sensor nodes. One or more sinks or base stations are located in the sensor area. The information is routed to the Base Station (BS) either directly in single hop communication or through other sensor nodes in multi-hop communication. Most of the WSNs applications use multi-hop communication, which helps to consume less node energy.

The BS is either a fixed or mobile node, which has the capability to connect the sensor network to the internet where the user can access and process the data. Routing in WSNs is very challenging due to the inherent characteristics that distinguish this network from other wireless networks or cellular networks. The most important constraint on WSNs is the limited battery power of sensor nodes. Limited computational power and memory size are other constraints which affect the amount of data to process or store in an individual node. The typical WSN architecture is shown in Figure 1-2.

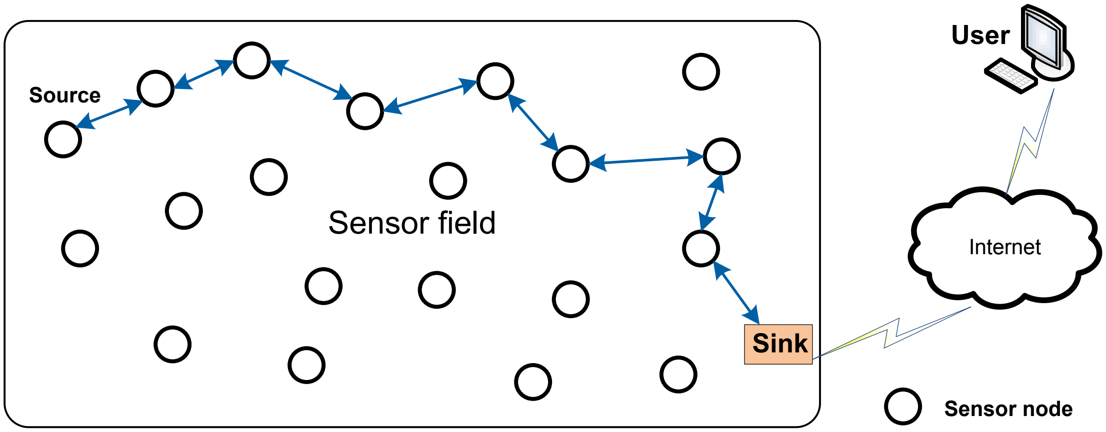

Figure 1-2: Wireless Sensor Network

The utilization of WSNs in different areas including industry, commercial sector, or military fields is increasing rapidly all over the world. Healthcare becomes the major area in industry and commercial sector where WSNs are used. The wearable and implant sensors help the healthcare professionals to monitor the patient's vital signs. The advancement of sensor technology used in Wireless Body Sensor Networks (WBSNs) or

Body Area Networks (BANs) is improving drastically. Some of the innovative wearable sensors used in BANs are discussed below.

Researchers from university of Illinois proposed the Band-Aid-like circuits to use as mini-tattoos on the human skin. This smart skin circuit is first mounted on a paper and then that paper is placed on the skin as shown in Figure 1-3a. The lightweight, tiny size and flexibility of this sensor provide comfort to the patient. Figures 1-3b and 1-3c show the sensor's flexibility and easy peel off from the skin respectively [4, 5].

The new proposed touch-hear speech recognition system contains a finger implant sensor transmitter and an ear wearable sensor receiver. This system helps to convert the text into voice and also provide the different pronunciations of the words. Figure 1-4 shows the finger implant transmitter (Figure 1-4a), its function (Figure 1-4b), and ear receiver (Figure 1-4c) [5].

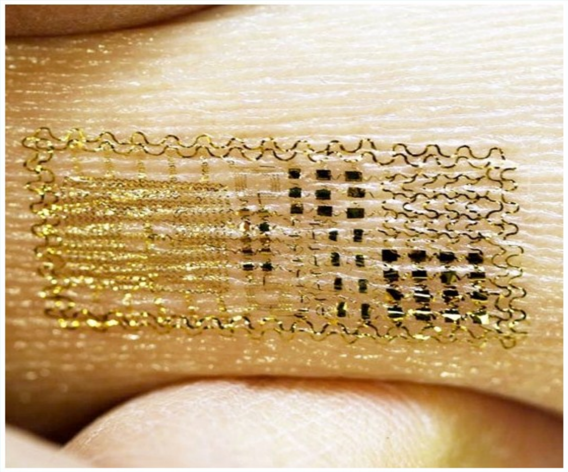

Figure 1-3a: Insertion of circuit on skin.

Figure 1-3b: Flexibility of this sensor.

Figure 1-3c: Easy peel of smart skin sensor.

Figure 1-3: Different positions of Band-Aid-like circuit sensor [5].

Figure 1-4a: Fingers implant transmitter sensors.

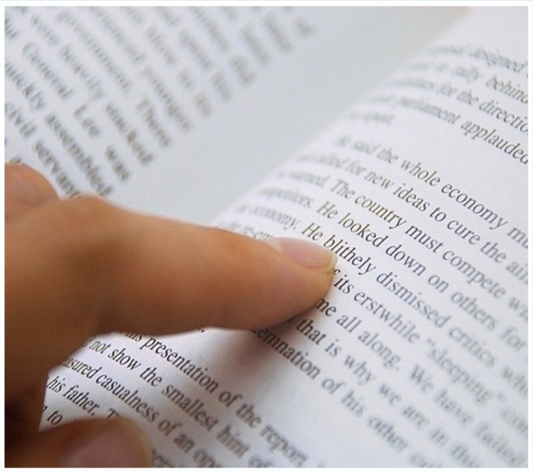

Figure 1-4b: Optical character recognition.

Figure 1-4c: Receiver sensor.

Figure 1-4: Sensor based touch hear speech recognition system [5].

1.2. PROJECT SCOPE

In this research we intend to find the solution for increasing network lifetime, selecting the optimal number of cluster heads, and energy efficiency problems in WSNs. Out of this research, we propose to obtain such a routing protocol whose energy cost is low and implementation is simple.

1.3. MOTIVATION

The use of WSNs in different applications is increasing with the rapid advancements in technology. Energy limitation is the major issue that needs to be considered. Most often, a battery is the only source of energy and the wireless sensor node consumes power during iterations. The node will immediately die when its battery runs out. The sensor node changes its states to resolve the energy problem. Typically, the three states of a sensor node are used: active state, idle state, and sleeping state. In the active state, the node transmits and receives data packets. Most of the node resources are used during the active state that causes the energy consumption. The idle state is when a node only performs the sensing operations without doing any data transmission or reception. The node in this state consumes less energy than when it is in the active state. The major cause of energy consumption in the active mode is the internal operations during transmission process. To stop transmissions in the idle mode is the basic reason for saving the battery power. In the sleep mode, the node turns off its radio part completely to save the node energy. Energy consumption in sleep mode is less than in the idle and active state [6, 7].

Conventionally in addition to using the different modes of a sensor node there are several other techniques of energy conservation. Some of these are given below:

- Scheduling of node states between active, idle, and sleep modes.
- Using of energy efficient routing protocol for data transmission.
- Using less transmit power if possible to reduce transmission range.
- Avoiding overhearing, collisions, and unnecessary listening.

In general all the wireless sensor nodes share the same wireless medium. The receivers of all nodes in an entire network receive the data transmitted by a single node. Any unwanted signal received at a node causes the waste of energy. This is called overhearing. The whole physical area of WSN is divided into sectors and clusters to diminish the effect of overhearing. The node transmission range can be adjusted by considering the size of the sector or cluster [6, 7, 8, 9].

The sensor node in WSNs essentially depends on battery power in contrast to other wireless networks. A node consumes energy during the operations of any task. At the end of transmission the node changes its mode from active to idle or sleep to avoid further energy consumption. A sensor node needs to capture the channel for data transmission. The node may start overhearing the carrier during the process of channel acquiring. This overhearing causes the unwanted waste of energy. To elude overhearing a technique called Time Division Multiple Access (TDMA) is used. In TDMA a specific time slot is assigned to each sensor node in WSN. This information is passed to all nodes in the network. A node only transmits the data on its turn; meanwhile all the other nodes do not try to capture the channel. This process helps to save energy consumption by avoiding overhearing [8, 9, 10].

The network and Media Access Control (MAC) layers in a sensor node play an important role during the data transmission between transmitter and receiver. Network layer finds the best route and MAC layer is used for carrier sensing and data forwarding. A significant amount of energy can be saved by using the proper Network and MAC layer protocols. Due to this reason researchers are attracted to work in these two areas [9, 10].

1.4. PROBLEM STATEMENT

The aim of this thesis is to propose a new energy efficient routing protocol for WSNs. The WSN consists of a large number of sensor nodes. Typically the sensor nodes are placed in a remote area to fulfill the needs of monitoring or surveillance. All the sensor nodes are battery-operated. The life of a node depends upon the battery. In addition to forwarding the node’s own data it also plays a role of an intermediate node by receiving and forwarding the other nodes' data towards the base station or sink.

The increasing use of WSNs in many critical applications attracts researchers to focus on finding the appropriate routing protocols. A number of successful efforts have already been made to achieve this goal, but still there is a need to work on this area for further improvements.

Network and data link layers in a sensor node play a vital role in the WSN communication. The network layer is used for path determination and the MAC sub-layer of data link layer controls the channel access and forward or receive the data to/from neighbor node or sink. Routing and MAC protocols are used for data communication in WSNs. The consideration of energy efficiency is essential for any kind of protocol. The purpose of this research is to design an energy-efficient routing protocol for WSNs.

1.5. THESIS OUTLINE

The organization of the remaining thesis is as follows.

Chapter 2: Wireless Sensor Networks
This chapter provides the background of Wireless Sensor Networks (WSNs). The discussion includes the development process of WSNs, the comparison of WSNs with Mobile Ad-hoc Networks (MANETs) and Wireless Mesh Networks (WMNs), design considerations of WSNs, and a brief discussion of current WSNs standards.

Chapter 3: Literature Review
This chapter starts with a discussion of WSN routing protocols, then it sheds light on the classification of WSNs routing protocols, their subcategories, advantages and disadvantages. At the end of this chapter the discussion of different proposed flavors of LEACH, their advantages and working mechanisms are provided.

Chapter 4: Methodology
In this chapter, we describe the architecture, procedure, and advantages of our proposed routing protocol.

Chapter 5: Performance Evaluation

This chapter describes how our proposed mechanisms are implemented in MATLAB. The simulation parameters and simulation results are discussed with appropriate graphs.

Chapter 6: Conclusions

This chapter provides the conclusions of our research.

CHAPTER 2 WIRELESS SENSOR NETWORKS

The major types of Wireless Sensor Network (WSN) applications in civilian areas are to monitor the changes in environment, objects, and interaction of these objects with the environment. The general overview of WSNs is discussed in this chapter. Section 2.1 provides the development process of WSNs. Section 2.2 discusses the comparison of WSNs with the Mobile Ad-hoc Networks (MANETs) and Wireless Mesh Networks (WMNs). Influencing factors on WSNs design and Wireless Networking Standards are presented in sections 2.3 and 2.4 respectively.

2.1. DEVELOPMENT PROCESS OF WSNS

The research in WSNs depends on other fields including sensing, computing, and communication. The advancements of these areas help the researchers to enhance the performance of WSNs. The initial use of WSN in defense applications was the driving force for researchers to work in this area. The development of WSNs was first started by the United States government while they were in cold war with Russia [7]. An acoustic sensor network was designed underneath the ocean at tactical positions to detect and track Russian submarines. The acoustic sensor used in this network senses the wave movements in the water. The name of that system was Sound Surveillance System (SOSUS). Another sensor network comprising radars for air defense was also configured by the United States government during the cold war. This air defense system uses hierarchical processing in which data is sent to the user after being processed at different layers. These systems, controlled by human operators, have a wired structure. This wired structure avoids the two major constraints of a wireless system, energy and bandwidth [7].

The first step towards modern sensor network research was taken by the Defense Advance Research Project Agency (DARPA) in the United States during the early 1980’s [7]. The researchers from the Massachusetts Institute of Technology (MIT) introduced a new program called Distributed Sensor Networks (DSNs) in 1980. Acoustic sensor arrays, consisting of three concentric triangles with nine microphones, were used to find the trajectory of low-flying fighter airplanes. DSN uses the collection of different physically scattered, low cost, and independent sensing nodes [7]. A computer system with a customized operating system and an array of three processors were the major parts of the mobile node. The processing of acoustic signals was done by these processors which consist of 256kB internal and 512kB shared memory. The microwave radio and Ethernet mediums were used for node and wired communication respectively. The different components of Distributed Sensor Networks used in 1985 are shown in the Figures 2-1, 2-2, and 2-3. The acoustic array with nine white microphones is shown in Figure 2-1. The acoustically quiet generator included in the mobile vehicle node as an energy source can be seen in Figure 2-2. The acoustic or tracking node and gateway node placed in the vehicle equipment rack is shown in Figure 2-3.

Figure 2-1: DSN Acoustic arrays with nine microphones [7].

Figure 2-2: Vehicle mobile node of MIT DCN [7].

Figure 2-3: Equipment rack in mobile vehicle node of DSN [7].

The introduction of DSN in the 1980s was an immense revolution in the field of WSNs. A new hardware and a MAC protocol for WSN were introduced by the researchers in Vienna University of Technology during their work on Wireless Self-Sustaining Sensor Network (WSSN) project. Low cost and energy efficiency are the two main features of this new circuit [8]. Figure 2-4 shows one of the nodes developed in that project.

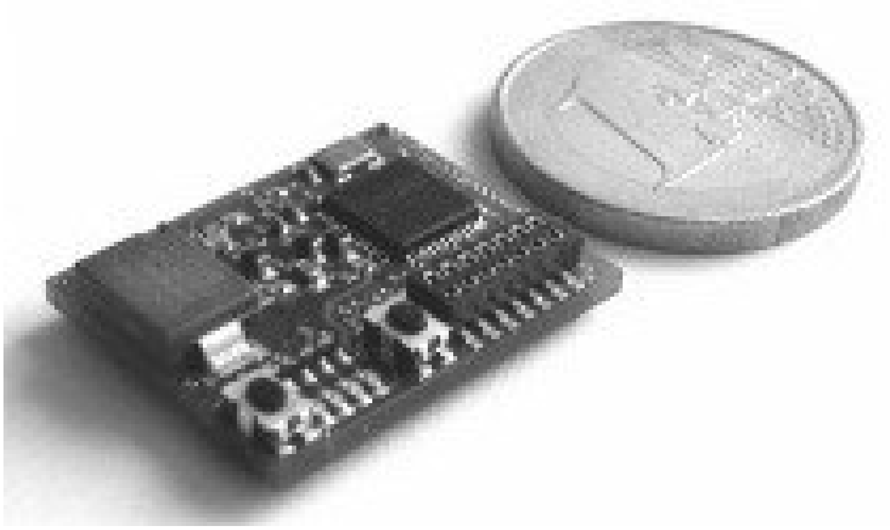

Figure 2-4: Node approximately equivalent to one euro [8].

A typical sensor node in a WSN consists of a micro-controller (CPU), transceiver (antenna), and power source (battery). The processor used in WSSN is RISC 16 bit CPU with 4-MHz speed, 8-kB flash memory, and 256-bytes random access memory (RAM). The node was equipped with a 1Mbps, 2.4GHz transceiver and a temperature sensor having ±0.5 centigrade accuracy. An additional interface was available to connect one more 10 bit analog sensor. The battery power used in each node was 3200mAh with input voltage of 2V. The node consumes about 100µW average power during the communication process of 120 bits of data every five seconds. The node can continue its operations with the same battery for 9 years if certain environmental conditions are presumed [8].

The energy scavenging and energy storage techniques are used to get this tremendous improvement in the node’s lifetime. The nodes use solar cells for energy scavenging. In this method the battery is charged by using environmental resources, especially the sun. A collection of ultra-capacitors and lithium accumulators provide storage to the nodes. To absorb the large amount of energy within a short period of time is an advantage of ultra-capacitors. But the leakage current of ultra-capacitors rises exponentially with the increase of input voltage. The design techniques used in WSSN facilitated the development of very small sensor nodes with the concept of extracting energy from the environment that increases the lifetime of the nodes for years.

2.2. COMPARISON OF WSNS WITH MANETS AND WMNS

The Wireless Ad-hoc Network (WANET) is a temporary wireless network between different nodes to satisfy the urgent needs of communication [9]. The three classes of WANETs are Mobile Ad-hoc Networks (MANETs), Wireless Mesh Networks (WMNs), and Wireless Sensor Networks (WSNs). A large number of protocols are available for WANETs. The unique requirements of WSNs are the major problem of using the existing WANET protocols for WSN. WSNs differ from other WANETs in seven main areas. The seven areas described in Akyildiz et al. [11] are network size, node density, node proneness to failure, changes in topology, communication modes, resource limitations, and node identification. The explanation of these areas is given below.

2.2.1. Network Size

Typically the number of nodes used in MANET or WMN is less than a hundred. On the other hand the number of sensor nodes used in WSNs varies from a dozen to several thousands. The two examples of MANET or WMN are WLAN and Bluetooth piconet. The Institute of Electrical and Electronics Engineers (IEEE) standards 802.11b/g/n are used for WLANs. IEEE 802.11b recommends only 32 nodes for a single access point. Bluetooth allows a maximum of eight devices to connect at a time [12].

2.2.2. Node Density

The tiny size of a sensor node limits the physical size of the battery used as energy source. A lower transmit power helps to increase the battery life but reduces the transmission range. In multi-hop communication a sensor node not only sends its own data but also forwards the other node data to the base station or sink. In other words, for a reliable data transmission every node must be placed within the transmission range of another node or sink. Due to this limitation, for the same deployment area, the node density in WSNs is generally higher than the MANET or WMN. The bigger sizes of nodes in MANET or WMN allow the use of a more powerful battery source. Cellular phones, iPads, and laptop computers are the common nodes used in MANETs and WMNs.

