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GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MASTER THESIS

EFFICIENT ROUTING PROTOCOL FOR ENERGY HARVESTING WIRELESS SENSOR NETWORKS (EH-WSNs)

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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a dissertation for the degree of Master of Science.

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ABSTRACT

EFFICIENT ROUTING PROTOCOL FOR ENERGY HARVESTING WIRELESS SENSOR NETWORKS (EH-WSNs)

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Wireless Sensor Networks are widely used in many areas such as health monitoring, temperature sensing, and numerous information gathering applications. However, these sensor nodes are usually battery powered and the lifetime of the network is constrained by the restricted battery capacity. The whole network will not be functioning properly when sensors' batteries are exhausted. Energy harvesting technique has been introduced for wireless sensor networks in recent years to provide extra energy source that can be harvested from the ambient environment, such as solar energy and wind power. This technique provides a possibility that, with efficient routing protocols, sensors can operate in an Energy Neutral state so that the energy consumption is less than or equal to the amount of energy harvested. It means that desired performance level can be supported perpetually. A sensor is said to be Energy Neutral when its energy consumption is less than or equal to the amount of energy that can be harvested in a certain period of time. In this way, a sensor can operate perpetually. A routing protocol is energy neutral when the protocol can prevent all the sensors in the network from consuming more energy than harvested. For WSNs, a series of energy-efficient routing protocol were proposed in-order to reduce the energy consumption. LEACH is a well-known clustering-based routing protocol that

tries to minimize energy dissipation in WSNs. Some protocols were derived from LEACH and adapted for the different situation in EH-WSNs.

In this thesis, we proposed an Energy Neutral LEACH routing protocol which is an extension to the traditional protocol LEACH. The main idea of our protocol consists in using Gateway nodes to reduce the data transmission ranges of CH nodes. When a CH collects data from all its cluster member nodes, it forwards the data to a gateway node, and then the data would be transmitted to the BS by this gateway node. EN-LEACH is able to ensure the energy neutral state of a sensor network. Besides maintaining the energy neutral status of a sensor, this protocol also aims at maximizing the overall network throughput, by efficiently utilizing the harvested energy such that, the amount of energy consumed by a sensor is no more than the amount harvested in a certain period of time.

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Finally, very special thanks to my lovely wife: Rahma Abdurrahman. For her endless support and help through the entire process of the project leading to this thesis.

Umar, B. MUHAMMAD
İzmir, 2014

TEXT OF OATH

I declare and honestly confirm that my study, titled "Efficient Routing Protocol for Energy Harvesting Wireless Sensor Networks (EH-WSNs)" and presented as a Master's Thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions, that all sources from which I have benefited are listed in the bibliography, and that I have benefited from these sources by means of making references.

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INDEX OF SYMBOLS AND ABBREVIATIONS

Symbols	Explanations
T_r	Threshold for election as cluster head
E_{elec}	Energy dissipation per bit for the transceiver circuit
eamp	Energy of multi-path model
efs	Energy of free space model
E_{tx}	Transmission energy
E_{rx}	Reception energy
E_{DA}	Data aggregation energy
E_{CH}	Energy dissipation by a cluster-head node
E_{GN}	Energy dissipation by gateway node
K	Packet size
d_0	Threshold distance for swapping amplification model
$E_{non\text{-}CH}$	Energy dissipation by a non-cluster head
E_{bgt}	Energy budget
$E_{M,u}$	Battery capacity
λ_u	Power depletion

Abbreviations

BS	Base Station
CH	Cluster Head
NCH	Non-Cluster Head
GN	Gateway Node
WSN	Wireless Sensor Network
EH-WSN	Energy-Harvesting Wireless Sensor Network
LEACH	Low-Energy Adaptive Clustering Algorithm
EN-LEACH	Energy Neutral-LEACH
OSI	Open System Interconnection
MAC	Medium Access Control
CDMA	Code Division Multiple Access
TDMA	Time Division Multiple Access
SPIN	Sensor Protocol for Information via Negotiation
MEMS	Micro-Electro-Mechanical Systems
ADC	Analog-Digital-Converter
FEC	Forward Error Correction
FDMA	Frequency Division Multiple Access
CSMA	Carrier Sense Multiple Access

2..1.1	R-MPE	Randomized minimum path energy
2..1.2	R-MF	Randomized Max-Flow
2..1.3	R-MPRT	Randomized Minimum Path Recovery Time
2..1.4	E-WME	Energy-opportunistic Weighted Minimum Energy

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Chapter One: Introduction

1.0 Wireless sensor network

With the help of technological advances in micro-electro-mechanical systems (MEMS) and wireless communications, low-cost, low-power, and multi-functional wireless sensing devices have been developed. When these devices are deployed over a wide geographical region, they can collect information about the environment and efficiently collaborate to process such information by forming a distributed communication network, called a *wireless sensor network* (WSN). Each of these sensors generally includes one or more sensing units, a data processing unit and a wireless communication unit. The sensing unit or units of a sensor node measures ambient condition of the surrounding and transform them into electrical signals. Such ambient conditions may be temperature, humidity, acoustic, seismographic data of the environment or may be motion, direction of living beings.

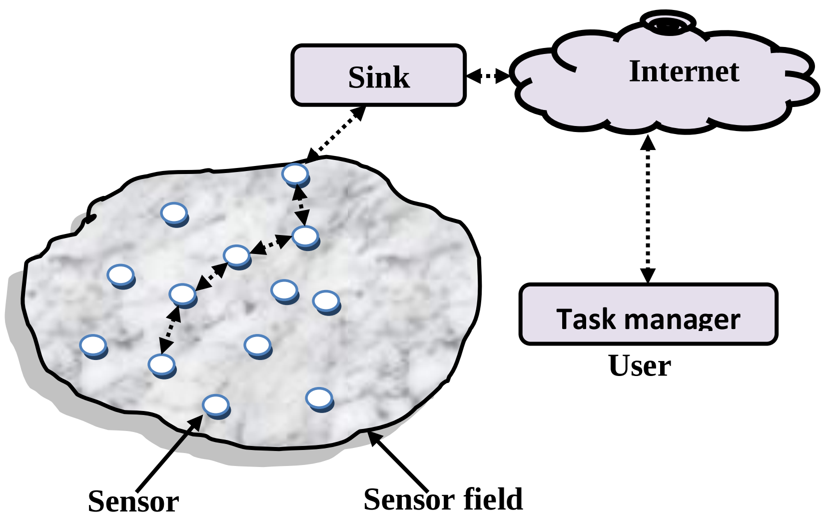


Figure 1.0 wireless sensor Network

A WSN is a special case of an ad-hoc wireless network, and assumes a multi-hop communication framework with no common infrastructure, where the sensors spontaneously cooperate to deliver information by forwarding packets from a source to a destination (BS). The number of practical applications involving WSNs keeps growing rapidly, and WSNs have been regarded as providing the fundamental infrastructure for future communications due to a variety of promising potential applications: monitoring the health status of humans, animals, plants, and the environment; control and instrumentation of industrial machines and home appliances; homeland security; detection of chemical and biological threats and leaks, etc. [1], [3], [2]. In many application areas the wireless sensor network must be able to operate for long periods of time, and the energy consumption of both individual sensor nodes and the sensor network as a whole is of primary importance. Thus energy consumption is an important issue for wireless sensor networks.

1.1 Sensing and Sensor

Sensing is a technique used to gather information about a physical object or process, including the occurrence of events (i.e., changes in state such as a drop in temperature or pressure). While a *Sensor* is a device that translates parameters or events in the physical world into signals that can be measured and analyzed. In other words, sensors are devices that translate aspects of physical reality into representations understandable and processable by computers. In a wireless sensor network, sensors play an important part, as sensing is one of its central roles.

1.2 Application areas of WSN

Wireless Sensor Networks are application specific, and they have been used in a wide variety of practical applications in recent years. These applications can be categorized into military, environment, medical, agriculture, industry, home and other commercial areas. Some examples of these applications are introduced below.

1.2.1 Environmental Application

One of the major application of WSN is in monitoring environmental phenomena and behavior which includes tracking the movements of birds, small animals, and insects; monitoring environmental conditions that affect crops , macro instruments for large scale Earth monitoring and planetary exploration, chemical/biological detection, precision agriculture, biological, Earth, and environmental monitoring in marine, soil, atmospheric contexts, meteorological or geophysical research, bio-complexity mapping of the environment and pollution study [5].

1.2.2 Military Application

Wireless Sensor Networks can be used by the military for a number of purposes such as enemy intrusion detection and monitoring enemy activity. The scalable deployment, dynamic topology, self-organization and reliable communication characterizes of WSN make it a very functional technique for military applications. However, there are still some limitations in existing products such as small number of nodes which is necessary to be improved to meet current military requirements [4].

1.2.3 Health Applications

An emerging application of Wireless Sensor Networks is patient monitoring system used in healthcare. In a hospital or at home, patients are asked to outfit with wireless, wearable sensors so that doctors, nurses or private medical practitioners can monitor the status of their patients. Placed on the body, various sensors are able to have detection of physiological events such as heart beat, blood pressure, breathe rate and so on. Then these data will be forwarded to a base station, which could be the patient's smart phone. Finally the base station could send them to the doctors' computer via internet. Thanks to the mobile characterize of WSNs, those patients with non-fatal illness may go back home or go to work under their doctors' monitoring [5].

1.2.4 Agricultural Applications

Wireless Sensor Networks are also used in agriculture area, such as in modern greenhouse. Greenhouse environment monitoring system is essential to improve the productivity through controlling the greenhouse climate. Continuous monitoring of some significant factors for the quality of plant grown such as temperature, light, humidity gives valuable information to the farmer to make better adjustment. Furthermore, compared with cabled measurement used in traditional greenhouse, this wireless monitoring system is cheaper and more flexible [6].

1.2.5 Industrial Applications

Wireless Sensor Networks can be designed and implemented in each type of industry, and a lot of applications can be identified in this area. Different from in other areas, e.g. environmental monitoring, industrial applications have strict requirements in terms of safety, reliability and efficiency. An application to the modern automobile has increased interest recently. The measurement and monitoring of mechanical status such as speed, fuel consumption rate, and tire pressure and illumination intensity offer the driver a safe and efficient automobile journey [7].

1.3 Components of a Sensor node

The wireless sensor nodes are the central element in a wireless sensor network (WSN). It is through a node that sensing, processing, and communication take place. It stores and executes the communication protocols and the data-processing algorithms. The quality, size, and frequency of the sensed data that can be extracted from the network are influenced by the physical resources available to the node. Therefore, the design and implementation of a wireless sensor node is a critical step. The sensor node consists of a power unit, sensing unit, processing unit and radio unit that is able to both transmit and receive data (transceiver). Sometimes the sensor node also has a mobility unit as well as a localization unit, e.g., a global positioning system.

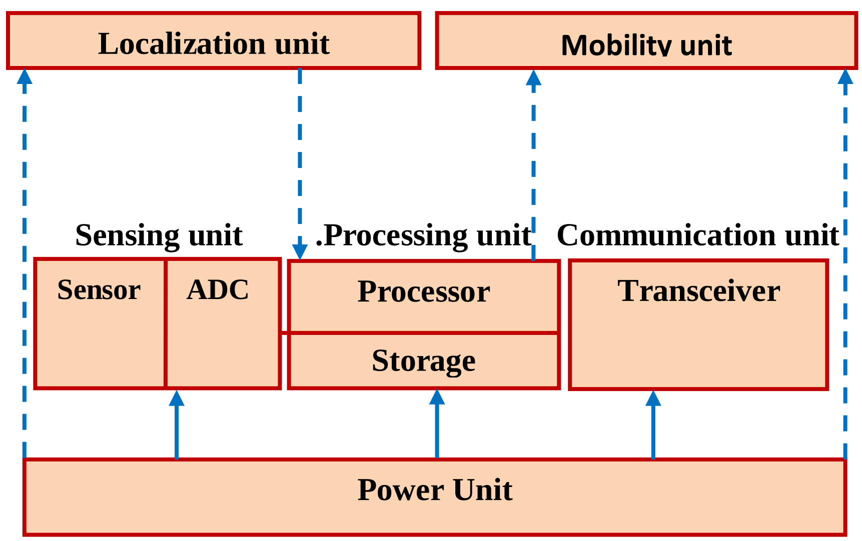


Figure 1.1: Architecture of a Sensor node [3].

1.3.1 Sensing

The sensing unit consists of two subunits, one or a group of sensors and an analog-to-digital converter (ADC). The ADC converts analog signals from the sensors to digital signals, used by the processing unit. The sensors are devices that respond to changes in the surroundings. The type of sensors being used on a sensor node depends on the application. The sensors can monitor speed, temperature, pressure, movement, humidity or vibrations to name a few.

1.3.2 Processing

The processing unit, usually a low speed CPU with small storage capabilities, performs tasks like routing and processing of sensed data etc. The choice of processing unit also determines, to a great deal, both the energy consumption as well as the computational capability of a sensor node.

1.3.3 Communication

The transmission between sensor nodes is wireless and can be implemented by radio, infrared or other optical media. Much of the current hardware for sensor nodes is based on radio link communication.

1.3.4 Power

The power unit provides power to the other units and is typically a battery. Since the battery limits the amount of energy available to the node, this affects the lifetime of the node, thus in the end it also affects the lifetime of the sensor network. The power consumed by the sensor nodes can be reduced by developing design methodologies and architectures which help in energy aware design of sensor networks. The lifetime of a sensor network can be increased significantly if the operating system, the application layer and the network protocols are designed to be *energy aware*. Power management in radios is very important because radio communication consumes a lot of energy during operation of the system.

1.4 WSN architecture

Sensor nodes are normally scattered in a sensing field, every sensor has the capability of sensing, processing in form of aggregating and communicating the data to the sink or base station using various schemes. The underlying protocol scheme in the OSI model for WSNs includes the application layer, transport layer, network layer, data link layer and the physical layer. As described in [8], the protocol stack shown in Figure 1.2, combines power and routing awareness, integrates data with networking protocols to communicates power efficiently through wireless medium, and promotes cooperative efforts of sensor nodes.

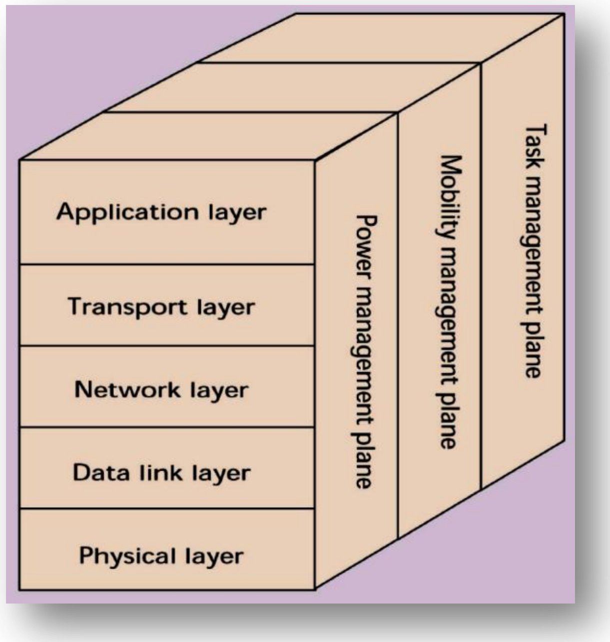


Figure 1.2: WSN architecture [8]

1.4.1 Application Layer

Responsible for traffic management and provide software for different applications that translate the data in an understandable form or send queries to obtain certain information.

1.4.2 Transport layer

The function of this layer is to provide reliability and congestion avoidance where a lot of protocols designed to provide this function is either applied on the upstream (user to sink), or downstream (sink to user).

In general, transport protocols [8] can be divided into:

a) *Packet driven*: all packet sent by source must reach destination'.
b) *Event driven:* the event must be detected, but it is enough that one notification message reaches the sink'.

1.4.3 Network layer

The major function of this layer is routing. This layer has a lot of challenges depending on the application but apparently, the major challenges are in power saving, limited memory and buffers, sensor does not have a global ID and have to be self organized.

1.4.4 Data link layer

Responsible for multiplexing data streams, data frame detection, MAC, and error control, ensures reliability of point-to-point or point-to-multipoint [3]. Errors or unreliability comes from:

- Co-channel interference at the MAC layer (responsible for Channel access policies, scheduling, buffer management and error control) and this problem is solved by MAC protocols.
- Multipath fading and shadowing at the physical layer and this problem is solved by forward error correction (FEC) and automatic repeat request.

1.4.5 Physical layer

It provides an interface to transmit a stream of bits over physical medium [8]. It is also responsible for frequency selection, carrier frequency generation, signal detection, modulation and encryption.

In the above architecture, Mobility management plane is used to detect sensor nodes movement and node can keep track of neighbors and power level (for power balancing). Task management plane will schedule the sensing tasks to a given area and determine nodes are off and which ones are on.

1.5 MAC protocol in WSN

In WSN, nodes usually have to share a common channel. Therefore, the MAC sublayer task is to provide fair access to channels by avoiding possible collisions. The main goal in MAC protocol design for WSN is energy efficiency in other to prolong lifetimes of sensors. The reasons for the unnecessary energy wastage in wireless communication are:

- **Packet collision:** it can occur when nodes don’t listen to the medium before transmitting. Packets transmitted at the same time collide, become corrupted and must be retransmitted. This causes unnecessary energy wastage.
- **Overhearing:** A node receives a packet which is address to another node.
- **Control packet overhead:** control packets are necessary for successful data transmission. They don’t, however, represent useful data. They are very short.
- **Idle listening:** the main reason for energy waste is when a node listens to an idle channel waiting to receive data.
- **Over emitting:** the node sends data when the recipient node is not ready to accept incoming transmission.

In order to satisfy WSN needs, the MAC protocols have to fulfill the following requirements:

- **Energy efficiency:** Most sensor nodes are battery powered and prolonging their lifetime is possible by designing energy-efficient protocols.
- **Collision avoidance:** The main goal is to reduce collisions as much as possible. This can be achieved either by listening to the channel (CSMA) or by using (TDMA) or frequency (FDMA) or code (CDMA) channel division access.
- **Scalability and adaptability:** the MAC protocol needs to be adaptable to changes in network topology caused by node movement and nature of wireless transmission.
- **Latency:** Latency represents the delay of a packet when send through the network. The importance of latency in wireless sensor networks depends on the monitoring application.
- **Throughput:** Represent the amount of data within a period of time sent from the sender to the receiver through WSN.
- **Fairness:** The MAC protocol needs to provide fair medium access for all active nodes.

1.6 Routing Protocols in WSN

Data collected by sensor nodes in a WSN is typically propagated toward a base station (BS) that links the WSN with other networks where the data can be visualized, analyzed, and acted upon. In small sensor networks where sensor nodes and a BS are in close proximity, direct (single-hop) communication between all sensor nodes and the BS may be feasible. However, most WSN applications require large numbers of sensor nodes that cover large areas, necessitating an indirect (multi-hop) communication approach. That is, sensor nodes must not only generate and disseminate their own information, but also serve as relays or forwarding nodes for other sensor nodes. The process of establishing paths from a source to a sink across one or more relays is called *routing* and is a key responsibility of the network layer of the communication protocol stack.