2.2.3. Node proneness to failure

The main function of WSNs is to monitor the changes from a remote area. The deployment of sensor nodes in an inaccessible area such as a disaster site increases the causes of node proneness to failure. The deterioration or damage happens in node performance due to the unusual circumstances. The effect of these circumstances can cause longer, missing, or redundant routing paths that can be the main source of battery power loss. Most of the time, it is impossible to replace or recharge the node battery. However, the MANETs and WMNs use rechargeable batteries. The replacement of batteries in MANETs and WMNs is also not an issue because of their use in an accessible area.

2.2.4. Changes in Topology

The nodes in MANETs and WMNs are normally static, accessible, more reliable, and have a higher power source. Generally, nodes join the network temporarily. The changes in MANETs or WMNs topology are not frequent. In contrast to MANET and WMN, WSN contains hundreds of nodes and these nodes depend on each other for forwarding the data packets towards the sink. The limited power source, lower transmission range, unreachable deployment area, mobility, and environmental interferences cause frequent changes in the WSNs topology. Malfunction or complete failure of the nodes in WSNs is common. Many techniques are used to make WSNs more adaptable by considering its limitations.

2.2.5. Communication modes

Different protocols are used for the communication of WSNs. A node sends broadcast messages with routing updates to the other nodes in the network. These periodic updates help the nodes to discover the neighbor nodes and keep the routing table up to date. The communication mode employed in WSNs includes point to multipoint communication for network setup and maintenance. However, the general communication mode in MANETs and WMNs is point to point (P2P).

2.2.6. Resource limitations

The tiny size of a node in WSNs is one of the major causes of resource limitations. The limitations of WSNs node include less bandwidth, low energy source, slower processing speed, and less memory size as compare to the MANETs or WMNs node. Table 1 shows the comparison of WSNs with MANETs and WMNs.

Table 1: Resource limitations of WSNs

Resource name	WSNs	MANETs and WMNs
Bandwidth	few kbps	Few kbps to few Mbps
Energy source – battery	Non-rechargeable low power	Rechargeable and high power
Processing power	Few MHz	GHz
Memory	Few kB to few MB	Giga bytes (GB)

2.2.7. Node identification

The node identifiers used for WSN nodes have a local significance. The small number of bits is used for a node ID in the data packet header. Transmit energy is saved because of fewer less number of bits are required to send or receive. On the other hand, the MANETs and WMNs assign a unique node ID for each node. The MAC addresses and IP addresses are the commonly used node identifiers in MANETs and WMNs. Due to different formats used for the node IDs in WSN and other WANETs make the compatibility between these networks difficult. Therefore a new protocol is required for communication between WSNs and other WANETs.

2.3. DESIGN CONSIDERATIONS OF WSNS

Different situations of environment and objects such as movement, sound, pressure, and temperature can be monitored by using the WSNs. Sensor nodes are the key components used to achieve these tasks. These sensor nodes are placed in the area called sensor area where monitoring is required. A wide range of WSNs applications are possible. The important properties of WSNs required during its design process are discussed in this section. These properties are fault management, scalability, cost, operational environment, node deployment, hardware requirements, transmission media, and power [11].

2.3.1. Fault Management

An important consideration during the design of WSNs is the fault management. Node failure in WSNs can happen at any time due to battery run out, environmental situations, physical damage, or other unknown reasons. In a best network design, the effect on the performance of WSNs is minimal due to one or more node(s) failure. In [13] the authors Hoblos et al. model a fault tolerance function $R_k(t)$ by using the Poisson distribution. The node's probability of success (not having failure) during time interval (0, t) is given below.

$$R_k(t) = e^{-\lambda_k t} \tag{2.1}$$

where λ_k is the rate at which node k fails and t denotes the time period.

Different levels of fault tolerance are assigned to avoid the high computations. For example a WSN used to monitor the temperature or humidity in a home is more secure and there are fewer chances of node failure. In this case a low level fault tolerance is acceptable. On the other hand, a WSN deployed in a battlefield needs a high level fault tolerance because the chances of node failure due to the hostile surrounding environment are higher.

2.3.2. Scalability

A large number of nodes are deployed to get better monitoring results from the sensor area. The common problem of node failures in WSNs makes it essential to use the redundant nodes. A simple WSN is comprised of hundreds to thousands of sensor nodes. The number of nodes goes to millions in cases where WSNs are used in larger areas. The scalability must be considered at the time of WSN design. Reliable communication is possible if the proper resources are used to accommodate the large number of node data. The data from sensor nodes are received by the sink or base station. The number of base stations or sinks also depends upon the node density. The following formula for density μ is given in [14].

$$\mu(R) = \frac{(N\pi R^2)}{A} \quad (2.2)$$

where N is the number of sensor nodes deployed in area A and R is the radio transmission range. μ(R) represents the number of nodes within the transmission radius of each node in the area A.

2.3.3. Cost

Typically a WSN consists of hundreds to thousands of sensor nodes. The cost of the whole network depends upon the individual prices of the sensor nodes. To justify the use of a WSN in terms of cost effectiveness, the cost of sensor nodes in WSN must be less than the traditional sensors. A sensor node price must be less than 1$ to consider WSNs a viable alternate to traditional networks [11].

2.3.4. Operational Environment

The operational environment of WSNs ranges from very stable to extremely hostile. The different possible operational locations are homes, the bottom or surface of oceans, hospitals, combat zones, moving vehicles, and other inaccessible places.

2.3.5. Node deployment

A large number of sensor nodes are used in WSNs. The chances of node failure increase due to hostile environments, power failures, or other reasons. To avoid the effect of node failure on the overall network performance, a careful handling of network topology is important. The issues associated with network topology are categorized in three phases: pre-deployment phase, post-deployment phase, and re-deployment phase [11]. The brief details of each phase are given below.

2.3.5.1. Pre-deployment Phase

The node deployment in this phase should be planned in a way that reduces installation cost, increases flexibility, supports self-organization, and provides fault tolerance.

Different methods can be used to deploy the nodes. For example, the thousands or millions of nodes in an inaccessible environment, such as a battlefield, are placed by dropping them from a plane or delivering them via missile. The use of a plane or missile makes the deployment safer and more cost effective. For indoor or other accessible locations, the nodes are deployed one by one by human beings or robots [11].

2.3.5.2. Post-deployment Phase

The possible node failure after deployment is due to its change of energy level, position, or functional behavior. Exhausting the energy is one of the major issues. The mobile node may become unreachable due to its position changes. The signal jamming or noise can make the node to function improperly.

2.3.5.3. Re-deployment Phase

The deployment of new nodes in the network can be for two reasons: to replace the failure nodes or to add more monitoring tasks. The life of a sensor node depends upon its power source. The re-deployment can happen at any time or can be scheduled after a certain time of initial deployment to maintain the performance of sensor area monitoring.

2.3.6. Hardware requirements

The four basic components of a sensor node are the processing unit, communication unit, sensing unit, and power source. The basic units of a node can be seen in Figure 2-5. The sensing unit consists of many sensors. The sensors send the sensed data to the Analog to Digital Converter (ADC) for digital conversion. The processing unit receives the data. The processing unit consists of a processor which works with the support of internal memory. Memory is used to store the data temporarily during the processing. After processing, the communication unit transmits the data to the other nodes or base station. The communication unit contains a transmitter and receiver. The receiver manages to receive the data packets from other nodes or base stations and forward it to the processing unit for further actions. The power source in a node is responsible for fulfilling the energy requirements of all the components.

A node may consist of three optional units in addition to the basic units. A power scavenging unit can be added with the node to get the power from other resources such as the sun. A location finding system such as GPS calculates the position of the node with respect to the base station. In disaster situations it is very important to determine the location of a node. The node can be moved with the help of a mobilizer unit. The addition of new hardware components provides extra features, however these components require additional resources. Energy consumption is one of the major issues.

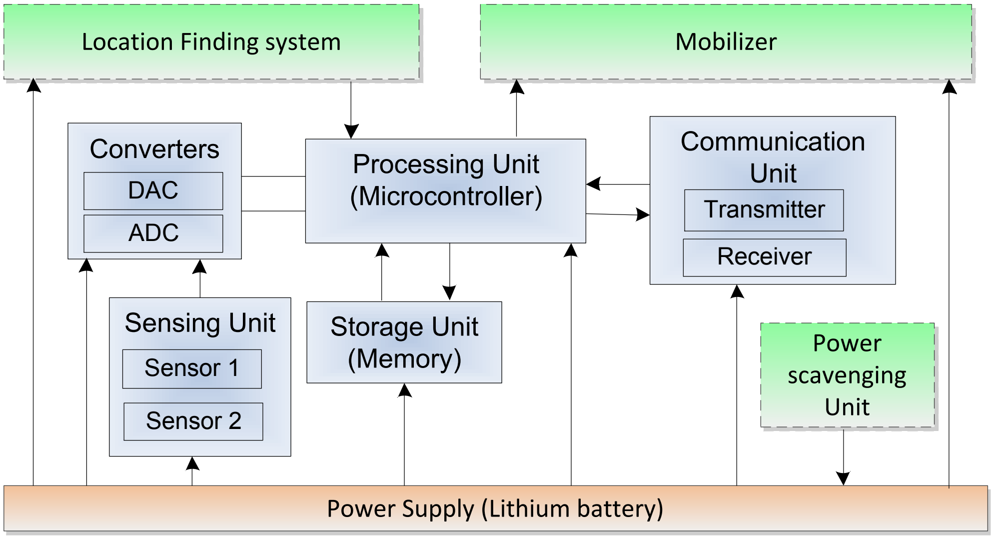

Figure 2-5: Basic Parts of Sensor Nodes.

2.3.7. Transmission Media

The wireless medium of communication is used in WSNs to send or receive the data from or to sensor nodes. The transmission links can be Radio Frequency (RF), infrared, or other optical media. The use of a universal available media is necessary to avoid confining the usage of WSN to a certain area. The Industrial Scientific and Medical (ISM) band used for Radio Frequency communication is universally available. The ISM band uses around 2.4 GHz unlicensed band. The RF communication is one of the most popular used media for WSNs. The RF communication is used by the sensor nodes developed for WSSN and Wireless Integrated Network Sensors (WINS) projects organized by TUV and the University of California Los Angeles (UCLA), respectively [15]. Most of the cordless devices are compatible with the Wireless Local Area Network

(WLAN). The transmission power used in WSNs is very low due to less power available in its battery. The researchers from the University of California Berkeley consider the specialized optical link for communication between sensor nodes in the project named Smart Dust [16]. The optical links in Smart Dust are used in autonomous sensing, computing, and communication systems. The two communication patterns, passive and active, were studied. The Corner-Cube Retro-reflector (CCR) and laser diode with a steerable mirror are used for passive and active transmissions, respectively.

2.3.8. Power

A sensor node has a limited battery power which makes the sensor node's life cycle completely dependent on it. In WSNs, every node generates its own data and routes the other nodes' data. Whenever a node dies due to resource depletion, changes in network topology happen and thus the data route changes. Each sensor performs a specific task; each senses data according to its hardware design and transmits it after required processing. Data sensing, data processing, and data transmission/reception are the three major energy consuming parts of the node. The communication is the highest energy consuming process. The active and startup states of the transceiver consume most of the energy. The minimum possible size of data packets are used for communication by a sensor node. The power consumption is reduced when the message duration is shortened. The energy consumption during processing tasks can be reduced by simplifying the processing computations. The energy consumption through the sensing process depends upon the nature of the sensing task. The continuous nature of a sensing task needs a continuous source of power. Shih et al. [17] calculates the power consumption (P_C) for communication as:

$$P_c = N_T * [P_T * (T_{on} + T_{st}) + P_{out} * (T_{on})] + N_R * [P_R * (R_{on} + R_{st})] \qquad 2.3$$

where,

N_T represents the number of times the transmitter is switched on per unit time,

P_T represents the transmitter power consumption,

T_{on} represents the transmitter on time,

T_{st} represents the transmitter start-up time,

P_{out} represents the transmitter output power,
N_R represents the number of times that the receiver is turned on per unit time,
P_R represents the power consumed by the receiver,
R_{on} represents the receiver on time, and
R_{st} represents the receiver start-up time.

2.4. WIRELESS NETWORKING STANDARDS

The IEEE 802.15 working group was established as part of the 802 LAN/MAN Standards Committee in IEEE Computer Society. The purpose of the 802.15 working group is to develop the standard for Wireless Personal Area Networks (WPANs) which should be compatible for short distance wireless networks.

The 802.15 working group is further divided into seven task groups. The goal of 802.15 task group one is to introduce a standard for WPANs based on the physical and MAC layers of the Bluetooth specification [18]. The 802.15 task group two defined a standard for coexistence of WLAN (802.11) and WPAN (802.15). The 802.15 task group three and four are developing the models for High data Rate and Low data Rate WPANs respectively. The work on standards for mesh networking is assigned to the 802.15 task group five. The IEEE 802.15 Task Group 6 is assigned to develop a low power and low frequency short range communication standard protocol for Body Area Networks (BANs). The 802.15 task group seven is working to develop the standard for visible light communication. The brief details of these standards are given below.

2.4.1. IEEE 802.15.1 (Bluetooth)

IEEE 802.15.1 standard supports a short transmission range, low power, and low cost wireless communication among different portable devices. The transmission range is about less than 10 meters. The power and cost requirements are about 1 to 100 mW and less than $5, respectively. The ISM band radio frequency 2.4 GHz is available universally without any charge. Bluetooth uses this 2.4 GHz RF with Frequency Hopping Spread Spectrum (FHSS) for communication purposes [18].

The Bluetooth network contains two components: piconet and scatternet. Piconet is the ad-hoc wireless network which consists of a minimum of two and a maximum of eight nodes. One of these nodes must be a controlling node called master and the rest of them are the slaves. A piconet can contain maximum 255 slaves but only seven can be active at a time. Three bits are used for the node address, which limits the maximum of seven slaves in a piconet. The first address which contains all zeros of these three address bits is not assigned to any node and is used for broadcast purposes. The master node controls the contention-free communication of the slaves within a piconet. All the nodes in a piconet can communicate with each other via the master node.

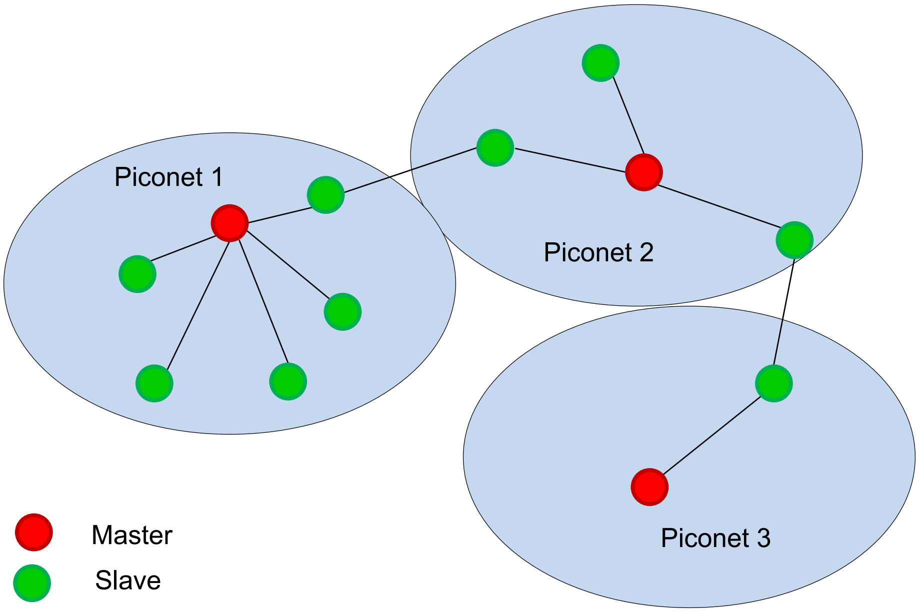

Figure 2-6: Scatternet network architecture.

Two piconets are connected together if a node from one piconet is linked with a node in another piconet. The combination of two or more piconets forms a scatternet. An example of a scatternet is shown in Figure 2-6. The communication mode in a scatternet can be both point-to-point and point-to-multipoint. In Figure 2-6, the communication between master and slaves in piconets 1 and 2 is point-to-multipoint whereas point-to-point communication is shown in piconet 3 of Figure 2-6. The master node in a piconet works as a router in a piconet and a node behaves like a gateway of two piconets when it participates in two piconets at a time. The gateway node can communicate with one piconet at a time by using the time division duplex technique.

The Logical link Control and Adaptation Protocol (L2CAP), Link Manager Protocol (LMP), baseband, and radio sub-layers of transport layers are defined in Bluetooth wireless technology. Four major Bluetooth versions are introduced until now. The new versions are compatible with the older versions. The new standard provides all the features of previous versions.

2.4.2. IEEE 802.15.2 (Coexistence)

The scope of IEEE 802.15 task group two is to provide the recommendations for the coexistence of Wireless Personal Area Networks (WPANs) with other wireless devices operating in unlicensed frequency bands such as Wireless Local Area Networks (WLANs) [19]. The proposed standard was published in 2003 and then the task group went in hibernation.

2.4.3. IEEE 802.15.3 (High Rate WPAN)

The IEEE 802.15 task group three developed a new standard for the cheaper cost, less complex, low power, and higher data rate communication of devices in Wireless Personal Area Networks (WPANs). The 802.15.3 proposed in 2003 is a physical and MAC layer standard which supports the data range of 11 Mbps to 55 Mbps. The enhancements were proposed after the first release of the 802.15.3 standard in 2003. The new amended standards are IEEE 802.15.3a, 802.15.3b-2005, and 802.15.3c-2009.