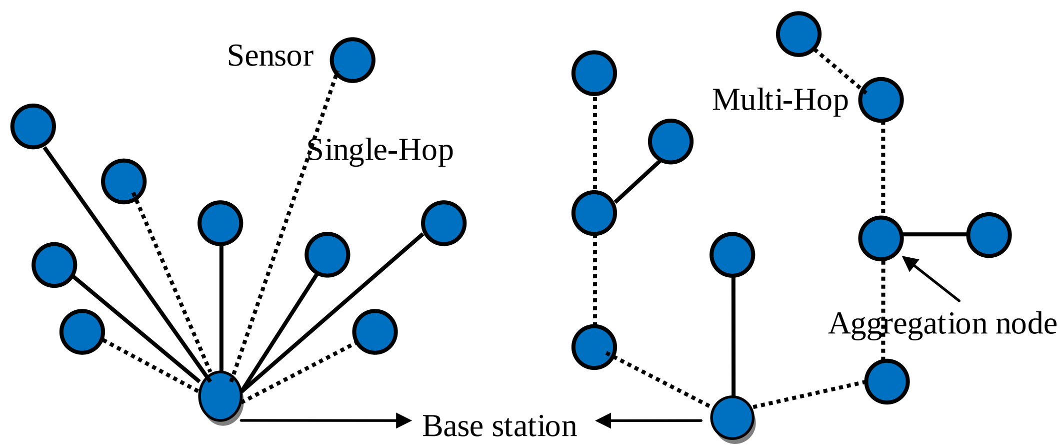


Figure 1.3: Single-hop versus Multi-hop communication in WSN [2].

A proper routing protocol can greatly improve the performance of networks. In a sensor network with battery operated sensor nodes, the lifetime and the power consumption become very important, and many researchers are focusing on designing energy efficient routing protocols that prolong network lifetime. For WSNs, a series of energy-efficient routing protocol were proposed in order to reduce the energy consumption. LEACH is a well-known clustering-based routing protocol that tries to minimize energy dissipation in WSNs. Some protocols were derived from LEACH and adapted for the different situation in EH-WSN.

1.7 Challenges of routing protocols in WSN

Routing methods in WSNs have to deal with a number of challenges and design issues. Despite advancement in technology, sensor nodes in WSNs still have restrictions such as limited battery power, bandwidth constraint, limited computing power and limited memory. It creates the need for routing protocols to be highly adaptive and resource aware. Some of the challenges of routing protocol are [18]:

1.7.1 Node deployment: Node deployment in WSN is application dependent and affects the performance of the routing protocol. The deployment can be either deterministic or randomized. In deterministic deployment, the sensors are manually placed and data is routed through pre-determined paths; but in random node deployment, the sensor nodes are scattered randomly creating an infrastructure in an ad hoc manner. Hence, random deployment raises several issues as coverage, optimal clustering etc. which need to be addressed [18].

1.7.2 Energy consumption without losing accuracy: sensor nodes can use up their limited supply of energy performing computations and transmitting information in a wireless environment. As such, energy conserving forms of communication and computation are essential. Sensor node lifetime shows a strong dependence on the battery lifetime. In a multihop WSN, each node plays a dual role as data sender and data router. The malfunctioning of some sensor nodes due to power failure can cause significant topological changes and might require rerouting of packets and reorganization of the network [18].

1.7.3 Node/Link Heterogeneity: Some applications of sensor networks might require a diverse mixture of sensor nodes with different types and capabilities to be deployed. Data from different sensors, can be generated at different rates, network can follow different data reporting models and can be subjected to different quality of service constraints. Such a heterogeneous environment makes routing more complex.

1.7.4 Fault Tolerance: Some sensor nodes may fail or be blocked due to lack of power, physical damage, or environmental interference. The failure of sensor nodes should not affect the overall task of the sensor network. If many nodes fail, MAC and routing protocols must accommodate formation of new links and routes to the data collection base stations. This may require actively adjusting transmit powers and signaling rates on the existing links to reduce energy consumption, or rerouting packets through regions of the network where more energy is available. Therefore, multiple levels of redundancy may be needed in a fault-tolerant sensor network [18].

1.7.5 Scalability: The number of sensor nodes deployed in the sensing area may be in the order of hundreds or thousands, or more. Any routing scheme must be able to work with this huge number of sensor nodes. In addition, sensor network routing protocols should be scalable enough to respond to events in the environment. Until an event occurs, most of the sensors can remain in the sleep state, with data from the few remaining sensors providing a coarse quality.

1.7.6 Network Dynamics: Most of the network architectures assume that sensor nodes are stationary. How-ever, mobility of both BS‘s and sensor nodes is sometimes necessary in many applications. Routing messages from or to moving nodes is more challenging since route stability becomes an important issue, besides energy, bandwidth etc. Moreover, the sensed phenomenon can be either dynamic or static depending on the application, e.g., it is dynamic in a target detection/tracking application, while it is static in forest monitoring for early fire prevention. Monitoring static events allows the network to work in a reactive mode, simply generating traffic when reporting. Dynamic events in most applications require periodic reporting and consequently generate significant traffic to be routed to the BS [18].

1.7.7 Transmission Media: In a multi-hop sensor network, communicating nodes are linked by a wireless medium. The traditional problems associated with a wireless channel (e.g., fading, high error rate) may also affect the operation of the sensor network. As the transmission energy varies directly with the square of distance therefore a multi-hop network is suitable for conserving energy. But a multi-hop network raises several issues regarding topology management and media access control. One approach of MAC design for sensor networks is to use CSMA-CA based protocols of IEEE 802.15.4 that conserve more energy compared to contention based protocols like CSMA (e.g. IEEE 802.11). So, Zigbee which is based upon IEEE 802.15.4 LWPAN technology is introduced to meet the challenges [18].

1.7.8 Connectivity: The connectivity of WSN depends on the radio coverage. If there is continuously exists a multi-hop connection between any two nodes, the network is connected. The connectivity is *intermittent* if WSN is partitioned occasionally, and *sporadic* if the nodes are only occasionally in the communication range of other nodes.

1.7.9 Coverage: The coverage of a WSN node means either sensing coverage or communication coverage. Typically with radio communications, the communication coverage is significantly larger than sensing coverage. For applications, the sensing coverage defines how to reliably guarantee that an event can be detected. The coverage of a network is either sparse, if only parts of the area of interest are covered or dense when the area is almost completely covered. In case of a redundant coverage, multiple sensor nodes are in the same area.

1.7.10 Data Aggregation: Sensor nodes usually generate significant redundant data. So, to reduce the number of transmission, similar packets from multiple nodes can be aggregated. Data aggregation is the combination of data from different sources according to a certain aggregation function, e.g., duplicate suppression, minima, maxima and average. It is incorporated in routing protocols to reduce the amount of data coming from various sources and thus to achieve energy efficiency. But it adds to the complexity and makes the incorporation of security techniques in the protocol nearly impossible.

1.7.11 Data Reporting Model: Data sensing and reporting in WSNs is dependent on the application and the time criticality of the data reporting. In wireless sensor networks data reporting can be continuous, query-driven or event-driven. The data-delivery model affects the design of network layer, e.g., continuous data reporting generates a huge amount of data therefore, the routing protocol should be aware of data-aggregation

1.7.12 Quality of Service: In some applications, data should be delivered within a certain period of time from the moment it is sensed; otherwise the data will be useless. Therefore bounded latency for data delivery is another condition for time-constrained applications. However, in many applications, conservation of energy, which is directly related to network lifetime, is considered relatively more important than the quality of data sent. As the energy gets depleted, the network may be required to reduce the quality of the results in order to reduce the energy dissipation in the nodes and hence lengthen the total network lifetime. Hence, energy-aware routing protocols are required to capture this requirement [18].

1.8 Clustering Architecture

Clustering techniques in wireless sensor networks aims at gathering data among groups of nodes, which elect leaders among themselves. The leader or cluster-heads has the role of aggregating the data and reporting the refined data to the BS. The advantages of this scheme is that it reduces energy usage of each node and communication cost. One of the earliest work proposing this approach in WSNs is [22] LEACH (Low Energy Adaptive Clustering Hierarchy). Recently, there have been lots of other clustering techniques which are mostly variants of LEACH protocol with slight improvement and different application scenarios. SEP (Stable Election Protocol), DEEC (Design of a distributed energy-efficient clustering), EDACH (Energy-Driven Adaptive Clustering Hierarchy) and EEUC (An Energy-Efficient Unequal Clustering Mechanism) are all clustering techniques proposed with the objective of minimizing energy usage, while extending network life time. Clustered sensor network can be classified into two main types: homogeneous and heterogeneous sensor network. While energy efficiency in WSNs remains a function of uniform distribution of energy among sensor nodes, classifying clustering techniques depends on the objectives in mind.

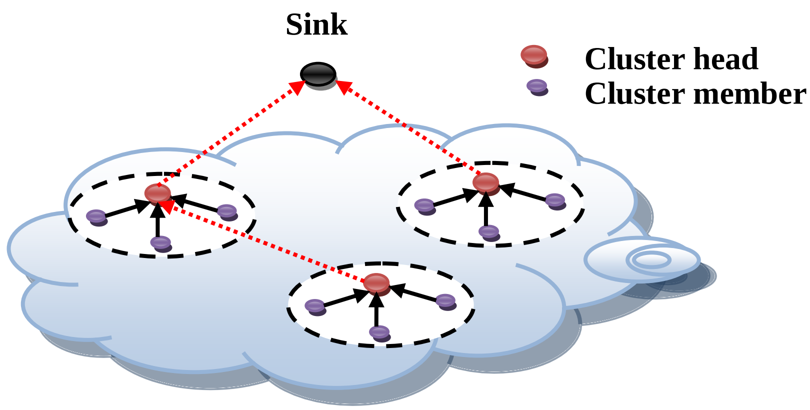


Figure 1.4: Example of cluster hierarchy in a sensor network

1.9 Energy Harvesting Technology

In order to further improve the lifetime of Wireless Sensor Network, there has been another technique called *energy harvesting* being used in each node. Energy harvesting is the process by which energy is extracted from the environmental sources (e.g. solar power, wind and thermal energy) and converted into usable electrical energy. Since sensor nodes are usually deployed in harsh environments without human intervention, their lifetime is limited by the life of their batteries. But because the environmental energy is sustainable, the continuous operation of WSN is possibly achieved through energy harvesting. For the battery-operated case, standard batteries can be replaced by rechargeable ones, and with a solar panel as the energy harvester each node can regain “free” energy continuously during daytime and therefore extend the lifetime of the whole network.