A higher speed ultra-wideband (UWB) PHY improvement was proposed in IEEE 802.15.3a. At that time many researchers observed that UWB is more successful than Bluetooth due to faster speed, cheaper cost, and lower transmit power. The UWB has been used for military communications by United States forces since 1970. The typical data rate of UWB is 200-400 Mbps. The data transmission in UWB is based on impulse radio rather than traditional carrier-based radio. Usually, the signals are transmitted via sub-nanosecond pulses with 100 μW per MHz of transmission bandwidth. IEEE UWB standard proposed the 4 nanoseconds increment of pulse duration. It supports a data rate of 110 Mbps and 480 Mbps over 10 meters and one meter, respectively. The US Federal Communications Commission (FCC) allocates the frequency spectrum 3.1-6.1 GHz for

UWB [20].

The task group 3a proposed the enhancements in 802.15.3 by improving MAC layer implementation and interoperability in 2005. The IEEE 802.15.3b-2005 was compatible with the previous versions. The task group 3c, formed in March 2005, proposed the WPAN millimeter wave (mmWave) based alternative physical layer (PHY) protocol with a data rate of 5 Gbps on 60 GHz band for the existing IEEE 802.15.3 standard. The FCC allocates the frequency spectrum 57-64 GHz unlicensed band for the IEEE 802.15.3c-2009 standard. The MAC layer efficiency is improved by adding aggregation and block acknowledgement features to make it compatible with high data rates used on PHY layer. The high speed internet, real-time video streaming, high definition televisions, and wireless data bus instead of cable are some of the mmWave High Rate WPAN (HR-WPAN) applications [19, 21].

2.4.4. IEEE 802.15.4 (Low Rate WPAN)

The IEEE 802.15 task group four was assigned the job of developing a standard that supports a low data rate up to 250 kbps, is much less complex, and consumes very low power. The main feature of this standard is to extend the battery life months or even years. It provides the protocol for PHY and MAC layers. A number of standardized or propriety network layer routing protocols work over the IEEE 802.15.4 standard. One of the examples is ZigBee which works over the PHY and MAC layers of the IEEE 802.15.4 standard. Figure 2-7 shows the IEEE 802.15.4 and ZigBee protocol stacks. The ZigBee alliance was formed in 2002 by an association of companies to overcome the need of a new protocol for reliable, low cost, low power, and universally-accepted wireless communication. The IEEE and ZigBee Alliance collaboration is similar to the IEEE and Wi-Fi Alliance. The possible applications of the IEEE 802.15.4 standard include sensors, building or home automations, and remote controls [22].

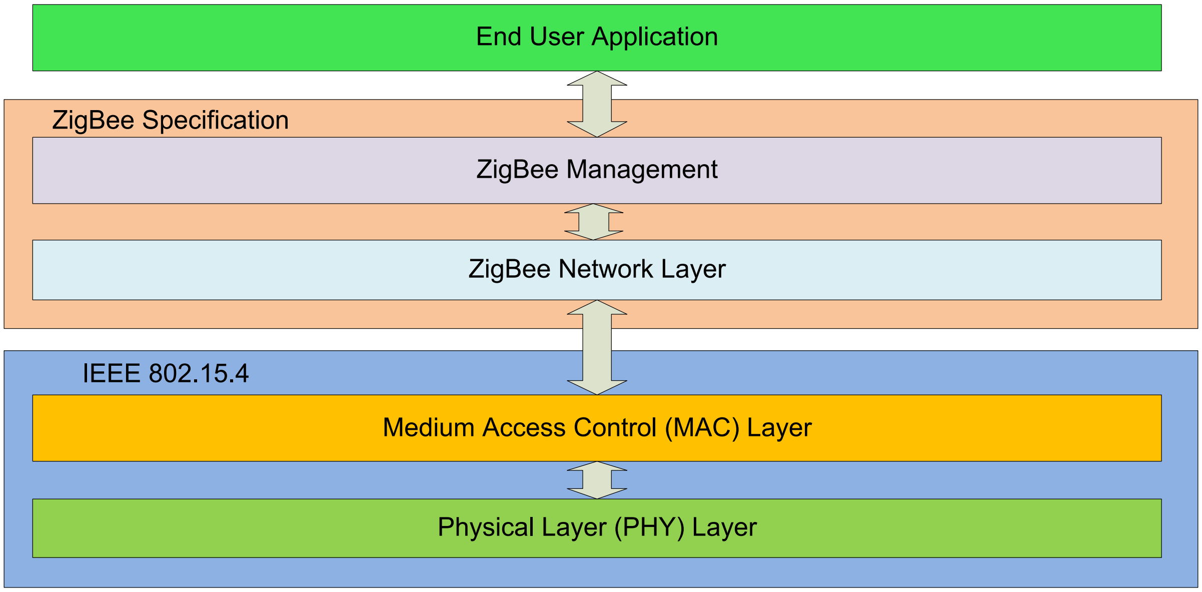

Figure 2-7: IEEE 802.15.4 and ZigBee protocol stack

The IEEE 802.15.4 original version released in 2003 specifies two Direct Sequence Spread Spectrum (DSSS) physical layers. The physical layer works at a time with one of three free available frequency bands. The first band is only for Europe and supports 868-868.6 MHz with one communication channel. The second band, which allowed 902-928 MHz frequencies with up to ten channels in the 2003 version and increased to 30 in a later 2006 version, is for North America. The frequency spectrum 2.4 GHz to 2.4835 GHz is used worldwide with the support of up to 16 channels and it provides 250 kbps. The data rates for first and second bands are up to 40 kbps. The 2006 version of IEEE 802.15.4 improved the data rate of these bands with the support of 100-250 kbps.

The two addressing modes, 16 bits short and 64 bits extended, are used in the IEEE 802.15.4 standard. Some of the important features of physical layer are the link quality indication, receiver energy detection, and clear channel assessment. The maximum data packet size is 128 bytes including 104 bytes payload and 24 bytes header. The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) technique is used to capture the channel. The ZigBee uses network, security, and application layers over the physical and MAC layers of the IEEE 802.15.4 standard [12]. The ZigBee network layer supports the network topologies named peer-to-peer (ad-hoc), star, mesh, and cluster networks as shown in Figure 2-8. The three types of nodes used in IEEE 802.15.4 are

Full Function Device (FFD), Reduced Function Device (RFD), and PAN coordinator. The PAN coordinator initializes the formation of a ZigBee network. A single PAN coordinator with a 16 bit ID of all zeros is allowed in a ZigBee network. Reduced function device is a node which can send and receive its data without routing capability. Full function device is responsible to route the network data like a router. In a peer to peer or ad-hoc network, the nodes are directly connected to each other. The inter-node communication is possible via a PAN coordinator in the star network. The connection of FFDs with the central PAN coordinator forms the cluster tree network. The nodes belonging to one FFD can reach the nodes of another FFD via a PAN coordinator. In a mesh network, end nodes can be connected at a time with both the routers and the PAN coordinator. The availability of redundant paths and interconnection of all nodes via FFDs or the PAN coordinator in the mesh network provides the reliability and scalability [23].

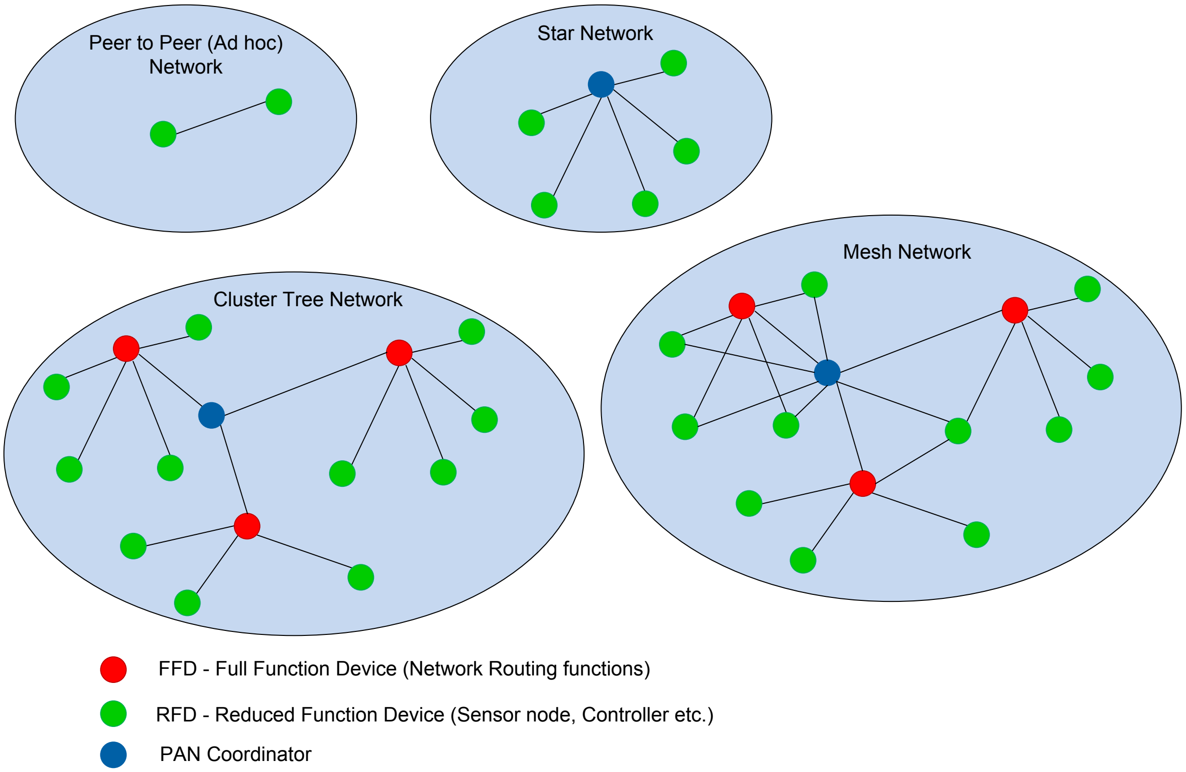

Figure 2-8: ZigBee Network Topologies

The Ad-hoc On Demand distance Vector (AODV) routing protocol and Motorola’s cluster tree protocol approaches are used for the network layer protocol of ZigBee standard. ZigBee algorithm is a hierarchical routing protocol with table driven features. As a reactive ad-hoc network routing protocol, the AODV continuously floods the routing query in the network unless it gets to the destination [24]. Each route query receiver node in the path stores the neighbor node's ID, which generates this route query. When the destination receives the route query it generates a unicast reply to the source node on the same path constructed during the route query.

ZigBee offers a security and application support sub-layer on the application layer in addition to the routing protocol on the network layer. The ZigBee Device Object (ZDO) helps to determine the device role i.e. FFD or RFD. The application support sub-layer provides the services of a node to match the other devices from the same vicinity based on their services. The security layer enhances the encryption of MAC layer frames by 128 bits Advanced Encryption Standard (AES) encryption.

2.4.5. IEEE 802.15.5 (Mesh Networking)

IEEE 802.15 task group 5 is responsible for developing a standard with the support of mesh capabilities for both high rate and low rate Wireless Personal Area Network (WPAN) devices [25].

2.4.6. IEEE 802.15.6 (Body Area Networks)

In November 2007, the IEEE 802.15 task group 6 was formed to develop the standard for Body Area Network (BAN), which should be compatible with low transmission range of about 3 meters, up to 10 kbps data rate, and support QoS features. IEEE 802.15.6 standard defines not only the communication procedures of the devices in or around the human body but should also be suitable for the applications related to medical and consumer electronics, or other personal devices [26]. A typical diagram of BAN communication is shown in Figure 2-9 [27].

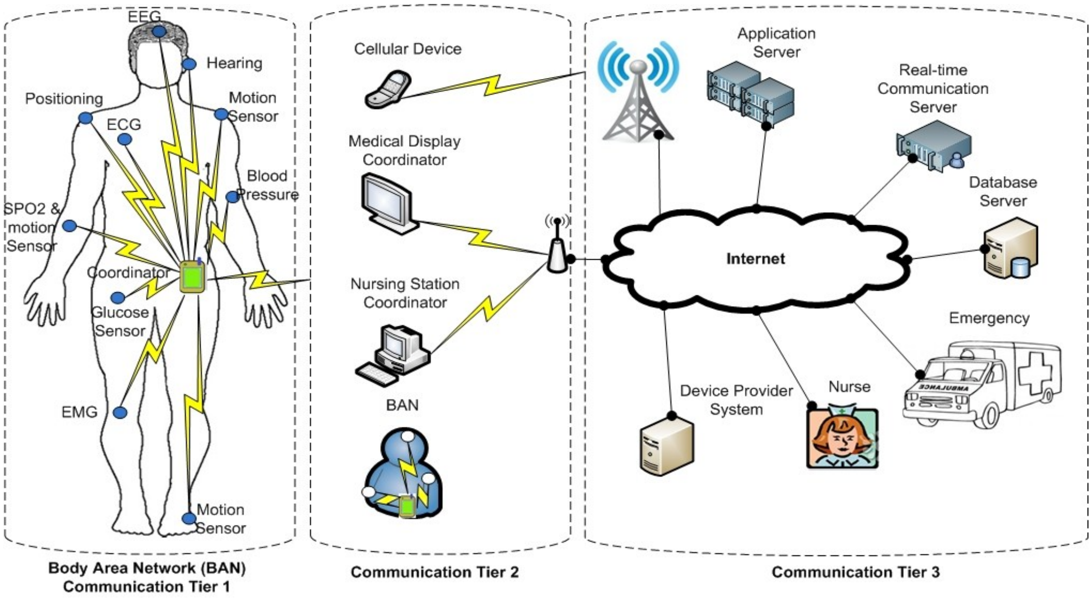

Figure 2-9: Body Area Network communication [27]

The implant and wearable sensors connected with a human body send the data to the coordinator node, which transfer these data towards communication tier 2. A tier 2 device then routes these data to the central database server for further processing.

2.4.7. IEEE 802.15.7 (Visible Light Communication)

The IEEE 802.15 task group 7 is responsible for defining a standard for short-range wireless optical communication using visible light. The new standard IEEE 802.15.7 addresses the issues of using the Visible Light Communication (VLC) for Wireless Personal Area Networks (WPANs) [28].

CHAPTER 3 LITERATURE REVIEW

Wireless Sensor Network (WSN) is a kind of ad-hoc network that has become an interesting area for researchers. Routing is an issue for these sensor nodes due to the limited availability of resources. The sensor nodes are used to measure the physiological data in the environment. The energy, processing capabilities, and sensing abilities are limited in a wireless sensor node. The sensor nodes are used in battlefields, disaster areas, monitoring the enemy's activities, and deployed at boarders to prevent illegal activities. The sensed information and aggregated data delivery are necessary for efficient communication between sensor nodes and the base station. The literature survey presented in this chapter is divided into six major sections. The general review of WSN routing protocols and its classification are given in sections 3.1 and 3.2, respectively. The location-based, flat, and hierarchical routing protocols are briefly discussed in sections 3.3, 3.4 and 3.5, respectively. Section 3.6 deals with the detailed study of clustering protocols based on Low Energy Adaptive Clustering Hierarchy (LEACH) used in WSNs.

3.1. WSN ROUTING PROTOCOLS

The challenges and characteristics of WSNs are different than the conventional Wireless Ad-hoc Networks (WANETs) due to their specific requirements. Therefore, the designing task of a routing protocol in WSNs requires more careful considerations than the other wireless ad-hoc networks (MANETs or WMNs). As outlined below, the issues to consider for an efficient and reliable communication in WSNs include network topology, data reporting methods, node and link heterogeneity, mobile adaptability, energy efficiency, coverage, data aggregation, and quality of service [29, 30].

- **Network topology:** The deployment of sensor nodes during the formation of WSNs is done by two methods, dynamic and static. The nodes are placed randomly in the dynamic method while manual placement of nodes on the predefined locations is done in the static method. Due to the large number of nodes in a small area, less energy source and lower transmit power, energy efficient multi-hop communication is feasible. In multi-hop communication, each node performs dual operations, sends its own data and forwards other nodes' data. The routing protocol should be able to manage the proper routing paths in case of node failure.

- **Data reporting methods:** The data reporting techniques used by sensor nodes are query driven, event driven, time driven, and hybrid. Sensor nodes send the data to the base station as per application requirement. The time driven data reporting is required for the application which needs continuous monitoring. In event driven reporting, the sensor nodes send the data when a specific event happens; for example, sensors used for fire detection only send the data at the time of fire. Query driven means the sensor node sends the data in response to a query from the base station. In some cases, the application requires the hybrid method in which more than one technique is used to do the proper monitoring. The routing protocol should be able to provide a suitable solution for reliable communication used by any data reporting methods.

- **Node and link heterogeneity:** Generally the nodes used in WSNs are homogeneous but many applications need to use the heterogeneous nodes. The capabilities of processing, communication, and power resources are the same across homogeneous sensor nodes. On the other hand, the nodes with different capabilities form a heterogeneous network. An example of heterogeneous nodes in WSN is the use of different sensors to monitor temperature, blood pressure, and other vital signs of a patient. Different link speeds of these nodes are required in the same network. The protocols should be able to handle the heterogeneous nodes. Another common example is the use of cluster head in WSN. The hierarchical protocols are able to help the selection of a cluster head and then the other nodes communicate with the base station via this cluster head.

- **Mobile adaptability:** Most of the WSNs use the fixed nodes and base stations. However, sensing the node or sink mobility can be a demand of an application in different scenarios like vital sign monitoring of a mobile patient in the hospital.

The routing protocol should manage the communication properly for mobile nodes.

- **Energy efficiency:** Routing protocols need to maintain the connectivity between the nodes and the base station with minimum energy consumption. The periodic routing updates help the nodes to refresh the status of neighbor nodes. The flooding of these updates can shorten the node's lifetime due to the additional energy required.

- **Coverage:** Each sensor node can sense the environment within a certain range of area coverage. The design of WSNs requires the deployment of the nodes in a way that can get the maximum coverage. The routing protocol needs to choose another node from the same sensor area where a node fails to ensure the proper coverage of the whole sensor area.

- **Data aggregation:** Several methods, such as duplicate suppression, median, and minima-maxima, are used in routing protocols for data aggregation to avoid the redundant transmissions and enhance the energy efficiency. These techniques also help to reduce the traffic load and increase the throughput.

- **Quality of Service:** Reliability-sensitive and delay-control algorithms are used for routing protocols to fulfill the QoS demand of different WSN applications. These protocols help to monitor the sensor areas during a critical situation.

3.2. CLASSIFICATION OF WSN ROUTING PROTOCOLS

Several WSN routing protocols have been proposed by researchers in the last few years. The WSN routing protocols can be classified in three ways: by its protocol operations, by network structure, and by packet destinations [30, 31, 32]. Figure 3-1 shows the classification of WSN routing protocols. The details of this classification are given below.

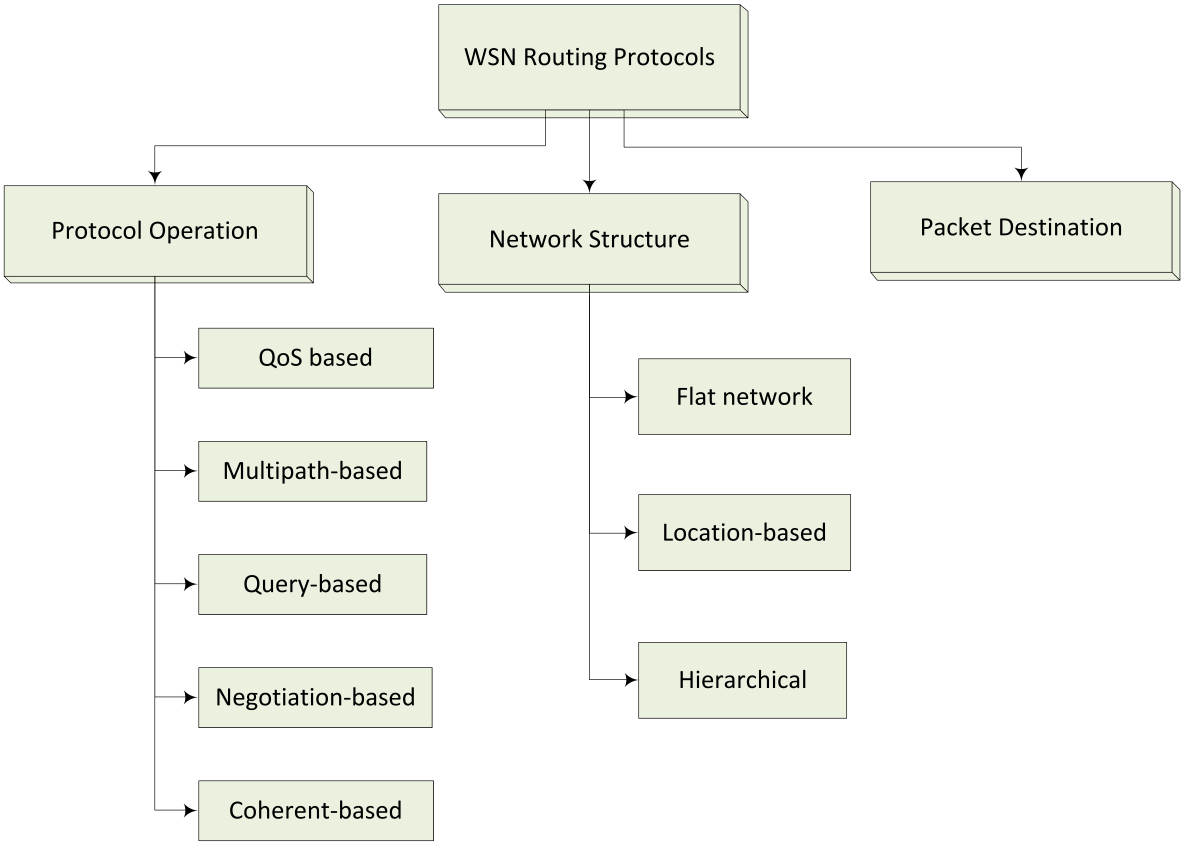

Figure 3-1: Classification of WSN routing protocols

3.2.1. Protocol operation based classification

In this classification, different routing functionalities of the routing protocols are considered. The protocol operation based routing protocols are divided into different types [30]:

- **Multipath-Based Routing:** The routing protocols in this category use the multiple paths between a source and destination for data transmission to enhance the network performance. The directed diffusion protocol [33] is an example of multipath-based routing.
- **Query-Based Routing:** These protocols depend upon the queries from a destination. The source node sends its sensed data in response to a query generated by the destination node. A natural language or high level query language is used to generate these queries. An example of these protocols is the

rumor routing protocol [34]. The directed diffusion protocol [33] is also counted in query-based routing protocols.

- **Negotiation-Based Routing Protocols:** In these protocols, a high level of descriptors is used for the negotiation between the nodes to prevent redundant data and reduce duplicate information. Generally this negotiation is done between the source and the next node or base station before real data transmission. SPIN [35] is an example of this type of routing.

- **QoS-Based Routing:** The algorithm used by these protocols ensures the QoS requirements of the data. Some of the QoS metrics are reliability, delay, and bandwidth. Balancing energy consumption while satisfying QoS conditions is an important task for these routing protocols. SPEED [36] protocol is a good example of QoS-based routing.

- **Non-coherent and Coherent Data Processing Based Routing:** Different data processing techniques are used to reduce the processing computations, which help to reduce the energy consumption of the node. Coherent and non-coherent are the two major data processing methods used for this purpose. In the non-coherent data processing technique, the sensed raw data are processed locally by the node and then the node transfers it to the aggregator. Aggregator is a node which receives the data from many sensor nodes and sends these data to the sink or base station after aggregation. In the coherent method, the minimum processing is done locally by the sensor node. After receiving the data, the aggregator is responsible for the major and complex part of processing. Examples of coherent and non-coherent data processing techniques are Multiple Winner Algorithm (MWE) [37] and Single Winner Algorithm (SWE) [37], respectively.

The below Figure 3-2 shows the protocol operation based classification of WSNs.

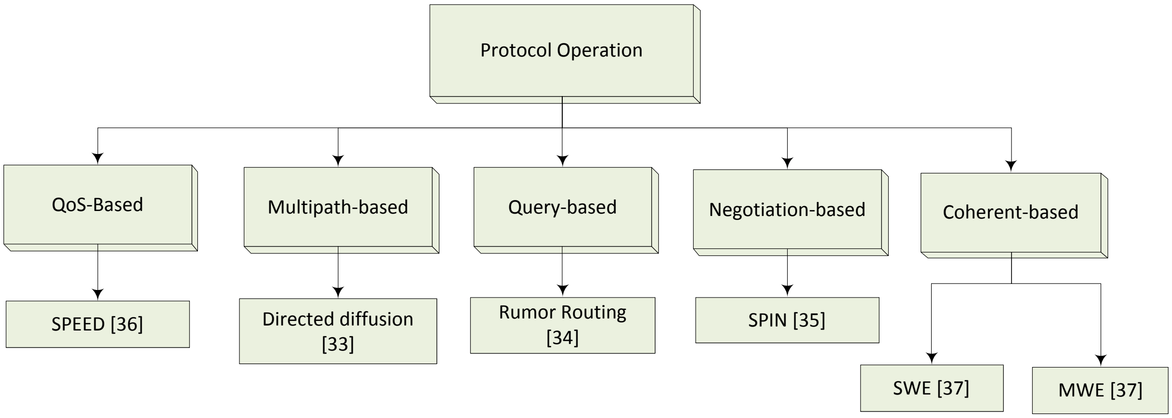

Figure 3-2: Types of WSN routing protocols based on protocol operations

3.2.2. Packet destination based classification

The routing techniques based on packet destination depend upon the number of destination nodes, such as a single node, a set of nodes, or all nodes in the network [38]. Figure 3-3 shows the subclasses of these routing protocols.

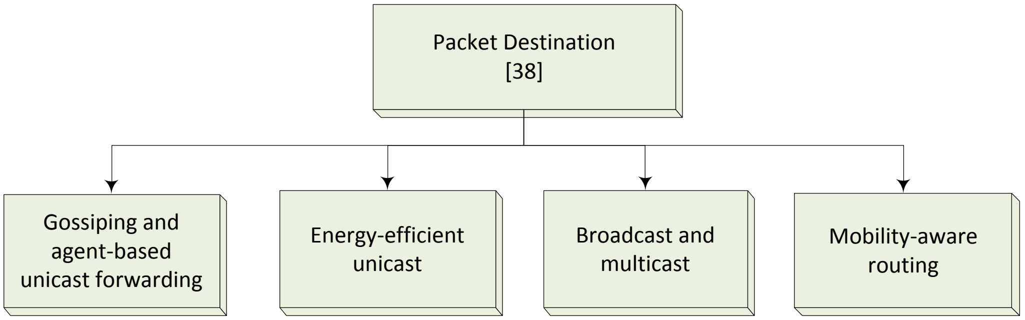

Figure 3-3: Types of WSN routing protocols based on packet destination

- **Gossiping and agent-based unicast forwarding:** The schemas used in this method avoid the routing tables by using flooding, such as simply forwarding all received messages. In this way a node saves energy by routing without using routing tables but it increases the network traffic. Gossiping is the technique in which the messages are forwarded to a random node instead of being broadcasted. Gossiping reduces the network traffic but increases the propagation delay of the data.

- **Energy-efficient unicast:** In these techniques, the cost between the two nodes is calculated and the next hop with the minimum cost is chosen by considering the residual node energy. The network lifetime can be increased by selecting the shortest route which requires low transmit power.

- **Broadcast and multicast:** Broadcast is a commonly used operation in WSNs. The node transmits the data packets to all nodes in the network during a broadcast operation. Subsets of nodes are used as destinations in multicast routing protocols.

- **Geographic routing:** The routing protocols in this class use the concept of geo-casting or position-based routing. In geo-casting routing, a large network area is split into different sub-areas geographically. The nodes can send the data to each other within a specific geographical area. When the positions of source and destination nodes are known and routing is done with respect to their positions, then position-based routing protocols are used.

- **Mobility-aware routing:** The mobile ability of a node is considered in these types of routing protocols. The mobility can be in terms of mobile sensor nodes, mobile base station, mobile sensed phenomenon, or a combination of these.

3.2.3. Network structure based classification

The underlying network architecture plays an important role in the operations of the routing protocol in WSNs. In this section the review of routing protocols with respect to network structure is provided. By network structure based classification, the routing protocols can be divided into three categories as shown in Figure 3-4. The explanation of these categories is given in the next sections.

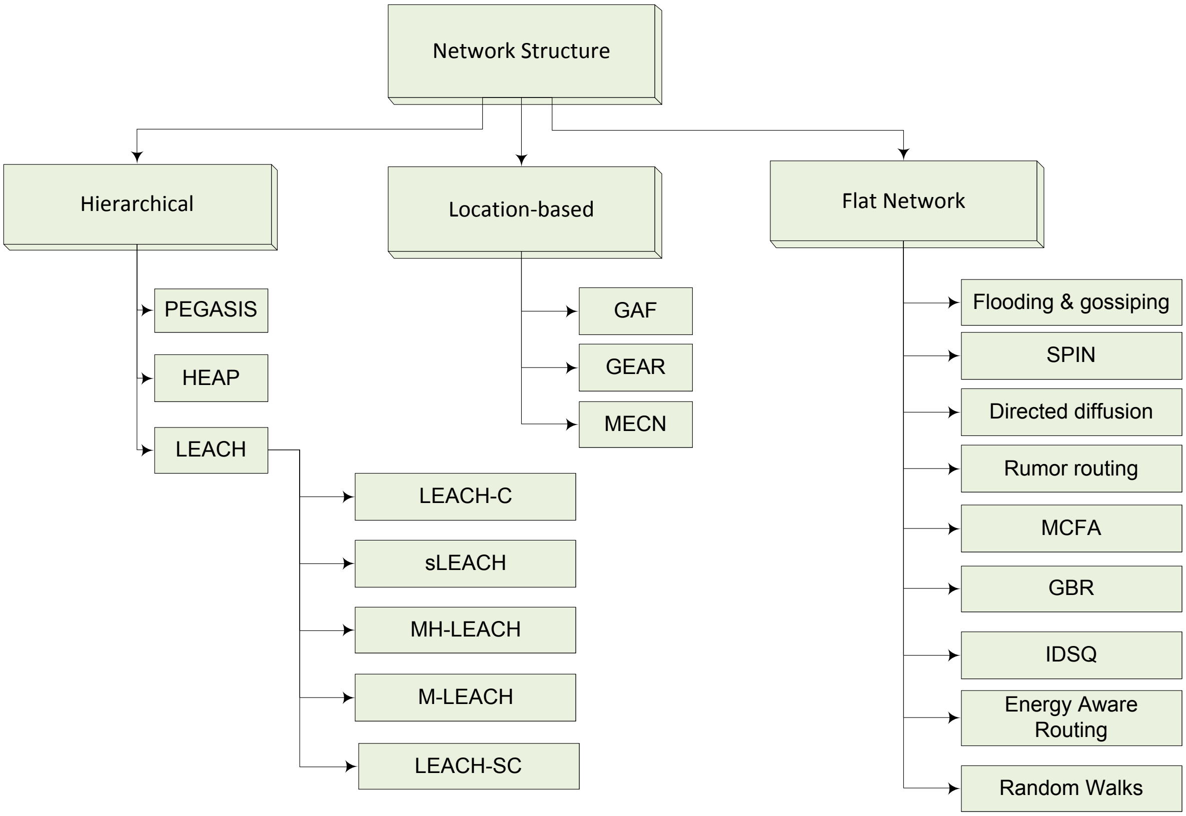

Figure 3-4: Types of WSN routing protocols based on network structure

3.3. LOCATION-BASED ROUTING PROTOCOLS

The location information of the sensor nodes in WSNs is used to calculate the distance between the nodes, which helps to choose the next hop. The deployment of nodes in WSN is spatial in nature. The sensor nodes are addressed by using their location information since there is no addressing scheme for WSNs such as IP-addressing. The node's location information assists the location-based routing protocols to send the data in a desired region instead of the whole network [31]. Some of the examples of location-based routing protocols are Minimum Energy Communication Network (MECN) [39], Trajectory-Based Forwarding (TBF) [40], Geographic Adaptive Fidelity (GAF) [41], and Geographic and Energy Aware Routing (GEAR) [42].

3.4. FLAT ROUTING PROTOCOLS

The multi-hop routing approach is used by flat routing protocols. All the nodes in the network play the same role. The base station generates the queries to the nodes and in response nodes transmit data towards a base station. Scalability and simplicity are the two major advantages of this kind of routing protocols. Because all the nodes play the same role, these protocols can easily accommodate a large number of nodes or can add more nodes. Simplicity emerges from not choosing any cluster head. All the nodes only send the data to the next hop or base station. The complexity involved for electing the cluster head is not required. The disadvantage of these routing protocols is the hotspots. Every node is capable of sending its own sensed data and of forwarding the other nodes' data to the base station. The energy in nodes around the sink drains quickly due to forwarding a lot of other nodes' data to the base station. The list of some of the important flat routing protocols is given below.

- Flooding and Gossiping
- Sensor Protocols for Information via Negotiation (SPIN)
- Directed diffusion
- Rumor routing
- Minimum Cost Forwarding Algorithm (MCFA)
- Gradient-Based Routing (GBR)
- Energy-Aware Routing
- Routing based on random walks
- Minimum Energy Communication Network (MECN)

3.5. HIERARCHICAL ROUTING PROTOCOLS

In hierarchical routing, the network is divided into clusters to achieve efficiency. The selection of cluster heads and formation of clusters are the two important concerns of hierarchical routing protocols. The advantage of hierarchical routing is the aggregation of data. The data from all member nodes are sent to the cluster head and then the cluster head forwards these data towards the sink after applying compression techniques. The aggregated data are easy to handle and simple to process. One of the major drawbacks of hierarchical routing is the increase in energy consumption of cluster heads due to their additional functions. The nodes are selected as cluster heads in rotation manner, which overcomes this issue. The selection of cluster heads and the formation of clusters in each round require more computations, which also causes more energy consumption.

Low Energy Adaptive Clustering Hierarchy (LEACH) is one of the first hierarchical protocols for WSNs. The main idea behind the proposal of LEACH is to save the energy of wireless nodes. Many enhancements have been proposed based on LEACH protocol to improve the performance of different network parameters. The detailed study of LEACH and its upgrade versions are given in the next section. Other than LEACH, some other hierarchical routing protocols are: Hierarchy-based Anycast Routing (HAR), Hierarchical Energy-Aware Routing for Sensor Networks (HEAR-SN), and Balanced Aggregation Tree Routing (BATR).

3.6. LEACH

The LEACH [43] protocol is the basic clustering-based energy-efficient routing protocol. The clustering techniques proved to be very useful to reduce the energy consumption and increase the network lifetime. The entire network is divided into clusters in the LEACH routing protocol. One sensor node in each cluster must act as a cluster head and all remaining sensor nodes are member nodes of that cluster. Communication between the member nodes and sink is only possible via the cluster head. From each cluster, only the cluster head can directly communicate with the sink. The cluster heads collect, aggregate, and forward the data from member nodes to the sink. The cluster head consumes more energy due to the additional functions and this node can die quickly if it continuously plays the role of a cluster head. LEACH resolved this problem by changing dynamically the role of nodes as cluster heads.