1.9.1 Energy Harvesting WSN

The process of extracting energy from the environment in order to power devices is called energy harvesting (EH). Any device that operates on harvested energy is known as an Energy Harvesting System (EHS). An energy harvesting node refers to a low power wireless sensor node that derives its power from an energy harvesting device. A network of these nodes is known as an energy harvesting wireless sensor network (EH-WSN).

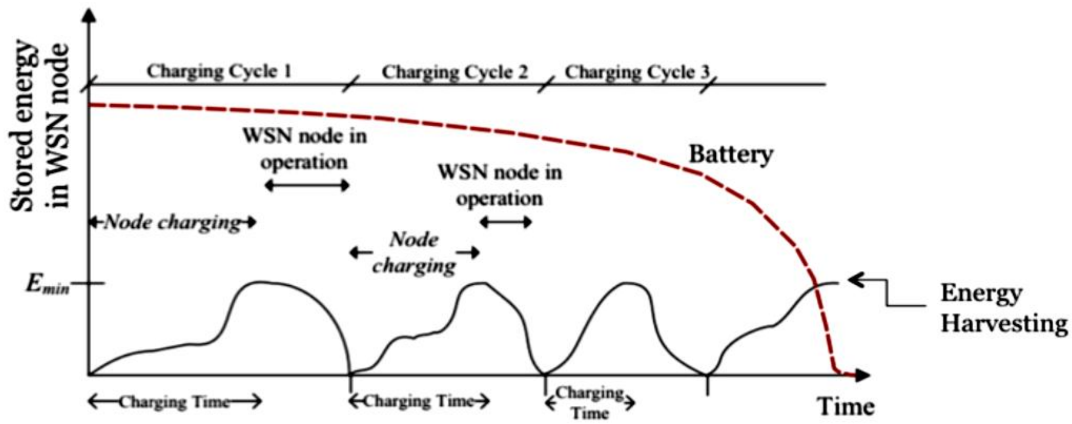


Figure 1.5: Characteristics of Energy Sources [9]

EH-WSN present a promising solution for solving the energy constrains of WSNs. However, as the rate of charging is usually much lower than the rate of energy consumption for the sensor nodes, EH-WSN nodes can only be awake for a short period of time before it needs to shut down in order to recharge. Moreover, the time taken to charge up the sensor is not constant due to environmental factors. Figure 1.5 above shows the salient difference in the characteristics of these two energy sources.

1.9.2 Energy Harvesting Method

There are mainly three energy harvesting methods namely: thermal energy, radiant energy and mechanical energy (see fig. 1.6).

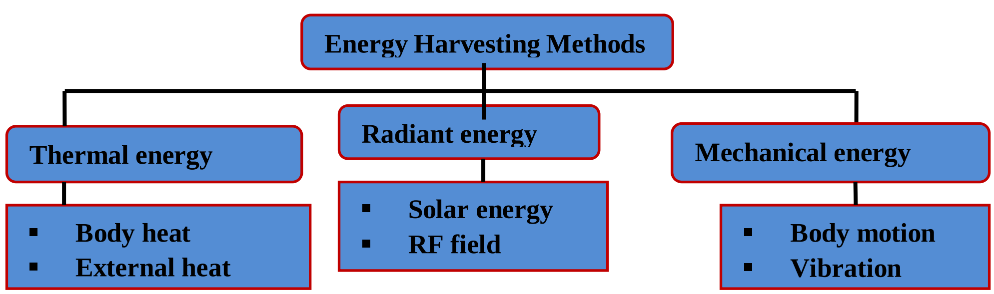


Figure 1.6: taxonomy of ambient energy sources for energy harvesting [9]

- **Radiant energy:** Silicon solar cells exploit the photovoltaic effect to convert sunlight into electricity. When the photons of sunlight strike the silicon cell, their energy may be absorbed and transferred to electrons of the silicon, which are then able to escape from their normal positions in the silicon to become part of the current in an electrical circuit. This phenomenon is called the photovoltaic effect. Since solar energy is a convenient harvesting source, lots of implementations of solar energy harvesting sensor nodes have already existed, for example, Heliomote, Everlast, Prometheus, and HydroWatch.

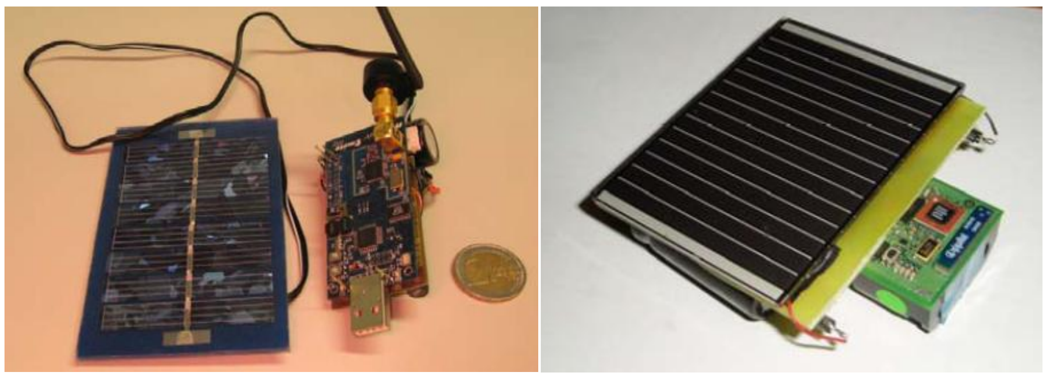


Figure 1.7: example of solar harvesting.

- **Mechanical energy:** Vibrations can generate electric energy. There are mainly three methods to harvest vibrations, including piezoelectric materials, inductive systems, and capacitive systems.
- **Thermal energy:** The thermoelectric effect is the direct conversion of temperature differences to electric voltage. Thermoelectric devices utilize this effect and can generate electricity when there is a temperature gradient across the device. Compared with vibration-based devices, thermoelectric devices can function for a much longer duration due to the absence of any moving parts.

1.9.3 Unique characteristics for EH-WSN

There are typically two types of EH-WSNs. One treats the harvested energy as a supplement to the chemical battery to maximize the lifetime of WSNs. The other is using the harvested energy as the only source to the WSNs for perpetual operation.

Key differences of hardware structure between battery-powered WSNs node and EH-WSNs node is on the energy supplement module. The energy supplement module of EH-WSNs mainly consists of energy harvesting device and energy storage device while only battery in battery-powered WSNs node [10], as illustrated in fig.1.8 and fig. 1.9. These differences introduce some unique characteristics for EH-WSNs.

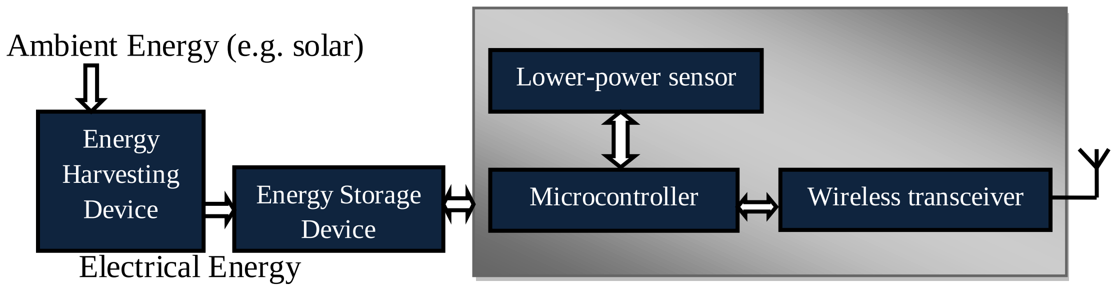


Figure 1.8: Hardware architecture of EH-WSNs node.

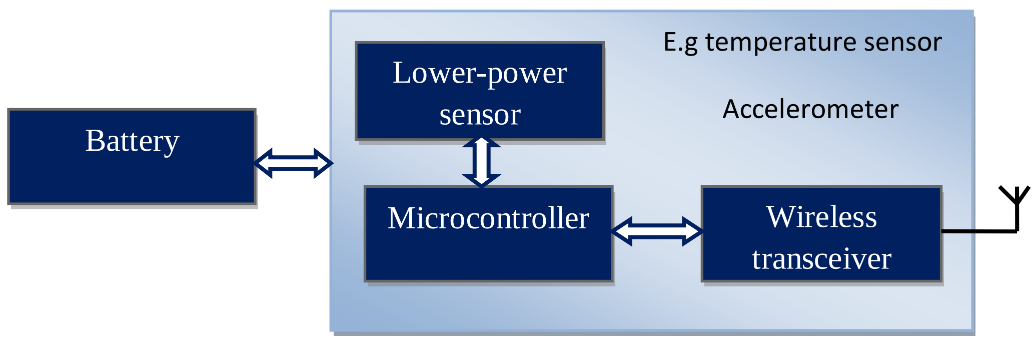


Figure 1.9: Hardware architecture of battery-powered WSNs node.

1.9.4 Energy Harvesting WSN Architectures

In general, energy harvesting architectures for sensor nodes can be divided into two categories, harvest-use architecture and harvest-store-use architecture [11], as shown in fig. 2.0 and fig. 2.1.

1.9.4.1 Harvest-use architecture

In harvest-use architecture, the energy harvesting system powers the sensor node directly. Therefore, In order to keep the sensor operational, the power output of the harvesting system must be continuously above the minimum operating point. Otherwise, the sensor node will be disabled.

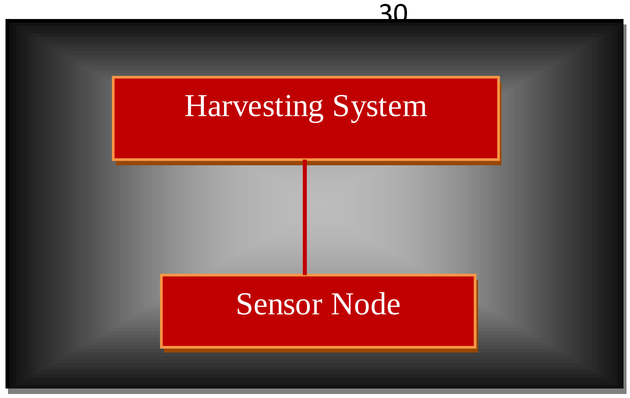


Figure 2.0: Harvest-use

1.9.4.2 Harvest-store-use architecture

The harvest-store-use architecture has an additional energy storage component compared with the harvest-use architecture. The energy is harvested by the harvesting system and stored in the energy storage component. The energy storage would be quite useful when the harvested energy is more than the sensor's current need. The stored energy can either be used later when there is no harvesting opportunity or the energy usage of the sensor node has to be increased to improve the performance.

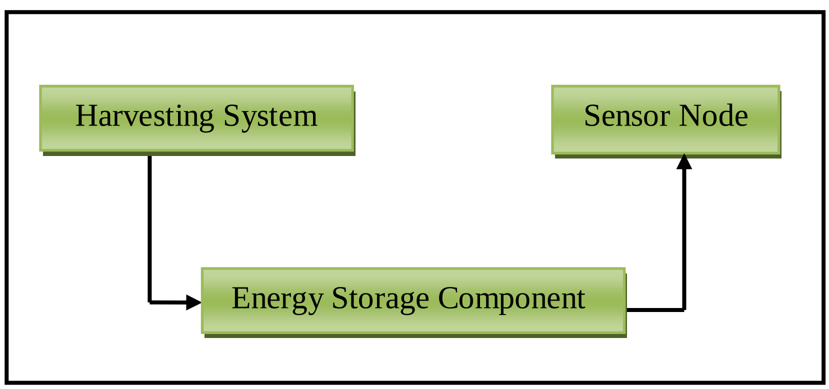


Figure 2.1: Harvest-store-use

1.9.5 Benefits of Energy Harvesting

Energy harvesting provides numerous benefits to the end user and some of the major benefits about EH suitable for WSN are stated and elaborated in the following list. Energy harvesting solutions can:

- Reduce the dependency on battery power. With the advancement of microelectronics technology, the power consumption of the sensor nodes are getting lesser and lesser, hence harvested environmental energy may be sufficient to eliminate battery completely.

- Reduce installation cost. Self-powered wireless sensor nodes do not require power cables wiring and conduits, hence they are very easy to install and they also reduce the heavy installation cost.
- Reduce maintenance cost. Energy harvesting allows for the sensor nodes to function unattended once deployed and eliminates service visits to replace batteries.
- Provide sensing and actuation capabilities in hard-to-access hazardous environments on a continuous basis.
- Provide long-term solutions. A reliable self-powered sensor node will remain functional virtually as long as the ambient energy is available. Self-powered sensor nodes are perfectly suited for long-term applications looking at decades of monitoring.
- Reduce environmental impact. Energy harvesting can eliminate the need for millions on batteries and energy costs of battery replacements.

1.9.6 Routing Protocols in EH-WSN

Energy harvesting techniques have made it possible to overcome the energy resource limitation suffered by traditional Wireless Sensor Networks. In particular, it is now possible for the network to operate perpetually if sufficient energy is harvested to replenish the energy that is being consumed. Hence the need to prolong network lifetime is no longer the primary objective for the design of network routing protocols. Instead, the aim now is to maintain the network in an Energy Neutral state under which a certain performance level can be maintained perpetually. Compared to battery-powered WSNs, the EH-WSNs have some unique characteristics; therefore most of the existing WSNs routing protocols may not be efficient to be directly used in EH-WSNs. There is some specific Routing algorithms base on the idea of EH-WSN which will be discussed in chapter 2.

1.10 Contribution

- In this thesis, we extend the traditional routing protocol LEACH to Energy neutral LEACH (EN-LEACH).
- EN-LEACH ensures network-wide energy neutral state of sensor nodes as well improves the overall network throughput.
- Defining analysis metrics.
- Writing codes to implement simulator by using Matlab program.
- Simulation of network for the proposed routing algorithms and compared against LEACH.
- Behavioral analysis of the results from the simulation scenarios.

1.11 Thesis structure

Chapter 1: In this chapter we describe the wireless sensor network. We introduce some possible application areas where sensor networks are usable. We also give you a short overview of the design of the sensor node as well as network design issues, EH-WSN and their related topic. It also includes the motivation and the contribution of this thesis.

Chapter 2: Energy-Efficiency Routing Protocols in WSN and EH-WSN: Explain Energy- Efficient Routing protocols in WSN and classify them in to different groups as well discusses about routing protocols in EH-WSN.

Chapter 3: Energy Neutral LEACH: This chapter presents the details of our proposed routing protocol Energy neutral LEACH (EN-LEACH).

Chapter 4: Simulator architecture: Implementing simulator based on the feature of the proposed routing algorithms and analysis metrics.

Chapter 5: Simulation Runs: Reports the simulation flow to analyze the behavior of the chosen metrics respect to the proposed routing algorithms and simulation scenario.

Chapter 6: Conclusion.

Chapter Two: Energy-Efficient Routing Protocols for WSNs and EH-WSN

The main contribution of this Chapter is to explore the energy-efficient routing protocols in wireless sensor networks (WSNs), discusses the various policies for selecting a routing algorithms as well as their classification into four main categories: Network Structure, Communication Model, Topology Based and Reliable Routing Schemes. We also study some of the existing routing algorithms for EH-WSN.

2.1 Routing Protocols in WSN

The network protocol is one of the significant elements in WSNs, and it is independent on the underlying network architecture, requirements and applications. The OSI model (fig. 2.2) is divided into different layers and it is used as reference for WSN. In this section, we focus on the state-of-the-art network layer protocols for wireless sensor network (WSN), known as *routing* protocols. The most important feature of a routing protocol, in order to be efficient for WSNs, is the energy consumption and the extension of the network's lifetime. For WSNs, a series of energy-efficient routing protocol were proposed in-order to reduce the energy consumption.

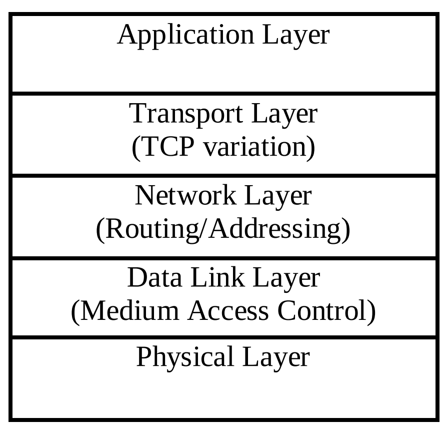


Figure 2.2: Sensor Network Protocol Stack

2.2 Energy-Efficient Routing Protocols in WSN

Energy efficiency is a dominant consideration no matter what the problem is. This is because sensor nodes only have a small and finite source of energy. The main design goal of WSNs is not only to transmit data from a source to a destination, but also to increase the lifetime of the network. This can be achieved by employing energy-efficient routing protocols. Depending on the applications used, different architectures and designs have been applied in WSNs. The performance of a routing protocol depends on the architecture and design of the network, and this is a very important feature of WSNs. However, the operation of the protocol can affect the energy spent for the transmission of the data. Therefore, Energy efficiency is a critical issue in WSNs. The existing energy-efficient routing protocols often use residual energy, transmission power, or link distance as metrics to select an optimal path. There are some terms related to the energy efficiency on WSNs that are used to evaluate the performance of the routing protocols and here are the most important ones [12]:

2.2.1 Average Energy Dissipated

This metric is related to the network lifetime and shows the average dissipation of energy per node over time in the network as it performs various functions such as transmitting, receiving, sensing and aggregation of data.

2.2.2 Average Packet Delay

This metric is calculated as the average one-way latency that is observed between the transmission and reception of a data packet at the sink. This metric measures the temporal accuracy of a packet.

2.2.3 Packet Delivery Ratio:

It is calculated as the ratio of the number of distinct packets received at sinks to the number originally sent from source sensors. This metric indicates the reliability of data delivery.

2.2.4 Energy Spent per Round

This metric is related to the total amount of energy spent in routing messages in a round. It is a short-term measure designed to provide an idea of the energy efficiency of any proposed method in a particular round.

2.2.5 Distance:

The distance between the transmitter and receiver can affect the power that is required to send and receive packets. The routing protocols can select the shortest paths between nodes and reduce energy consumption.

The selection of the energy efficient protocols in WSNs is a really critical issue and should be considered in all networks.

2.3 Routing techniques in WSNs-Classification

Routing protocols deals with data transmission from one sensor node to another. Routing in WSNs is very challenging due to the inherent characteristics that distinguish such network from other wireless networks. Classification of routing protocols can be made based upon four main schemes: *Network Structure*, *Communication Model*, *Topology Based* and *Reliable Routing*. The routing protocols belonging to the first category can be further classified as *flat* or *hierarchical*. The routing protocols belonging to the second category can be further classified as *Query-based* or *Coherent and non-coherent based* or *Negotiation-based*. The routing protocols belonging to the third category can be further classified as *Location-based* or *Mobile Agent-based*. The routing protocols belonging to the fourth category can be further classified as *QoS-based* or *Multipath based*.