LEACH works in rounds. The operations that are carried out in each round consist of two phases known as setup and steady state phases. The organization of clusters and selection of cluster heads (CHs) are done in the setup phase of the LEACH. The data are sent to the sink during the second or steady state phase.

In the setup phase, the formation of clusters and the election process of cluster heads are performed. First of all, the whole network is divided into clusters. Now the cluster head election process starts in each cluster. There are many ways to elect the CH. Some of the wireless nodes in the network ignore the negotiation process with other nodes and elect themselves autonomously as CHs. The CH selection criteria of a member node are the recommended percentage P and the earlier record as a CH. If a node is not a CH in preceding 1/P rounds, it produces a number between zero and one (0-1). Only nodes with a generated number less than threshold T (n) are eligible to become CHs. The formula used to calculate the value of threshold is given in equation 3.1.

$$T\ (n) = \begin{cases} \frac{P}{1-P*(r mod \frac{1}{P})} & if\ n\ \in G \\ 0 & Otherwise \end{cases} \tag{3.1}$$

where

G = Group of nodes not selected as CHs in preceding 1/p rounds;

P = Recommended percentage of CH;

r = Current round.

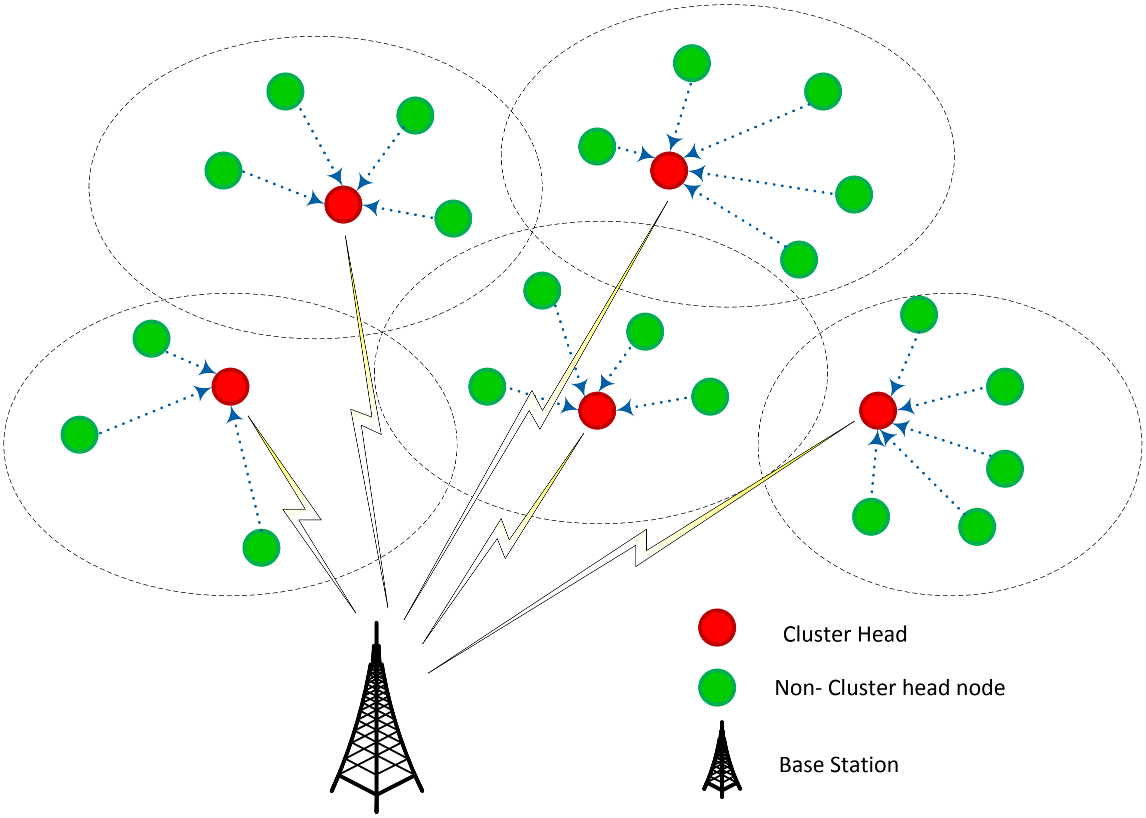

Figure 3-5: LEACH Architecture

The basic architecture of LEACH is shown in Figure 3-5. A node cannot be selected as a

CH if it has already performed a CH role in the last 1/p rounds but all nodes that were CHs before 1/p rounds will again be candidates for the selection of CHs [43, 44, 45]. The uniform service of each node as a CH prevents the uneven energy consumption of the member nodes. The CSMA/CA protocol is used by the CH to broadcast its status. After receiving the broadcast messages from CHs, the non-cluster head nodes use the Received Signal Strength Indication (RSSI) as a parameter to select their CH. Each CH creates a Time Division Multiple Access (TDMA) schedule for their cluster members. The CH and member nodes communicate with each other during their assigned time slots in the steady state phase. The member node is only in active mode during its communication with a CH. Otherwise the member node goes to sleep mode during an unallocated time slot. The management of the member node in this way reduces the energy consumption and increases the battery life of the node. The CH collects the data from all the cluster member nodes. The CH transmits that data to the base station after compression. The time duration of setup phase is lower than the steady state phase. Many protocols were proposed for the enhancement of LEACH. Some of them are discussed below.

3.6.1. LEACH-Centralized (LEACH-C)

LEACH-C [44] is proposed by Heinzelman et al. The conventional LEACH protocol does not guarantee the best possible number of CHs and their effectual locations [46, 47]. The problem is due to the clusters formation method used by the LEACH algorithm. LEACH-C is therefore proposed to enhance the cluster creation part of the LEACH protocol.

All nodes are required to send their ID, location, and energy information to the base station during the setup phase of LEACH-C [44]. The base station is responsible for assigning the role of CH to any member node by using its central control algorithm. The central control algorithm first specifies the average energy level and then compares that energy level to the energy level of the received signal energy [46]. The base station picks the optimal number of CHs from the nodes with an energy level greater than the average energy level. A list of IDs of these selected nodes is transmitted by the base station to all nodes. From this list, a node having minimum distance from its member nodes is elected as CH of that cluster. The approach used in LEACH-C reduces the energy consumption of CH and member nodes. The following assumptions are taken in this protocol:

- Every node can calculate its energy.
- Every node knows its location.
- Every node can communicate to the base station.

The successful data transmission during the steady state phase of LEACH-C increases. Some of the disadvantages of using the LEACH-C protocols are given below.

1. During the setup phase, all the nodes in the network are required to send their information to the base station. This process causes additional energy consumption from each node.
2. The central control algorithm runs on the base station to select the CHs. The IDs of selected CHs are passed to all nodes. Every node needs to compare its ID with the IDs of CHs to determine its role as a CH. These additional computations consume more energy from the nodes.

3.6.2. Multi-Hop LEACH

It is difficult for all CHs to communicate directly with the base station when the sensors' deployed area is very large. High transmission power is required to send the data from CHs to the base station if the base station is far away from the CHs. LEACH only assumes that all CHs are at single hop distance from the base station, which is not a suitable approach for this scenario [48]. An approach, Multi-Hop LEACH, addresses this issue [49]. Multi-Hop LEACH is an enhancement of LEACH, which reduces the energy consumption of the CHs in large WSNs [48, 49, 50]. The formation of clusters and selection of the CHs is done in the setup phase. During steady state phase, the non-cluster head nodes send their data to the CHs. The CHs aggregate and transmit that data towards the base station directly or through other CHs. The two types of Multi-Hop LEACH communications are intra-cluster and inter-cluster.

The Multi-Hop LEACH protocol communication architecture is shown in Figure 3-6.

The random selection of CHs is the same as in LEACH. The most feasible and energy efficient path is selected for that CH which is far from the base station. The method used for the selection of intermediate CH is the distance between the CH and the base station. The CH closer to the base station receives the data from the other CH which is far from base station. This helps to save energy of those CHs which belong to the clusters with larger distance from the base station as higher transmission energy cost is required for communication with larger distances.

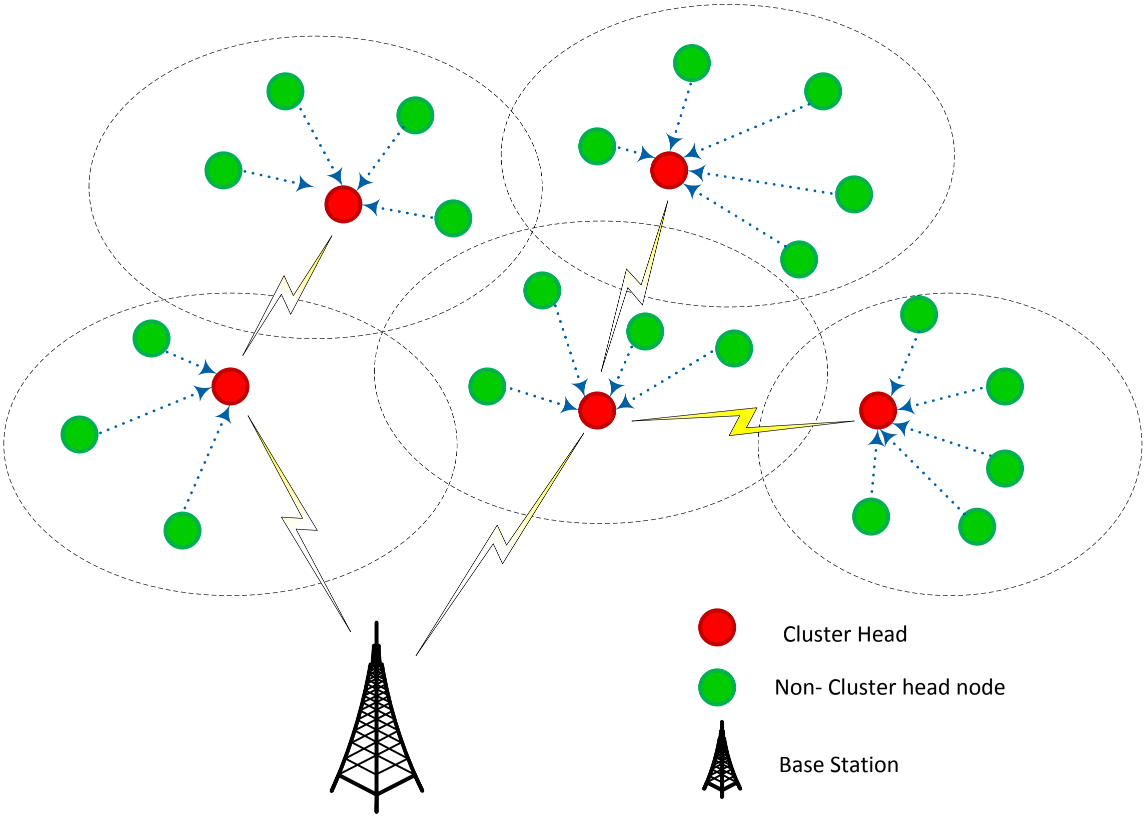

Figure 3-6: Multi-Hop LEACH Architecture

3.6.3. Stable Election Protocol (SEP)

Most of the hierarchical routing protocols such as LEACH [43] consider the homogeneous nodes with respect to their energy in the WSNs. The nodes selected as CH consumes more energy due to performing additional functions that results in early death of these nodes. The stability region, time interval before the death of first node, is low in these protocols. SEP [51] provides a mechanism for using the heterogeneous nodes, a percentage of nodes with higher initial energies, in WSNs which increases the stability region. The nodes with higher initial energies are called advanced nodes. The following assumptions are considered in this protocol.

- A percentage of the total number of sensor nodes contains additional energy resources.
- The deployment of sensor nodes is randomly and uniformly distributed.
- All the nodes are static.
- Sink is placed in the centre of the sensor field.
- The dimensions of sensor field are given.

SEP [51] considers the weighted election probabilities of the nodes in which the advanced as well as normal nodes are selected as cluster heads to ensure the balanced energy consumption. The residual energy is used as a parameter for the selection of the cluster heads. The additional energy of the advanced node helps to prolong the network lifetime. As compare to other protocols, the death of first node in SEP occurs after more rounds which results in higher stability region.

3.6.4. Solar-aware LEACH (sLEACH)

In some cases sensor nodes are deployed in remote or non-accessible areas such as battlefields or jungles. One of the major issues in the sensor node is to maintain the required power. The life span of WSNs can be improved by using solar panels with sensor nodes. The solar-aware LEACH protocol is proposed for application specific WSNs to tackle these situations [52]. Some nodes are enhanced with solar power in sLEACH. The nodes with solar power are stronger candidates for the selection of CHs. The concepts of LEACH and LEACH-C (discussed earlier in this section 3.6) are used in sLEACH protocol.

3.6.3.1. Solar-aware centralized LEACH

In this protocol the base station uses the enhanced central control algorithm for the selection of the CHs. The nodes driven by a solar power system are given priority for the selection of CHs due to their higher residual energy. All nodes in sLEACH send their solar power status along with their ID, location, and energy information to the base station. sLEACH uses the same CH selection criteria as in LEACH-C (i.e. nodes with higher energy will be chosen as CHs). The addition of solar-aware nodes helps to improve the performance of the entire network. The network performance and the life span of solar-aware nodes depend upon the duration of the node's exposure to the sun. The shorter sun exposure reduces the node's residual energy which leads to a change in the role of the node from cluster head to non-cluster head [53]. On the other hand, a non-cluster node can get more power than current CH with the help of a solar power system, which sends the message with the flag to CH. This node will be selected as CH.

3.6.3.2. Solar-aware distributed LEACH

The distributed fashion is used for the formation of clusters in solar-aware distributed LEACH [52]. It works in the same way as LEACH with two phases; setup phase and steady state phase.

- **Setup Phase:** The solar aware nodes are the stronger candidates during the selection process of the CH. Initially the probability of a battery operated node is the same as a solar driven node. To give more priority, the probability of solar aware nodes needs to be higher than battery operated nodes. The formula given in equation 3.1 is changed by equation 3.2 to consider the solar aware nodes.

$$T\ (n) = sf(n) * \frac{P}{1-(\frac{cHeads}{numNodes})} \tag{3.2}$$

where

sf(n) is the scaling factor.

The value of sf(n) for solar driven node is greater than 1.

The value of sf(n) for battery driven node is the reciprocal of the solar driven node's sf(n) value. For example if sf(n) of the solar driven node is 4 then sf(n) of the battery driven node will be ¼.

P= Optimal CH percentage.

cHeads= Number of cluster heads since the start.
numNodes= Total number of nodes.

The remaining process of the setup phase is the same as LEACH.

- **Steady state Phase:** During steady state the member nodes send the data to the base station via CH. The process of CH handover starts if the solar power level of a non-cluster head node increases more than the power level of the current CH node. The node with the higher energy level sends a flag to the current CH and is ultimately selected as the CH of the cluster.

The performance of distributed sLEACH increases by adding more solar operated nodes.

3.6.5. Mobile-LEACH (M-LEACH)

The support of the mobile sensor node is one of the missing features in LEACH routing protocol. M-LEACH is proposed with the mobility support of sensor nodes [54]. LEACH follows a non-realistic consideration that the energy and radio characteristics of all nodes are fixed and homogenous. In reality the numbers of nodes in clusters are different. Each CH deals with a different number of member nodes. The lifetime of CH dealing with a larger number of nodes is shorter.

The mobile LEACH protocol considers the node mobility during both setup and steady state phases. The mobility support is for both cluster head and non-cluster head nodes. The M-LEACH protocol assumptions are given below:

- The location of the base station is permanent;
- A GPS receiver is used to calculate the node’s location;
- At the starting point, the nodes are assumed to be homogenous with respect to their antenna gain.

The changes proposed by M-LEACH during setup phase for the selection of the cluster heads are given below.

- The nodes with more residual energy are preferred.

- In terms of mobility, nodes with lower speed are preferred.
- The used attenuation model is proposed in [55].
- The nodes with lower attenuation power are preferred.

The basic rule of energy based transmission is the transmitted signal energy multiplied by attenuation equals the received signal energy, as shown in equation 3.3.

$$P_{receive} = {P_{transmit}}/{r^a} \tag{3.3}$$

where

r = distance of transmission

a= RF attenuation constant

The value of 'a' is between 2 to 5 depending upon distance and transmission environment.

Due to the random movement of mobile nodes, the nodes can move to an area which is not in coverage range of any CH. To overcome this problem, the sensing area is further divided into sub-areas and optimization of CHs is performed in these sub-areas. The selection of CH is done in M-LEACH by using the following method.

The variable n is used to denote the number of sensor nodes in a sub-area. The (X, Y) coordinates of each node *i* are represented by (x_i, y_i). The distance from CH to node *i* is represented by d_i. The transmission attenuation of node i can be calculated by using equation 3.2. The value of s_j for sub-area j is calculated by equation 3.4.

$$s_j = \sum_{i=2}^{N_j} d_i^2 \tag{3.4}$$

The best possible location of CH in the sub-area can be found by using below equations

$$x_j^c = \frac{1}{N_j} \sum_{i=1}^{N_j} x_i \tag{3.5}$$

$$y_j^c = \frac{1}{N_j} \sum_{i=1}^{N_j} y_i \tag{3.6}$$

The nodes with lower mobility are preferred to become CHs. The cost factor C_i^j given in equation 3.7 is used for node i to become CH.

$$C_i^j = v_i^* * \sqrt{(x_j - x_j^c)^2 + (y_i - y_j^c)^2} \tag{3.7}$$

where

$$v_i^* = \begin{cases} v_t & if\ v_i < v_t \\ v_i & Otherwise \end{cases}$$

v_i= velocity of node i

v_t= threshold velocity

Any node with the minimum value of C_i^j will be selected as CH. The selected CH nodes broadcast the messages to all member nodes about their new status. Each node selects its CH from many different CHs on the basis of residual energy.