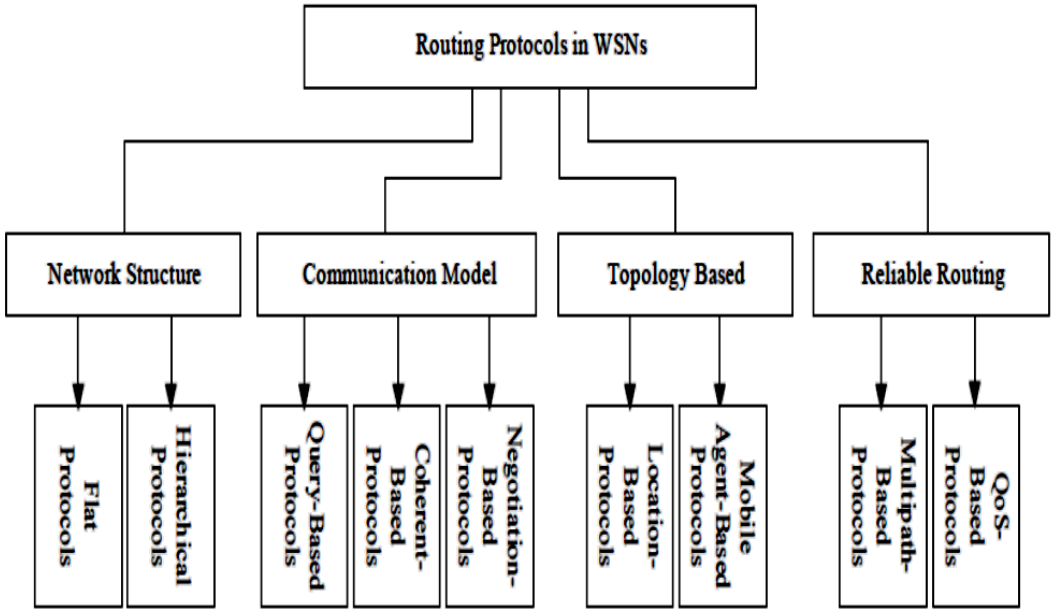


Figure 2.3: Classification of routing protocols in WSNs [13]

In flat-based routing, all nodes are typically assigned equal roles or functionality and it adopts a data centric routing e.g. Directed diffusion (DD), Rumor routing e.t.c. In hierarchical-based routing, however, nodes will play different roles in the network e.g. LEACH, PEGASIS e.t.c. In location-based routing, sensor nodes' positions are exploited to route data in the network e.g. geographic adaptive fidelity, SPAN e.t.c. A routing protocol is considered adaptive if certain system parameters can be controlled in order to adapt to the current network conditions and available energy levels. Furthermore, these protocols can be classified into multipath-based, query-based, negotiation-based, QoS-based, or coherent-based routing techniques depending on the protocol operation. In addition to the above, routing protocols can be classified into three categories, namely, proactive, reactive, and hybrid protocols depending on how the source finds a route to the destination. In proactive protocols, all routes are computed before they are really needed, while in reactive protocols, routes are computed on demand. Hybrid protocols use a combination of these two ideas. When sensor nodes are static, it is preferable to have table driven routing protocols rather than using reactive protocols. A significant amount of energy is used in route discovery and setup of reactive protocols. Another class of routing protocols is called the cooperative routing protocols. In cooperative routing, nodes send data to a central node where data can be aggregated and may be subject to further processing, hence reducing route cost in terms of energy use [13].

2.3.1 Hierarchal Routing Protocols

In a hierarchical architecture, higher energy nodes can be used to process and send the information while low energy nodes can be used to perform the sensing in the proximity of the target. This means that creation of clusters and assigning special tasks to cluster heads can greatly contribute to overall system scalability, lifetime, and energy efficiency. Hierarchical routing is an efficient way to lower energy consumption within a cluster and by performing data aggregation and fusion in order to decrease the number of transmitted messages to the BS. Hierarchical routing is mainly two-layer routing where one layer is used to select cluster heads and the other layer is used for routing. However, most techniques in this category are not about routing, rather on "who and when to send or process/aggregate" the information, channel allocation etc., which can be orthogonal to the multihop routing function. Examples of hierarchical-based routing protocols are; [21] Threshold sensitive energy efficient sensor network protocol (TEEN), PEGASIS and LEACH e.t.c.

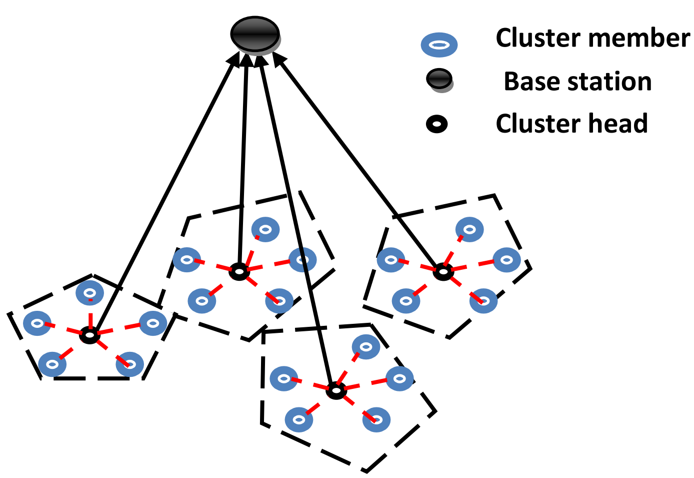


Figure 2.4: cluster-based hierarchical model [21].

2.3.1.1 LEACH protocol

Heinzelman, et al. [22] introduced a hierarchical clustering algorithm for sensor networks, called Low Energy Adaptive Clustering Hierarchy (LEACH). LEACH is the most popular energy efficient hierarchical clustering algorithm that tends to reduce energy consumption in WSN. LEACH clustering method is made by grouping nodes into cluster and it consists of cluster head and cluster members. Information is fused into Cluster Head (CH) before being transmitted to the base station. LEACH uses a TDMA/CDMA MAC to reduce inter-cluster and intra-cluster collisions. However, data collection is centralized and is performed periodically. Therefore, this protocol is most appropriate when there is a need for constant monitoring by the sensor network. The operation is divided into rounds; each round comprises of set-up phase and steady state phase [20].

2.3.1.1.1 Set up phase

LEACH randomly selects a few nodes as cluster heads and rotates this role to even distribute the energy load among the sensors in the network. For each node, the probability of being chosen as a cluster head can be formulated by:

$$P_i(r) = \begin{cases} \dfrac{P}{1 - P \times \left(r mod \frac{1}{P}\right)} & if\ i \in G(r) \\ 0 & otherwise \end{cases} \tag{1.0}$$

Where $P_i(r)$ denotes the probability that node i can be cluster head, p denotes the percentage of the node number that can be cluster heads in a round, r denotes the index of current round. G(r) denotes the set of nodes that have not been a cluster head in the most recent r mod (1/ p) round.

2.3.1.1.2 The Steady State Phase

In the steady state phase, the data is sent to the base station. The duration of the steady state phase is longer than the duration of the setup phase in order to minimize overhead.

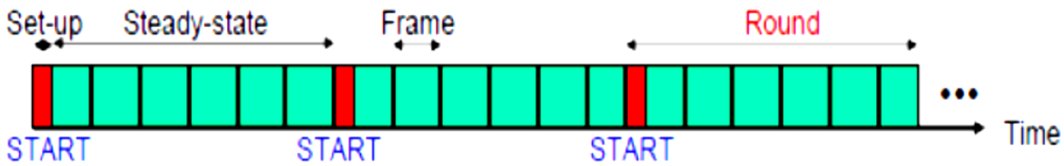


Figure 2.5: Time line showing LEACH operation [23].

2.4 EH-WSN Routing protocols

In this section we are going to present some routing protocols for EH-WSN. As discussed above; in WSN each sensor nodes are usually battery powered and the lifetime of the network is constrained by the restricted battery capacity. So the goal of efficient routing algorithm is to minimize the energy consumption and maximize the lifetime of network. The recent advances in ambient energy harvesting technologies allow a sensor node to get power from environment instead of using batteries. Each node has energy harvesting device which converts ambient energy into electrical energy. In following chapter we will discuss about the goal of EH-WSN routing algorithm and the energy neutral operation in EH-WSN. The last section describes some routing algorithms for EH-WSN with energy neutral operation capabilities.

2.4.1 EH-WSN routing algorithm overview

Energy-efficient routing has been widely explored for battery operated WSNs. EH-WSNs exhibit unique characteristics and among their main objective there is not only extending the network lifetime, but firstly is maximizing the workload in the energy-harvesting network, and secondly is to maintain the network in an Energy Neutral state under which a certain performance level can be maintained perpetually.

2.4.2 EH-WSN Routing algorithms

This section explores a literature survey on routing algorithms, which are suitable for maximizing the workload in the Energy Harvesting Wireless Sensor Network (EH-WSN).

2.4.2.1 Energy-opportunistic Weighted Minimum Energy (E-WME)

Lin et al. [50] presented the Energy-opportunistic Weighted Minimum Energy (E-WME) routing protocol which assigns each energy harvesting node with a cost that is related to the energy harvesting rate and then calculate the shortest path according to each node's cost. As we know most of the EH-WSN protocols for routing use the residual energy, mean while E-WME uses both residual energy and the replenishment rate of the transmitter.

In this algorithm, resources are allowed to refill energy storage and each node just has information about short-term energy replenishment. Replenishment can happen at different rates. There is possibility to have constant replenishment rate or flexible rate, but here we simply describe the algorithm in case of constant replenishment rate for each node. For each edge this metric has been modeled as [52]:

$$C_u = \frac{E_{M,u}}{(p_u + \epsilon)\log(\mu)} \cdot \left(\mu^{\lambda_u} - 1\right) \cdot e \tag{1.1}$$

Where p_u is energy replenishment rate, $E_{M,u}$ is battery capacity, λ_u is the power depletion, e is the energy needed to send a packet to neighbor nodes, μ and ϵ are constant. The λ_u shows the power depletion index and it can be defined as:

$$\lambda_u = \frac{E_{M,u} - E_{C,u}}{E_{M,u}} \tag{1.20}$$

That $E_{C,u}$ is the available energy exactly before processing the packet.

After defining the cost for each link we should find the minimum path cost to send data. We assume a path cost for sink is equal to zero. Every time the node *n* receive a beacon from node *i* ; add the cost link between node *n* and node *i* to the cost function of node *i* and then compare this result with the path cost to the sink that already have. Then choose the minimum one as a path cost from that node to the sink.

The algorithm gives results in a good performance because:

1. As we mentioned, it is a mix up the idea of minimum energy routing and residual energy. As an example, if in the routing path, we have two parallel

links which receive and transmit with the same residual energies, we can choose the link with the minimum energy. In other hand if we have two nodes with equal link energy cost, we choose the node that has the larger residual power.

2. In a network if the harvesting rate is different between nodes, the algorithm tries to choose nodes with faster energy harvesting rate in the path.