The mobile LEACH protocol uses a simple mechanism for mobility management. There is a possibility that the CHs or member nodes move away during the steady state phase. In case the CH goes away, the most suitable remaining node will act as CH. This kind of mobility negatively affects cluster pattern. M-LEACH overcomes this issue by using handover operation. A node willing to make handover generates two messages; JOIN-REQ and DIS-JOIN. The messages JOIN-REQ and DIS-JOIN are for new CH and current CH respectively. The member node transmission pattern is re-scheduled by all CHs when the handoff is complete.

3.6.6. LEACH Selective Cluster (LEACH-SC)

LEACH-SC protocol [56] introduces a new method of CH selection. Most of the previous methods use the residual energy and distance as parameters for the selection of CH. A problem was observed in these methods of CH selection. The main task of CH is to route the member nodes data to the base station. Even when the member node is closer to the base station than its CH, according to previous methods the node must send data to its CH first. The CH then transmits the same data to the base station. The energy cost increases in the case where the member nodes send the data to the CH in the opposite direction of the base station. The LEACH-SC mechanism resolves this issue, which results in lower energy cost of the sensor nodes and prolongs the network life. Like

LEACH, the LEACH-SC procedure works in rounds. Each round consists of setup and steady state phases. LEACH-SC improves the cluster formation portion of the setup phase. An enhanced cluster head formation algorithm is given in which only selected CHs transmit their IDs and location information to all nodes. The nodes receive this information based on their location. The information from the CH is received only by those nodes that are in that CH coverage range. The nodes choose only that CH which is closest to the base station and their own centre point. The selection of CH in this way reduces the overall energy consumption in steady state phase.

The mathematical analysis of LEACH-SC discussed in [56] is to prove the energy efficiency of the network when a sensor node selects a CH whose location lies nearest to the midpoint between the node itself and the base station.

3.6.5.1. Mathematical Model

The transmission energy of a *k* bit message can be calculated by the given formula.

$$E_{Tx}(k,d) = E_{Tx-elec}(k) + E_{Tx-amp}(k,d) \tag{3.8}$$

$$= \begin{cases} kE_{elec} + k\varepsilon_{fs}d^2 & if \;\; d < d_0 \\ kE_{elec} + k\varepsilon_{mp}d^4 & if \;\; d \geq d_0 \end{cases}$$

where

d = distance between transmitter and receiver of k bit message.

d_0 = threshold distance.

E_{elec} = Energy loss due to transmitter's internal circuit energy consumption per bit.

The equation 3.8 shows that free space channel model is used when $d < d_0$ and multipath fading model is considered when $d \geq d_0$. The energy cost of the receiver is calculated by equation 3.9.

$$E_{Rx}(k) = E_{Rx-elec}(k) = kE_{elec} \tag{3.9}$$

3.6.5.2. Optimization objectives

The following mathematical model is used to achieve the objective of low energy cost for the enhancement of network lifetime.

$$Min(E_{total}) \tag{3.10}$$

$$E_{total} = E_T + E_R + E_I + E_S \tag{3.11}$$

where

E_{total} = Total energy cost in the network.

E_T = Transmission energy cost.

E_R = Receiving energy cost.

E_I = Idle state energy cost.

E_S = Spectrum sensing energy cost.

Normally E_R, E_I and E_S are constants however E_T is variable. This reveals the fact that the only major factor influencing the total energy cost is the transmission energy. So it is concluded that the transmission cost determines the overall network energy cost. The equation 3.10 can be modified as following.

$$Min(E_T) \tag{3.12}$$

The equation 3.12 can also be changed with respect to the transmitting cost

$$\begin{aligned} Min(E_{Tx}(k,d)) &= E_{Tx-elec}(k) + E_{Tx-amp}(k,d) \\ &= \begin{cases} kE_{elec} + k\varepsilon_{fs}d^2 & if\ d < d_0 \\ kE_{elec} + k\varepsilon_{mp}d^4 & if\ d \geq d_0 \end{cases} \end{aligned} \tag{3.13}$$

where

k = Number of bits forwarding at distance d.

E_{elec} = Transmitter internal energy consumption per bit.

ε = Transmitter amplifier energy consumption per bit.

The equation 3.13 shows that *d* is a key factor to reduce energy cost of the network. So the simplified model is given below:

$$Min(d^n) \tag{3.14}$$

The value of n is 2 or 4. Generally the sensor nodes in WSNs are placed very close to each other and the two-way communication is used between them. Here, the assumption value of n is 2 so the optimization target is Min (d^2).

The distance between CH and node is represented by d_{toCH} whereas the distance between CH and sink is denoted by $d_{CHtoSink}$. These assumptions help to further simplify the optimization objectives as given below:

$$Min(d_{toCH}^2 + d_{CHtoSink}^2) \tag{3.15}$$

3.6.5.3. Optimization scrutiny

The graphical representation of our scenario is shown in Figure 3-7. The centre point between sink and node is denoted by M. A perpendicular is drawn on the line which is shown from node to sink. The touching point of perpendicular with the line is H. The assumptions are given below:

Distance from node to sink = d_{toSink} = c
Distance from node to CH = d_{toCH} = b
Distance between points H and M = x
Distance between Cluster Head and M = d
Distance between Cluster Head and H = h

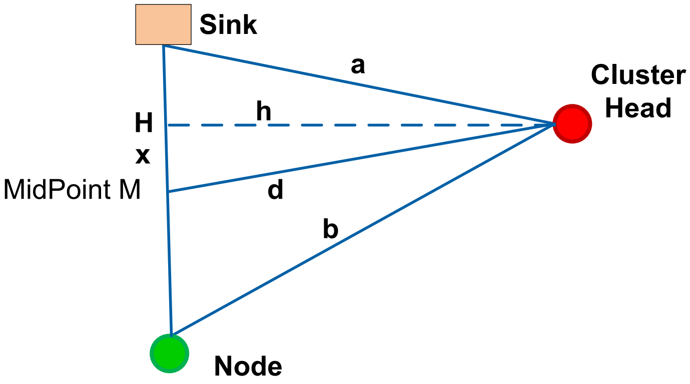

Figure 3-7: Graphical representation of scenario

The two trigonometric formulas are given below:

$$a^2 = h^2 + (\frac{c}{2} - x)^2 \tag{3.16}$$

$$b^2 = h^2 + (\frac{c}{2} + x)^2 \tag{3.17}$$

By adding the equations 3.16 and 3.17, we get

$$a^2 + b^2 = h^2 + (\frac{c}{2} - x)^2 + h^2 + (\frac{c}{2} + x)^2 = 2h^2 + \left(\frac{c^2}{2}\right) + 2x^2 \tag{3.18}$$

As we have $x^2 + h^2 = d^2$, by substituting $x^2 = d^2 - h^2$ in equation 3.18, we found

$$a^2 + b^2 = 2h^2 + \left(\frac{c^2}{2}\right) + 2d^2 - 2h^2 = \left(\frac{c^2}{2}\right) + 2d^2 \tag{3.19}$$

Equation 3.19 shows that when the value of d_{toSink} is fixed, $d_{toCH}^2 + d_{CHtoSink}^2$ is only related to *d* then equation 3.15 becomes

$$Min(d_{toCH}^2 + d_{CHtoSink}^2) = Min(d^2) \tag{3.20}$$

It concludes, whenever the node selects it's CH in such a way that its location is nearest to the midpoint between the node and the sink, the squared distance (d^2) of their communication is minimum.

3.6.5.4. Conclusion

When the distance between node and sink is fixed, the equation 3.21 minimizes the distance between the midpoint of node and sink with respect to CH. Hence, in LEACH-SC, member nodes should select a CH which is nearest to the midpoint of itself and BS that helps to optimize the communication cost.

$$Min(d_{toCH}^2 + d_{CHtoSink}^2) \tag{3.21}$$

CHAPTER 4 METHODOLOGY

In this chapter we present and discuss the methodology used for our proposed protocol called Advanced Zonal Rectangular LEACH (AZR-LEACH). Section 4.1 describes the background of our proposed protocol. The detailed study of our proposed routing protocol is provided in section 4.2.

4.1. BACKGROUND

In LEACH [43] protocol, the dynamic clustering mechanism is adopted in which a node elects itself to become a cluster head by some probability and broadcasts its status to the entire network. All the nodes are assumed to be homogeneous in terms of their energy. A cluster head consumes more energy than a non-cluster head node as the cluster head receives data from all cluster member nodes and then transmits their data to the base station directly by using single hop communication. Each node in the network has a chance to become a cluster head during network lifetime. A greater number of nodes may elect themselves as cluster heads than the desired number of cluster heads. This increased number may cause huge energy consumption due to performing the additional functions. The main drawbacks of LEACH protocol are uneven distribution of cluster heads, high transmission power required in the case of large areas, and lower stability region due to the early death of its nodes. To overcome these drawbacks LEACH-Centralized (LEACH-C) [45], Multi-Hop LEACH (MH-LEACH) [49], and Stable Election Protocol (SEP) [51] provide the methods to solve uneven distribution of cluster heads, single hop communication, and lower stability respectively.

LEACH-C [45] uses a centralized cluster head selection mechanism in which cluster heads are selected by the base station. In each round, the base station receives the current location and remaining energy information from all nodes in the network. Using the remaining energy information, the base station determines a set of nodes for the cluster head selection. The base station computes the average node energy of the network. If the remaining energy of a node is greater or equal to the average node energy, the node will be selected in the candidate set for the cluster head. After determining the candidate set, the base station finds the optimal number of cluster heads and clusters by using an approximation algorithm such as simulated annealing [57]. The simulated annealing algorithm runs on the candidate cluster head set to find the best cluster head node and clusters. Once the optimal cluster head and clusters are determined, the base station broadcasts the cluster heads IDs, cluster member node IDs, and transmission schedule for each cluster to all nodes in the network. Each node compares its ID with the cluster head ID, and if it matches, then it acts as the cluster head. Otherwise the node determines its slot in the transmission schedule and transmits data to the cluster head in its slot. One of the main drawbacks in LEACH-C [45] is repeated cluster formation overhead. There is also information and energy wastage because of fixed round time.

MH-LEACH [49] selects an efficient path from the cluster head to the base station. The sensor nodes send the data to their cluster head. The cluster head then aggregates the data and forwards it to the base station. Unlike LEACH which uses a single hop communication, MH-LEACH sends the data from the cluster head to another one, if available, closer to the base station. That cluster head forwards the data to the base station. The benefit of MH-LEACH is to save the transmission power for cluster heads that are farther away. However, the battery of cluster head closer to the base station runs out due to forwarding the data from all farther cluster heads.

SEP [51] introduces the concept of advanced nodes. The advanced nodes are equipped with higher energy resources. SEP uses the weighted elected probabilities for normal nodes to select advanced nodes as well as normal nodes for cluster heads. The method used in SEP increases the stability region but reduces the network lifetime and throughput.

In order to overcome the drawbacks of LEACH, LEACH-C, MH-LEACH, and SEP; we proposed a new routing protocol AZR-LEACH which is discussed in next section.

4.2. ADVANCED ZONAL RECTANGULAR LEACH

The proposed AZR-LEACH protocol is based on LEACH protocol. In order to overcome the shortcomings of LEACH [43], LEACH-C [45], MH-LEACH [49], and SEP [51] protocols, a static clustering technique is used to optimize cluster head selection in our enhanced protocol. The logical partitions of sensor deployment area into rectangular clusters, advanced clusters, and zones help to improve the efficient communication between cluster heads and the base station.

4.2.1. Architecture

The basic architecture of Wireless Sensor Networks used in our protocol is shown in Figure 4-1. We assume that the sensor nodes are deployed randomly and uniformly, are not movable, and are homogenous initially with respect to their antenna gain. It is also assumed that the dimensions of the sensor field are given and the coordinates of the base station are known. The base station is capable of receiving, aggregating, and then forwarding the data from the cluster heads to the desired destinations.

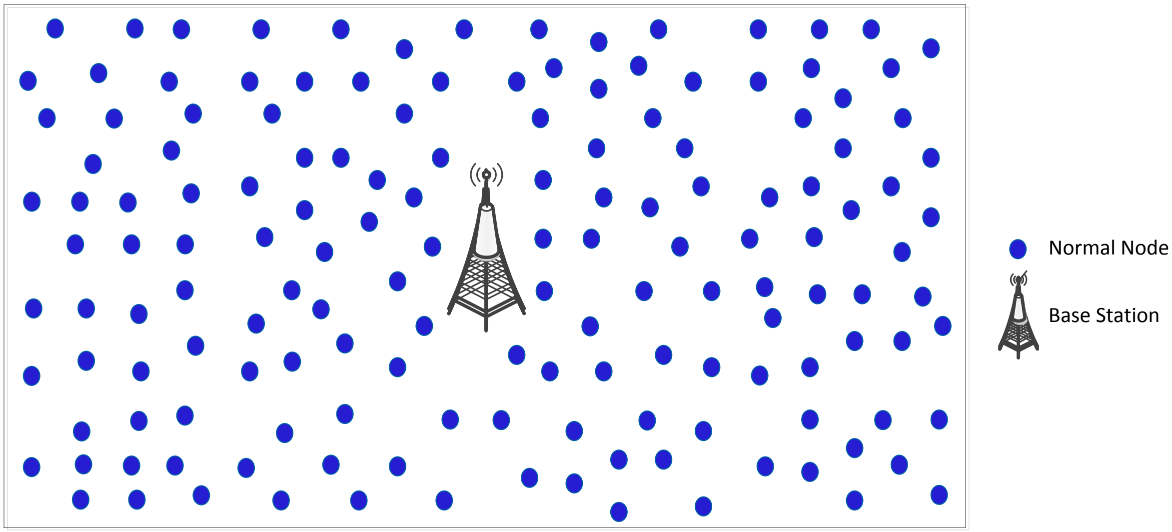

Figure 4-1: Basic WSNs architecture used for AZR-LEACH

4.2.2. Procedure

The LEACH protocol uses dynamic clustering technique. The proposed AZR-LEACH protocol opts for static clustering. The working procedure of AZR-LEACH is very simple. It is a round based protocol like LEACH, and every round consists of two phases: setup phase and steady state phase. Unlike LEACH, our proposed protocol introduces three additional concepts which are logical formations of rectangular clusters, selection of advanced clusters, and a combined group of rectangular clusters to form zones. The details of these additional concepts and phases used in AZR-LEACH are discussed below.

4.2.2.1. Rectangular Clusters

The entire network is divided into fixed rectangular clusters. These rectangular clusters are heterogeneous; that is each cluster may have a different number of nodes. Usually the base station is placed in the centre of the deployment area. The formation of rectangular clusters requires the dimensions of the deployment area. As mentioned earlier, it is assumed that the dimensions of the deployment area and position of the base station is known. The subdivision of sensor area starts from the centre and the area covered by each rectangular cluster is the same. For example if the total area is 500m X 500m and the base station is in the centre then 16 rectangular clusters with area 125m X 125m each will be formed as shown in Figure 4-2.

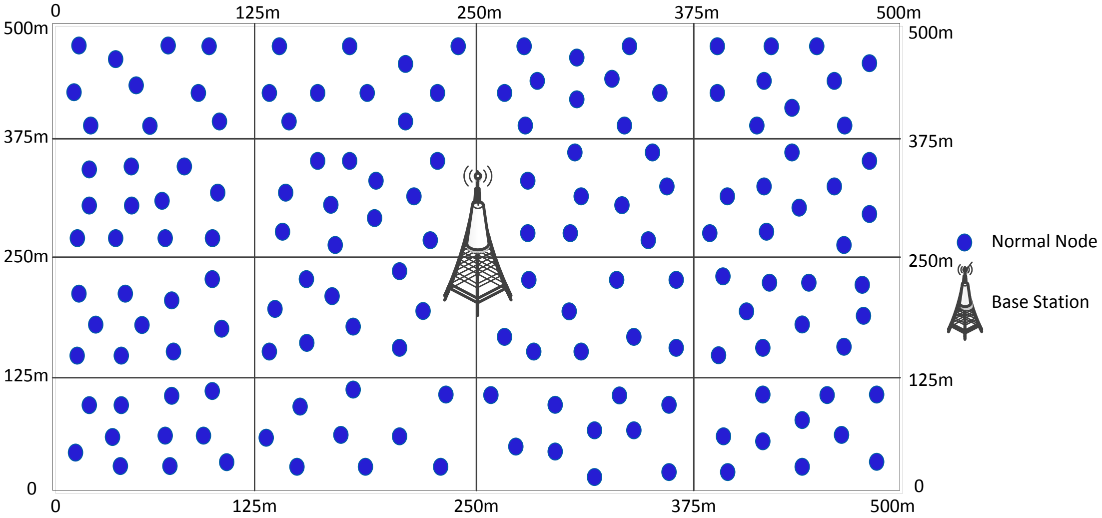

Figure 4-2: Rectangular clusters formation

4.2.2.2. Selection of Advanced Clusters

The clusters which are directly connected to the base station are selected as advanced clusters and the nodes in those clusters are known as advanced nodes. The advanced nodes are shown in Figure 4-3 in green. An advanced cluster head is capable of receiving the data from its own cluster member nodes as well as the other cluster heads and forwarding it to the base station. The use of advanced clusters and nodes helps to provide an energy-efficient support of Multi-Hop communication. The advanced cluster heads use lower transmission power than other cluster heads due to their closest location to the base station. Generally the base station is placed in an accessible location so the advanced nodes have easier access to it. The advanced nodes are also equipped with higher energy resources. In our experiments, we used 1.5 times more energy than the other nodes. Like SEP [51], using more energy in the advanced nodes helps to increase the stability region.