2.4.2.2 Randomized Minimum Path Recovery Time (R-MPRT)

The Randomized Minimum Path Recovery Time (R-MPRT) routing protocol proposed by Lattanzi et al. [51] assigns to each edge with a cost related to the energy required to transmit a packet and the energy harvesting rate. R-MPRT has two versions: R-MPRT-*org* and R-MPRT-*mod* which both represents the original and modified version of R-MPRT respectively.

2.4.2.2.1 R-MPRT-*org*

We refer to R-MPRT-*org* as the original version of R-MPRT and it’s really similar to the E-WME discussed in section *3.2.1*. But with a simpler cost function. Choosing a route at each node is based on energetic sustainability information. The idea is the same as E-WME, choosing a shortest path with considering the cost function. We can define a cost function to each edge as:

$$cost = \frac{\text{Packet energy}}{\text{Harvesting rate of the transmitter}} \tag{1.3}$$

This cost function is the inverse of cost function in R-MF, so the probability to send a packet in the path is inverse proportional to the corresponding path recovery time. Because; here the costs function is the same as recovery time. As explained before recovery time is the time needed to harvest energy needed for packet transmission.

The algorithm requires local knowledge of the network, because for sending the packet to other nodes, it should know about their cost function and choose the minimum one for sending data. The responsibility of sending the information of each node to the local neighbors is within the beacon transmission. For each path to the sink should compute the cost function of that path. At the end should choose the shortest path from each node to the sink which explained in 3.2.1 how to do it. Routing table in this theory is dynamic because it depends on the harvesting rate of each node.

2.4.2.2.2 R-MPRT-*mod*

This algorithm is the modified version of R-MPRT. The author found that R-MPRT-*mod* performs much better when it uses available energy of the transmitter instead of using the harvesting rate. The authors do not support this claim by providing any evidence.

$$cost = \frac{\text{Packet energy}}{\text{Available energy at the transmitter}} \tag{1.4}$$

2.4.2.3 Randomized Max-Flow (R-MF)

The R-MF algorithm uses an extended version of the Ford-Fulkerson algorithm to calculate the maximum flow from the sensors to the base station. The probability of sending a packet over an edge is proportional to the calculated maximum flow through that edge:

$$Capacity = \frac{\text{Harvesting rate of transmitter}}{\text{packet energy}} \tag{1.5}$$

This routing algorithm is based on using an off-line routing table, stored in each node that shows the node links used for packet transmission. The probability to use the edge *i* in node *n* is proportional to the max flow from that edge [49].

2.4.2.4 Randomized minimum path energy (R-MPE)

This algorithm works on the minimum energy required to reach the sink [51]. Path energy information (E_{path}) is sent downward within a message and stored in the local routing table of each node. This information propagation starts from the base station which has E_{path} equal to zero. When the message reach a node *n*, from edge *i*, it updates the packet energy required by that edge in the routing table:

$$E_{path_i} = E_{path} + pE_i \tag{1.6}$$

The probability of sending packet from an edge is inversely related to the corresponding path energy.

2.4.3 Routing Protocol for Perpetual Operated EH-WSNs

In this section we present routing protocols for perpetual operated EH-WSNs focusing specifically on those from research areas that have received greater attention. The amount of information routed by a sensor will directly determine its energy consumption; the design of routing protocols can play an important role in the energy neutral operation. A sensor node is said to be Energy Neutral when its energy consumption is less than or equal to the amount of energy that can be harvested in a certain period of time [46]. In this way, a sensor can operate forever (subject to hardware limitations). A routing protocol is energy neutral when the protocol can prevent all the sensors in the network from consuming more energy than harvested.

2.4.3.1 Energy neutral routing (ENR) protocol:

S. Peng et al. [47] proposed an Energy Neutral Routing (ENR) protocol that is able to ensure the energy neutral status of the sensors in the whole network, while improving the network performance level in terms of the packet delivery ratio. ENR protocol uses admission controls to regulate the traffic load according to their own energy budgets. The energy budget for each time slot is calculated as:

$$E_{bgt} = \frac{1}{N_t}\sum_{n=0}^{N_t} E_h(n) \tag{1.7}$$

Energy Neutral Routing (ENR) protocol operates in three phases:

1. Set-up phase
2. Admission control phase
3. Data propagation phase

The detail of the above three phases can be found in [47].

The main features of ENR include:

- Network wide Energy Neutral status guarantee: Able to ensure energy neutral status by simply carrying out admission controls locally at each node based on their energy harvesting status to admit or reject traffic routing requests. The control of routing requests makes ENR scalable with large networks.
- High packet delivery ratio: in ENR the traffic load is fairly distributed among the sensor nodes in the network according to their energy harvesting status.
- Linear upper bound for the amount of control messages exchanged for route establishing.

2.4.3.2 Energy Neutral Clustering for EH-WSNs:

S. Peng et al. [48] proposed a hierarchical routing protocol (ENC) that groups energy harvesting sensors into a number of clusters that ensures the energy neutral status of all sensors. Based on a novel Cluster Head Group mechanism, ENC can provide consistent data delivery with a low control message overhead. This in turn helps to improve the total amount of information bits that can be relayed to destinations as compared with other traditional clustering protocols. Unlike the single cluster head scheme in traditional clustering protocols, ENC uses more than one sensor to form the Cluster Head Group (CHG). *Cluster Head Group* (CHG) is a set of sensor nodes that will take turn to act as the cluster head of a cluster during one time slot. Thus, instead of having only one CH within each cluster, ENC allows a cluster to have more than one CH to form a CHG. A sensor that belongs to a CHG is referred to as a *CHG-node*. The details of ENC can be found in [48].

Chapter Three: Energy Neutral LEACH (EN-LEACH)

Hierarchical clustering algorithms are very important to increasing the lifetime of network. We propose EN-LEACH (Energy Neutral LEACH), which is an extension to the traditional hierarchical clustering routing protocol LEACH. The main idea of our protocol consists in using Gateway node in each cluster to reduce the data transmission ranges of CH nodes. When a CH collects data from all its cluster member nodes, it forwards the data to a gateway node, and then the data would be transmitted to the BS by this gateway node. EN-LEACH reduces the Cluster members energy consumption (by adopting intra-cluster communication within the cluster) and the Cluster head energy consumption (by adapting inter-cluster communication between CHs) to ensure the network energy neutrality. Before studying the details of the proposed algorithm, we first state the motivation behind this work and define some terms as used in this work.

3.1 Motivation

Wireless Sensor Networks are widely used in many areas such as health monitoring, temperature sensing, and numerous information gathering applications. However, these sensor nodes are usually battery powered and the lifetime of the network is constrained by the restricted battery capacity. The whole network will not be functioning properly when sensors' batteries are exhausted. Energy harvesting technique has been introduced for wireless sensor networks in recent years to provide extra energy source that can be harvested from the ambient environment, such as solar energy and wind power. This technique provides a possibility that, with efficient routing protocols, sensors can operate in an Energy Neutral state such that the energy consumption is less than or equal to the amount of energy harvested in a certain period of time. It means that desired performance level can be supported perpetually.

Clustering-based routing protocols for Wireless Sensor Networks have gained wide acceptance due to their characteristics of less energy consumption. The motivation behind this thesis is to ensure the energy neutrality of the WSN by utilizing the harvested energy. LEACH (W. Heinzelman et al., 2000) is one of the first hierarchical routing approaches for sensors networks. The idea proposed in LEACH has been an inspiration for many hierarchical routing protocols. To achieve this objective, we proposed an Energy Neutral LEACH (EN-LEACH) which is an extension to the traditional routing protocol LEACH.

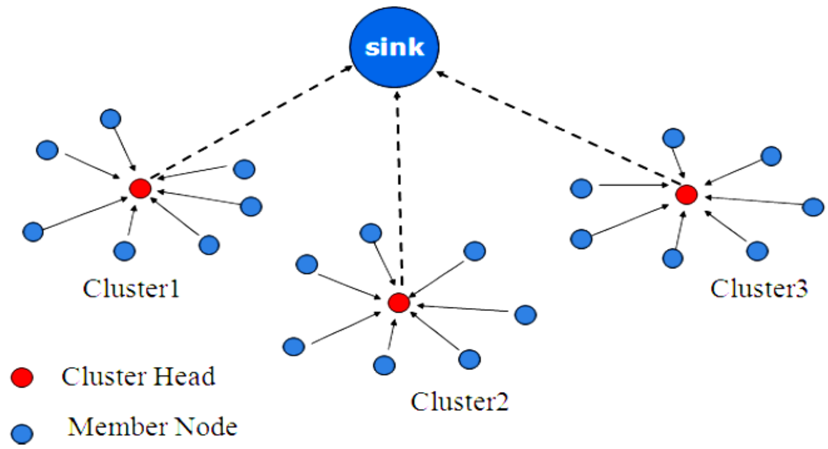


Figure 2.7: Clustering model of LEACH

Thus, in traditional clustering algorithms, such as LEACH, CH can communicate directly with the BS which increased the CH energy consumption and in turns causes *cluster failure.* But, in EN-LEACH we use intra-cluster communication inside the clusters (communication between cluster members and CH) and inter-cluster communication (between CHs and BS) to forward information to the base station by establishing a multi-hop route from all cluster heads to the base station (BS),

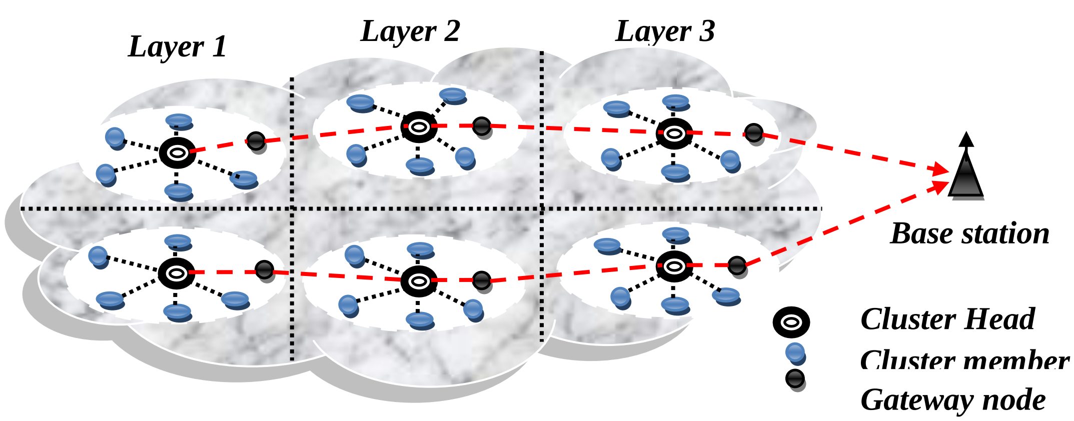


Figure 2.8: Clustering model of proposed routing (EN-LEACH) protocol

In this way, the energy consumption of CH and CM is reduced respectively, and information sensed by sensors can be consistently delivered to destinations by ensuring energy neutral state. In EN-LEACH the multi-hop route are constructed by the CHs and Gateway node. That is, cluster heads-Gateway nodes-cluster heads…repeatedly until reach the BS. During this process, the other nodes keep sleep to save energy.