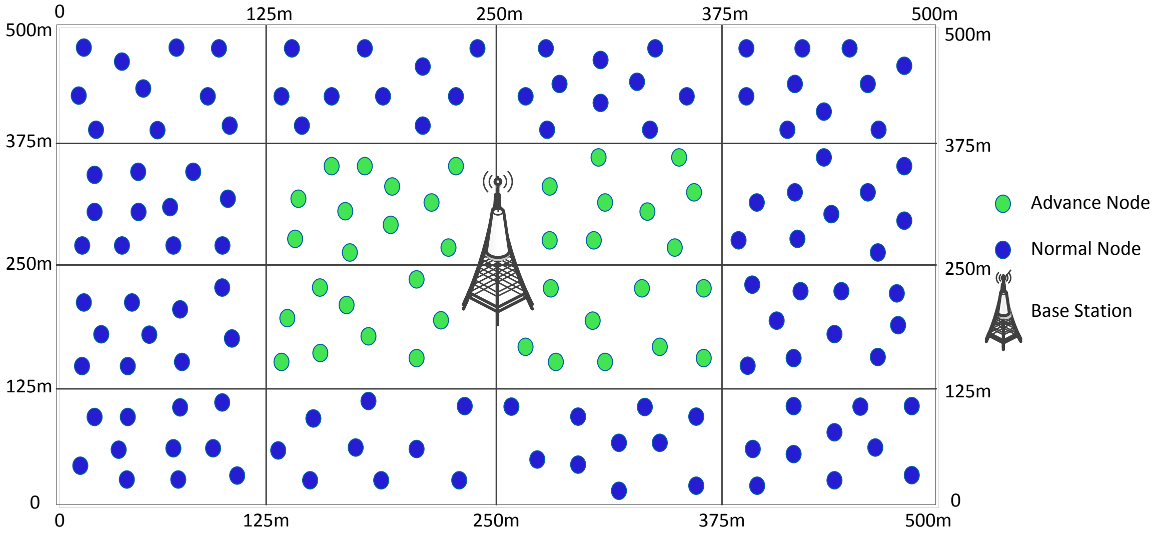

Figure 4-3: Advanced clusters and nodes

4.2.2.3. Formation of Zones

The group of rectangular clusters forms a zone. Each zone must contain at least one advanced cluster. The dotted lines in Figure 4-4 show the boundaries of the zones. The advanced cluster nodes participate in the selection of the advanced cluster head by using the same method as followed by other clusters. The idea of zone is to manage and balance the network traffic coming from the farther cluster nodes. The cluster heads from other zonal areas send their traffic to the cluster head of the advanced cluster which forwards it to the base station. The advanced cluster head communicates with only those cluster heads that belong to its zone.

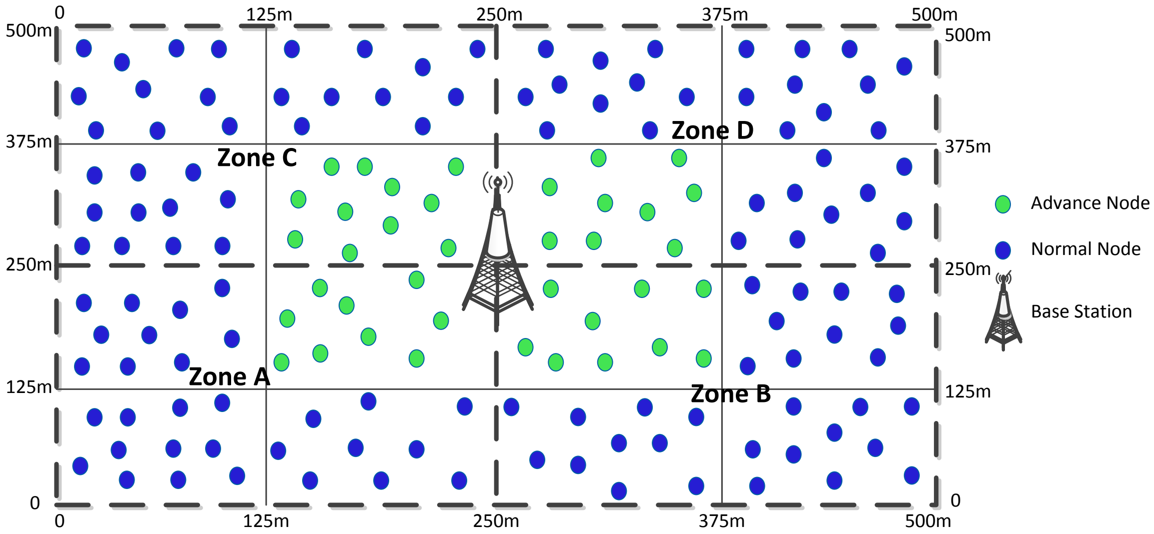

Figure 4-4: Formation of zones

In short, the nodes in a cluster can send the data only to their cluster head, and that cluster head can only send the data to the advanced cluster head of its own zone.

4.2.2.4. Setup Phase

In the setup phase, every node decides to become a cluster head or not. In LEACH [43] protocol, each node elects itself as a cluster head on the basis of the desired percentage of the cluster heads for the network and number of times a node has been a cluster head. Each node chooses a random number from zero to one and then calculates the threshold T (n). The node then compares the random number with T (n). If the random number is less than or equal to T (n), the node becomes a cluster head for the current round. The threshold for cluster head selection is calculated as:

$$T(n) = \begin{cases} \dfrac{P_d}{1 - P_d * \left((r) \bmod \frac{1}{P_d}\right)} & \text{if } n \in A \\ 0 & \text{Otherwise} \end{cases} \tag{4.1}$$

where P_d is the desired percentage of cluster heads, A is the group of nodes which are not selected as cluster heads in previous 1/p rounds and r is the current round. After several rounds, the energy of nodes in the network will become uneven, and nodes with high energy and low energy will have the same probability of becoming the cluster heads, so there will be an inappropriate cluster head selection. Unlike LEACH [43], our proposed protocol follows a different approach for cluster head selection. From each rectangular cluster, the node with the highest remaining energy will be selected as the cluster head. The current cluster head will decide the next cluster head for the next round in its cluster. All the nodes send their remaining energy information along with data packets to the cluster head. From this information, the current cluster head elects the node with the highest remaining energy as the cluster head for the next round. The rotation of CHs can be seen in Figures 4-5 and 4-6. After every round, a different CH is chosen. Every node will become a CH after 1/p rounds.

Using CSMA/CA protocol, the new cluster heads broadcast their status in their intra cluster range. Because the network is divided into fixed rectangular clusters, cluster heads do not have to broadcast their status to the whole network. Remaining non-cluster head nodes, which receive a broadcast message from the cluster head in their rectangular cluster, transmit a response message back to the cluster head in their rectangular cluster. The cluster head assigns TDMA slots to each node in its cluster and broadcasts this TDMA schedule to all the nodes.

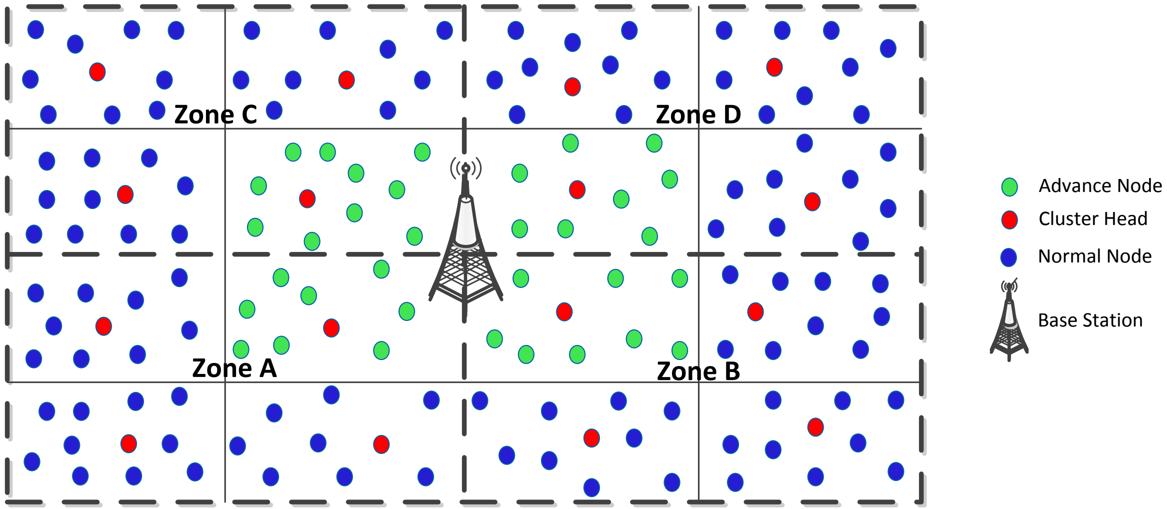

Figure 4-5: Cluster Head selection

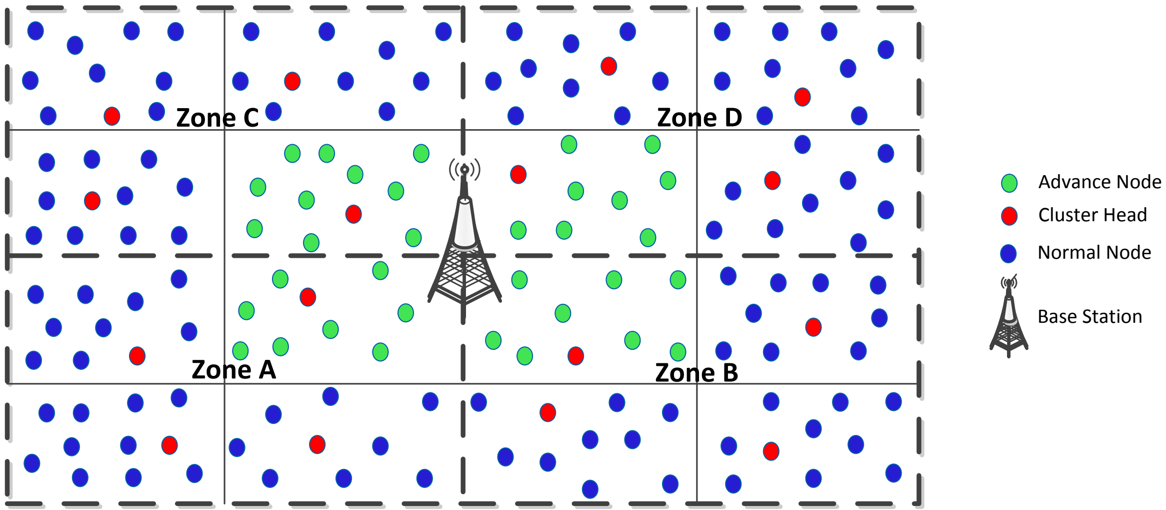

Figure 4-6: Rotation of Cluster Heads in AZR-LEACH

4.2.2.5. Steady state phase

After cluster heads selection and TDMA slots allocation, the steady state phase starts. The steady state phase of AZR-LEACH is almost similar to LEACH. Based on TDMA protocol, the communication starts between the cluster head and their respective CHs in their allocated time slots. The cluster node can only communicate with its respective CH in a predefined time slot. All cluster nodes remain in sleep mode during unallocated time slots. This leads to better energy efficiency of the protocol.

Non-cluster head nodes transmit their data to their associated cluster head in their rectangular cluster which aggregates the data of all non-cluster head nodes. Then this cluster head forwards the aggregated data to the advance cluster head node of its zone, which is directly connected to the base station. The advance cluster head node aggregates and compresses all data received from its zone cluster head nodes in addition to the non-cluster head nodes of the advanced cluster. After receiving all of the data, the advance cluster head node forwards this aggregated data to the base station as depicted in Figure 4-7.

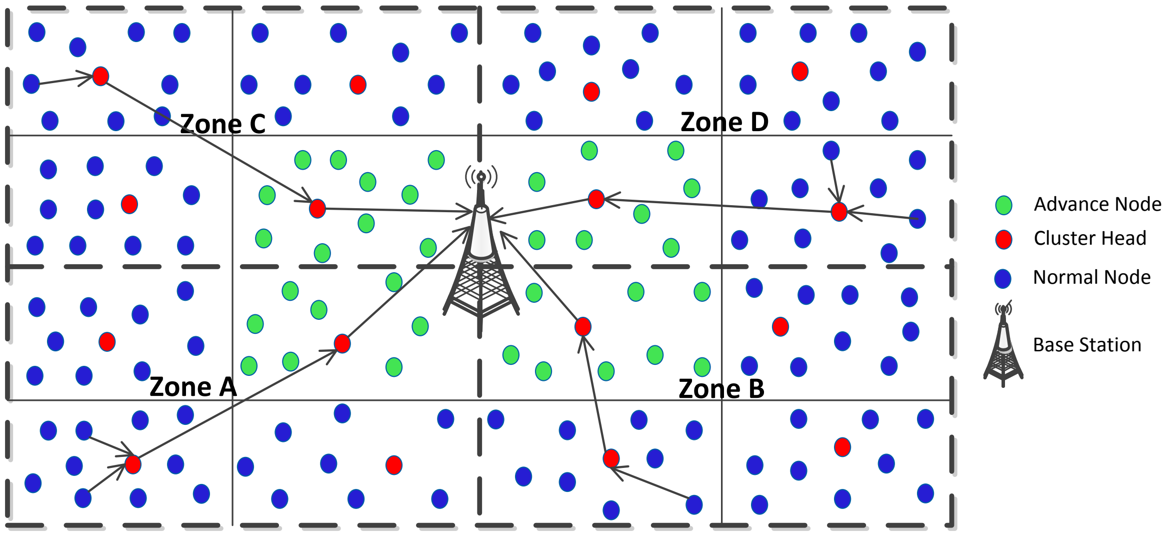

Figure 4-7: AZR-LEACH communication Paradigm

4.2.3. Advantages

The main advantages of AZR-LEACH over LEACH, LEACH-C, MH-LEACH, and SEP protocols are given below.

- **Simple Implementation:** The implementation of AZR-LEACH is very simple. Like LEACH, the cluster formation process is not required in the setup phase of every round.
- **Static rectangular clusters:** The static rectangular cluster formation proves to be more energy efficient than dynamic cluster formation. In dynamic cluster formation, the clusters are formed in the setup phase of every round which causes more energy consumption.
- **Balanced Cluster Head:** Each rectangular cluster contains one cluster head. The number of cluster heads, like the number of rectangular clusters, is fixed throughout the simulation until a complete cluster is dead.
- **Equally distributed network:** The division of whole deployment area in equally distributed sub-areas helps to balance the network traffic.

- **Energy efficient:** By dividing the network in rectangular clusters and zones reduces the traffic load. All nodes from a cluster send data to their own cluster head, and the cluster heads in a zone transfer that data to the advance cluster head. The multi-hop communication due to advanced cluster head nodes reduces the energy consumption.

CHAPTER 5 PERFORMANCE EVALUATIONS

Extensive simulations have been conducted by using the MATLAB simulation environment to compare the performance of our proposed Advanced Zonal Rectangular LEACH (AZR-LEACH) protocol with the Low Energy Adaptive Clustering Hierarchy (LEACH), Multi-Hop LEACH (MH-LEACH), and Stable Election Protocol (SEP). The results show that the AZR-LEACH extends the network lifetime, increases the overall throughput, reduces the energy consumption, and optimizes the number of cluster heads. In this chapter, simulation parameters used for our experiments are given in section 5.1. The simulation results are discussed in section 5.2.

5.1. SIMULATION PARAMETERS

The nodes are randomly deployed within the area of 500m X 500m. The base station is located at the centre of the deployment area with coordinates 250m X 250m. The population of nodes for this simulation is 200 (i.e. n=200). A sample of randomly deployed nodes for our experiments is shown in Figure 5-1. The equation 2.2 can be used to determine the density of the nodes in the sensor field. The different samples of randomly deployed nodes are used for each simulation and the results discussed in the next sections are the average values of 30 simulations.

We simulate LEACH [43], MH-LEACH [49], SEP [51], and AZR-LEACH protocols by using the parameters defined in Table 2.

Table 2: Simulation parameters

Parameters	Values
Network size	500m X 500m
Initial Energy	500 mJ
P_d	100 mJ
Data Aggregation Energy cost	50pj/bit j
Number of nodes	200
Packet size	4000 bit
Transmitter Electronics	50 nJ/bit
Receiver Electronics	50 nJ/bit
Transmit amplifier	100 pJ/bit/m^2

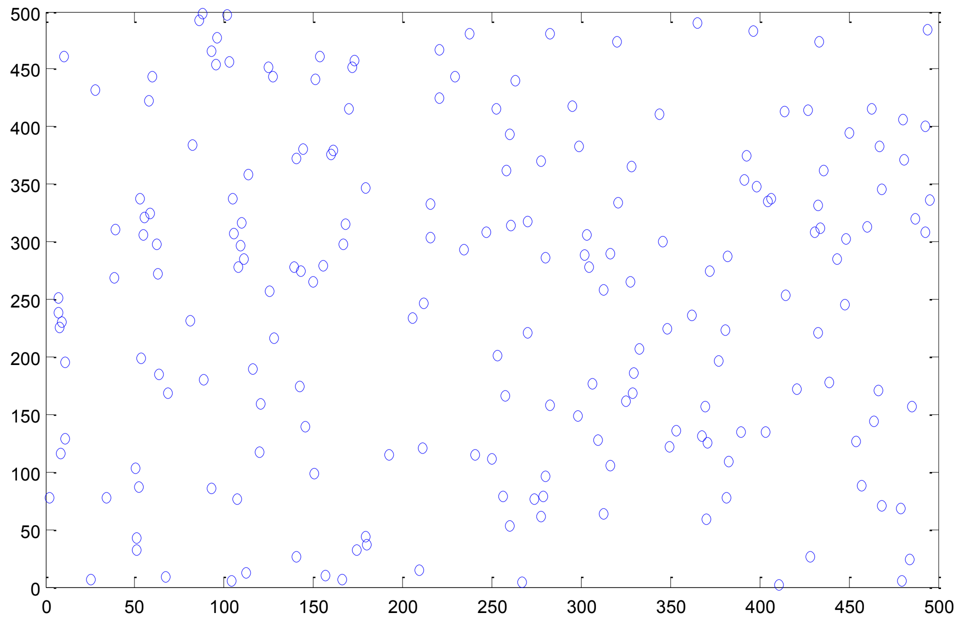

Figure 5-1: Random deployment of nodes

The following terms are used to evaluate the performance of clustering protocols [51]:

- **Stability Period:** The time interval between the start of the network operation and the death of the first sensor node is called stability period or stable region.
- **Instability Period or Unstable Region:** It is the time interval between the death of first node and the death of the last sensor node.
- **Network Lifetime:** The time interval between the start of the network operation and the death of the last sensor node is called network lifetime.
- **Number of Cluster Heads per round:** The total number of nodes selected as cluster heads from the whole network in each round. These cluster heads are responsible to receive the data from member nodes and then send these data, after aggregation, to the sink.
- **Number of Alive Nodes:** The total number of sensor nodes that have not yet depleted all of their energy.

- **Number of Dead Nodes:** The total number of sensor nodes that have consumed all of their energy and are not able to do any kind of functionality.
- **Throughput:** The rate of data sent from the cluster heads to the sink is called the throughput. The rate of data sent from member nodes to their respective cluster heads is also called throughput.
- **Reliability:** It depends upon the measurement of the stable region and the unstable region. The larger stable region and smaller unstable region means better reliability.

There is a trade-off between reliability and network lifetime. Network lifetime includes both stable and unstable regions. For the same stable region, a smaller unstable region means more reliability but a shorter network lifetime.

5.2. SIMULATION RESULTS

MATLAB tool is used to get the simulation results. As mentioned earlier, AZR-LEACH works in rounds. The total number of rounds used for our experiments is 1500. Simulations of AZR-LEACH in comparison with LEACH [43], MH-LEACH [49], and SEP [51] are performed to observe the frequency of dead and alive nodes per round, number of Cluster Head (CH) nodes per round, network lifetime, and overall throughput.

Figure 5-2 shows that AZR-LEACH has greater stability time as compared to LEACH [43] and SEP [51] but lower stability time than the MH-LEACH [49]. The first node of AZR-LEACH is dead after approximately 80 rounds whereas the first node of LEACH, MH-LEACH, and SEP is dead after approximately 39, 107, and 62 rounds respectively. By considering the total 1500 rounds, the stability period of LEACH, MH-LEACH, SEP, and AZR-LEACH are 2.6%, 7.1%, 4.13%, and 5.33% respectively. The MH-LEACH provides the better stability time but its overall network lifetime shown in Figure 5-3 is shorter than our protocol.

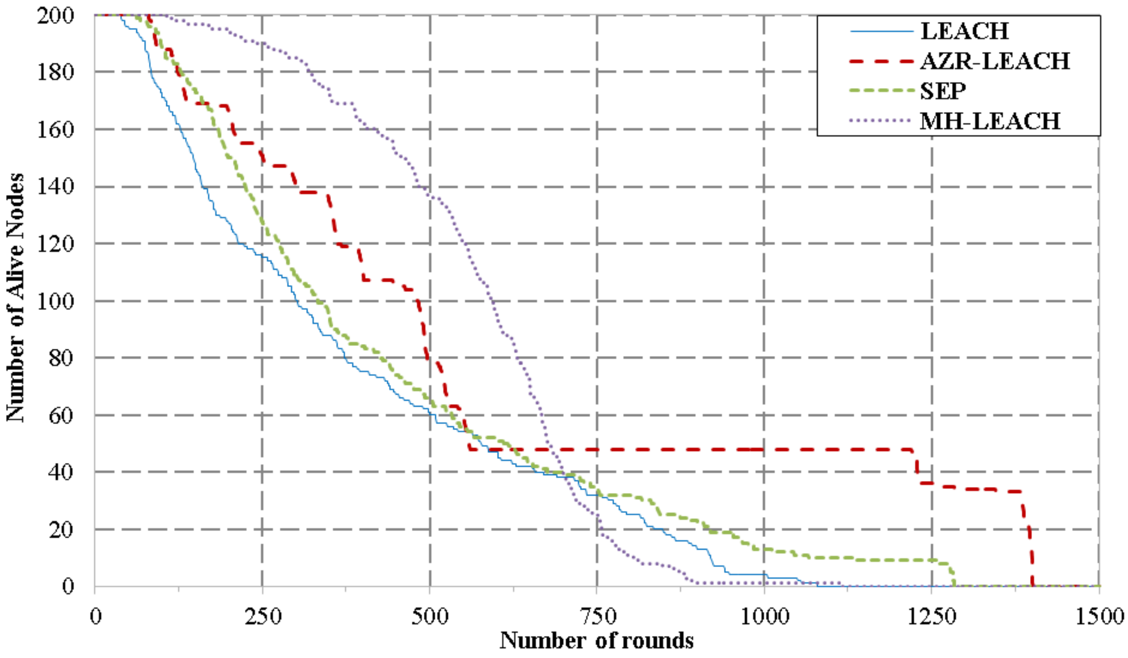

Figure 5-2: Total number of alive nodes in each round

The last node of LEACH [43], MH-LEACH [49], SEP [51], and AZR-LEACH is dead after approximately 1079, 1113, 1284, and 1401 rounds respectively. The network lifetime of AZR-LEACH is 23%, 20.56%, and 8.35% greater than LEACH, MH-LEACH, and SEP respectively as depicted in Figure 5-3.

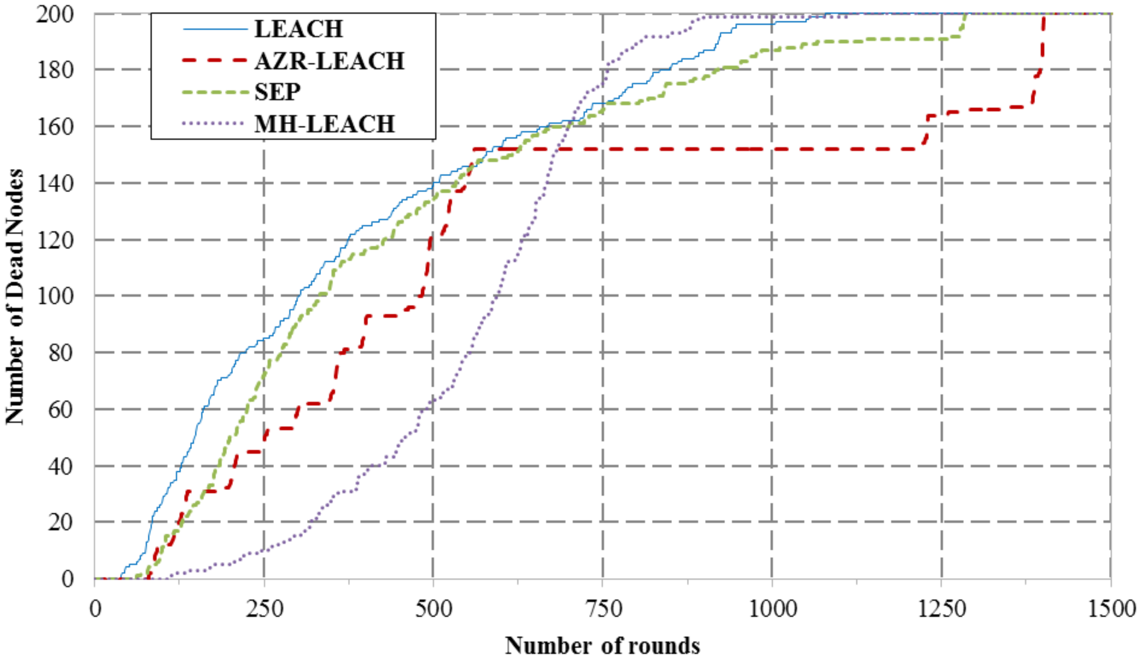

Figure 5-3: Total number of dead nodes in each round

Figure 5-4 shows that throughput of AZR-LEACH is significantly greater as compared to LEACH [43], MH-LEACH [49], and SEP [51] in stable and unstable regions. From this graph we see that AZR-LEACH guarantees about 23.39%, 31.51%, and 47.42% more packets to the base station in comparison with LEACH [43], MH-LEACH [49], and SEP [51] respectively. The throughput of AZR-LEACH is more than the other three protocols because of static clustering and the efficient number of cluster head selection. Thus, it proves that AZR-LEACH has higher throughput as compared to LEACH, MH-LEACH, and SEP.

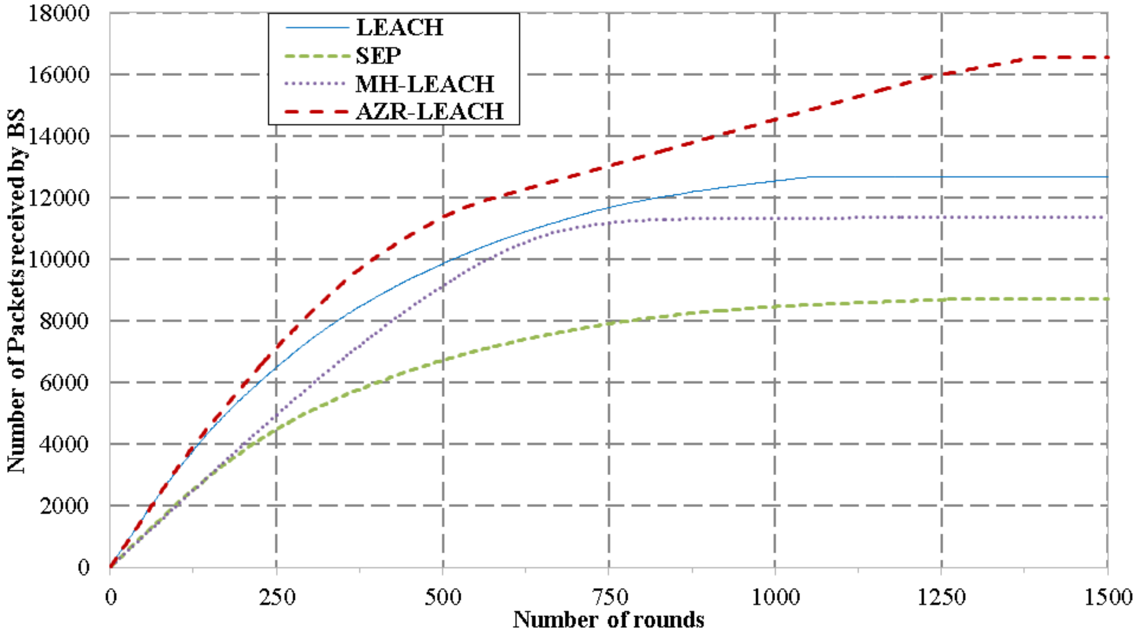

Figure 5-4: Comparative throughput

AZR-LEACH has an efficient number of cluster heads due to static clustering. LEACH [43], MH-LEACH [49], and SEP [51] select the number of cluster heads using distributed algorithms whereas a fixed number of cluster heads is selected during each round in AZR-LEACH. There is uncertainty in the selection of cluster heads in LEACH, MH-LEACH, and SEP. The numbers of cluster heads selected in each round by using these protocols are shown in Figure 5-5.

A lower number of selected cluster heads means each cluster head needs to forward more member nodes data, which results in the early depletion of the cluster head battery.

After becoming a cluster head, the node needs to perform the additional functions of cluster heads. A higher number of cluster heads causes more network energy consumption.

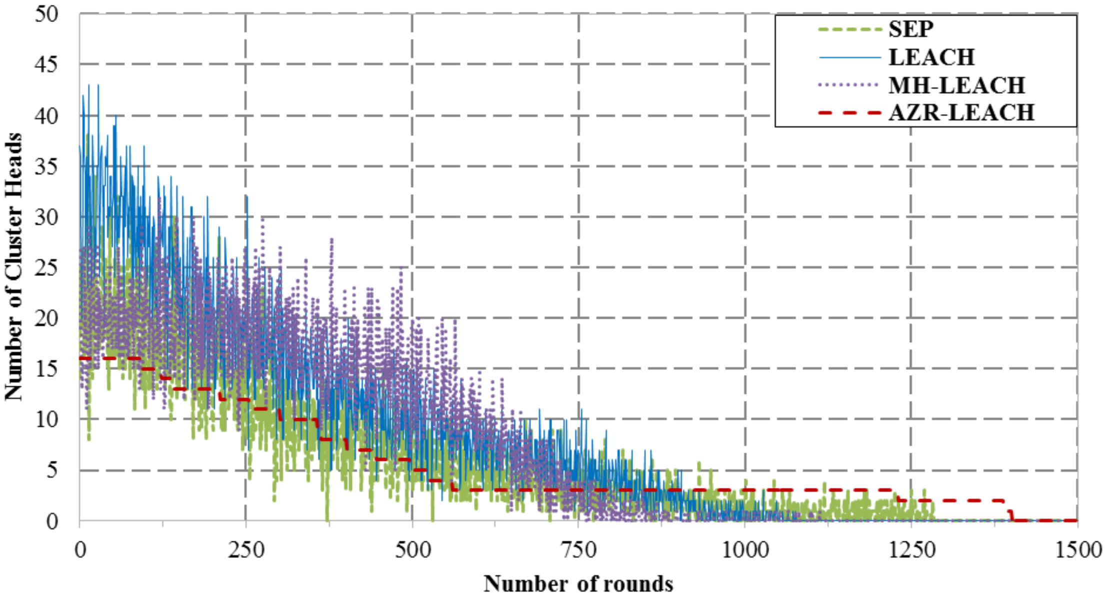

Figure 5-5: Cluster Heads in each round

Figure 5-6 shows the energy consumption comparison of LEACH [43], MH-LEACH [49], SEP [51], and AZR-LEACH. The AZR-LEACH protocol reaches the threshold level of 100 joules in 1400 rounds, while LEACH, MH-LEACH, and SEP consumes 100 joules of energy in 1078, 1112, and 1282 rounds respectively. This shows that our proposed protocol is about 23%, 20.57%, and 8.42% better in energy consumption than LEACH, MH-LEACH, and SEP respectively.

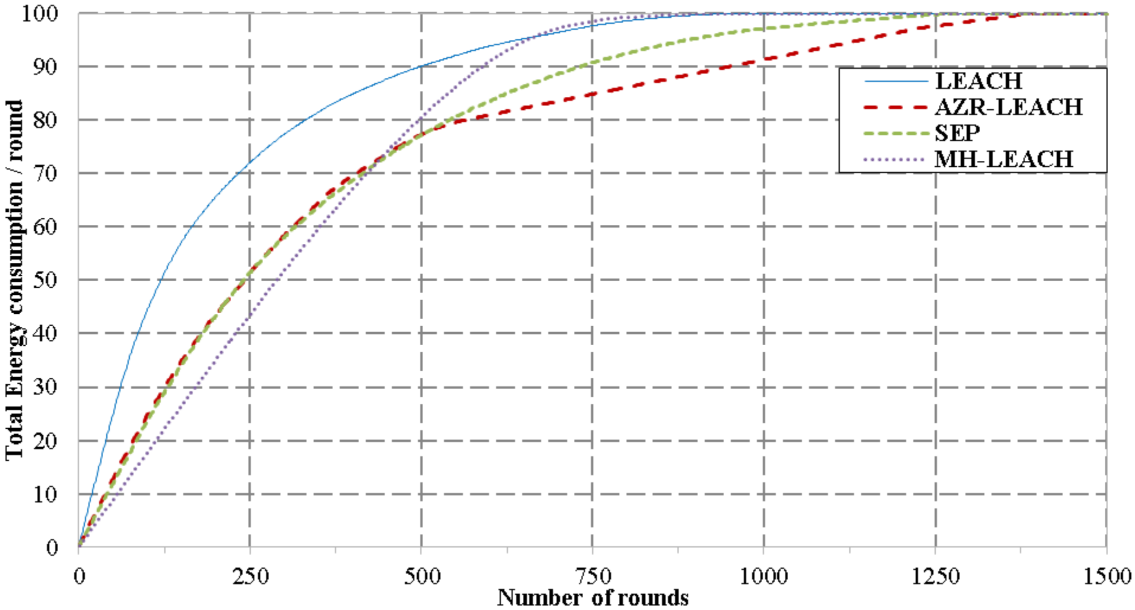

Figure 5-6: Network energy consumption per round

CHAPTER 6 CONCLUSIONS

Sensors are required to transmit the data as well as routing packets to the base station. The sensor battery life decays drastically if more of these operations are performed. The control of unnecessary data transmission or reception by using the proper communication protocol can help in better management of battery life. By considering the influencing factors such as latency, scalability, and energy awareness, the purpose of this research is to find an energy efficient routing protocol for Wireless Sensor Networks. The conclusion of our research is provided in this chapter.

6.1. CONCLUSIONS

In this thesis, we proposed an optimized routing scheme for WSNs. The main focus was to enhance cluster head selection process. Static clustering is used in our proposed scheme. In AZR-LEACH, cluster heads are selected in each cluster on the basis of residual node energy. The formation of rectangular clusters, selection of advanced clusters, and creation of zones make the WSN communication more energy efficient. In our proposed strategy, the stability period of network and network lifetime have been optimized. Simulation results show that there is significant improvement in all these parameters when compared with existing routing protocols LEACH, MH-LEACH, and SEP.

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