3.2 Definition of terms

This section briefly defines some terms used in this chapter, which is described below:

- **Clustering:** clustering is a process that divides the network into interconnected substructures called clusters.
- **Clusters:** clusters represents group of sensors and each cluster comprises of cluster head, cluster members, and a gateway node.
- **Cluster member (CM):** CMs are sensors that are constantly sensing information and sending the sensed information to the CHs in the form of data packets with a certain data rate.
- **Cluster head:** It is a coordinator within the substructure. Each CH acts as a temporary base station within its cluster and communicates with other CHs. it also gathers and aggregates the information received from the Cluster Members (CM) and transmit the aggregated data to the BS either directly or via intermediate nodes.
- **Base station:** It is the part of wireless sensor network that acts as interface between the sensor nodes and end users. The base station is located far from the sensor field and is assumed to have unlimited amount of energy and communication resources.
- **Gateway node:** The gateway nodes (GN) acts as intermediate node between CH and the BS, that is, it transmits the aggregated data received from CH to the base station.

- **Round:** this refers to the time span that includes the set-up phase and the steady-state phase.
- **Slot:** it is the TDMA time slot when an individual cluster member node transmits its sensed data to the Cluster head. The slot time of each CM node in a single cluster is equal.
- **Frame:** A frame contains all individual TDMA slots for member nodes of a cluster. After end of every frame, the CH sends aggregated data to the gateway node and finally to the BS.

3.3 Energy Neutral LEACH

In this section, the well known routing protocol LEACH was extended to Energy Neutral LEACH (EN-LEACH). The operation of EN-LEACH is divided into rounds and each round has mainly two phases: set up phase and steady state phase (fig. 4.16).

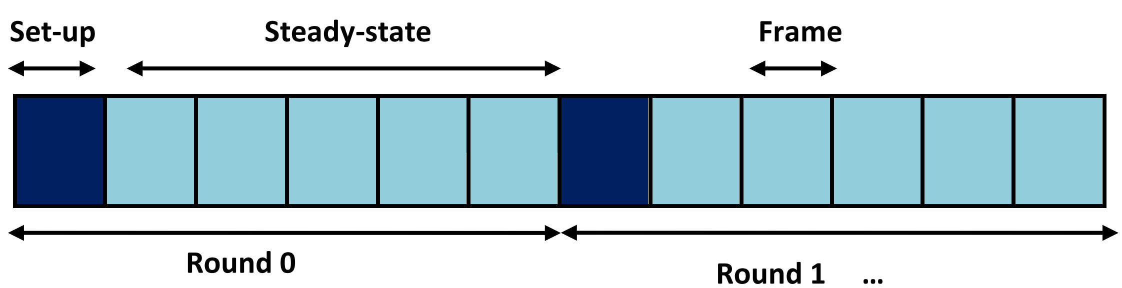


Figure 2.9: Time line showing EN-LEACH

3.3.1 Set up phase:

The set-up phase comprised of cluster head selection, gateway selection and cluster formation. It is constituted by gateway selection algorithm, cluster selection algorithm and cluster formation algorithm.

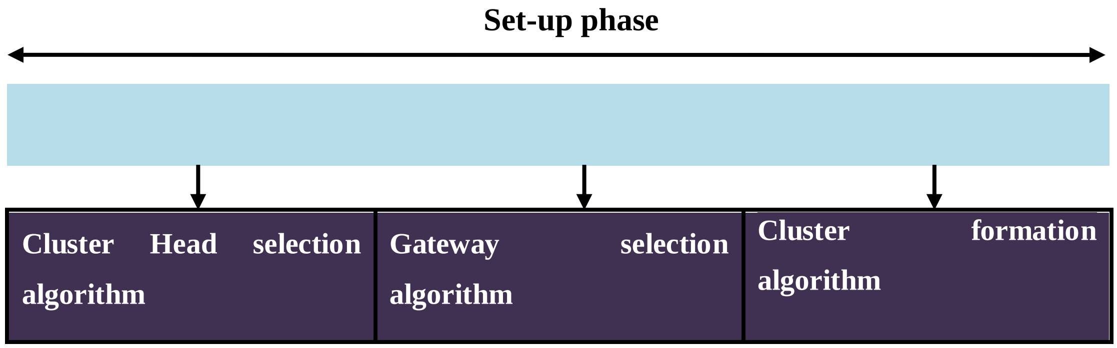


Figure 3.0: Time line showing set-up phase

3.3.1.1 Cluster head selection:

LEACH is designed especially for the battery-powered WSNs. Cluster heads selecting scheme makes the nodes to be cluster heads in turns, it can make the power consuming evenly distributed among nodes. In EH-WSNs, energy is infinite and the energy harvesting rates are usually various between nodes. Therefore, it is impropriate to still use the cluster head selecting algorithm. We expect that the nodes with a higher energy harvesting rate should have higher probability to be cluster heads; also there should be no limitation of time that a node can be the cluster head. In EN-LEACH, we improved cluster heads election algorithm of LEACH as:

$$T_k(r) = \frac{a \cdot E_{bgt_k}(r) + b \cdot E_{h_k}(r-1) \times P}{\sum_{n=0}^{N_t} E_{h_k}(n)} \qquad (1.8)$$

Where $T_k(r)$ is the probability of node *k* being cluster heads during the round *r*. a is the energy budget coefficient. $E_{bgt_k}(r)$ is The energy budget of node *k* at slot *n*. b is the harvest energy coefficient, $E_{h_k}(r-1)$ is the harvested energy during round *r* of the node *k*, and $\sum_{n=0}^{N_t} E_{h_k}(n)$ is the total harvested energy at slot *n*.

3.3.1.2 Cluster formation

On the initial deployment, the base station transmits a layer-1 signal with minimum power level. All nodes, which hear this message, set their layer as 1. After that, the base station increases its signal power to attain the next layer and transmit a layer-2 signal. All nodes that receive the message from BS but do not set the previous layer; set their layer as 2. This procedure continuous until the base station transmits corresponding messages to all layers. After dividing the network into layers and the selection of the CH, each node decides which cluster it belongs to and informs its CH that it will be a member of its cluster. This node must choose the closest one as the CH. To avoid collision each node transmits this information back to the CH using a CSMA MAC protocol. After a certain time determined a priori, each CH receives all the messages from the nodes that want to be included in its cluster and according to their number, creates a TDMA schedule of corresponding size. Next, it informs each one of its cluster nodes when it can transmit, according to the TDMA schedule which is broadcasted back to the nodes in the cluster. The radio of each cluster node can be turned off until the node’s allocated transmission time comes, in the goal to minimize energy dissipation in these nodes.

Table 1: Algorithm for setup phase

1. for each (node j)
2.   j selects random number y between 0 and 1.
3. ***If*** *(y < T (j))*
4.   j becomes CH.
5.   j broadcasts an advertising message for its CH status ***then****.*
6.   CH waits for join-request
7. ***Else***
8.   j becomes a NCH node ***then****.*
9.   NCH chooses the CH, this selection is based on RSS of advertise.
10.   NCH send join request to CH and become a member of its cluster.
11.   End ***if****.*
12.   for each (CH)
13.   CH creates TDMA schedule for NCH.
14.   Each NCH communicates to the CH in its time slot.
15.   End for
16. End for

3.3.1.3 Gateway selection

The control of data transmission tries to reduce the number of transmissions and thus, considerable energy conservation is achieved. The distance of each cluster may be quite long in which some CHs died while trying to communicate directly with the BS. To overcome this problem, each CH employs one or more intermediate nodes (gateways) along the path towards the BS to relay CH data. Identification of these Gateway nodes (GNs) in each cluster is responsibility of the BS.

The BS broadcasts the *id* and the locations of gateway nodes and the selected CH. The total number of nodes, which are assigned to be gateways nodes and CH, is supposed to be predefined. Since the *id* and the locations of gateway nodes are broadcasted, each CH must choose the closest as the intermediate node and informs it. The role of gateway node is to connect the CH to BS. They are responsible for transmitting packets received from the CH to the BS, thus the CH can preserve some energy in data forwarding.

3.3.2 Steady state phase:

Once clusters, CHs, GNs, and TDMA-based schedules are formed, data transmission begins. The non-cluster head nodes collect the sensor data and transmit the data to the cluster head, in their allotted time slots. The cluster-head node must keep its radio turned on to receive the data from the nodes in the cluster. The amount of information routed by a sensor will directly determine its energy consumption; the design of routing protocols can play an important role in the energy neutral operation. In our proposed protocol, two types of communication are performed in cluster maintenance phase. One of them is intra-cluster communication and the other is inter-cluster communication.

3.3.2.1 Intra-Cluster communication:

In each cluster, when a sensor node generates data, it transmits the sensed data to CH. The packets are forwarded to the neighbor node that has the shortest distance to the CH, and the next node relays toward the CH in the same manner. Intra-cluster communication is performed by means of Time Division Multiple Access (TDMA) mechanism. In this period cluster head assigns time slots to the node in the cluster.

Table 2: Algorithm for Intra-cluster communication

1. *for each (Cluster)*
2. *for each Non-Cluster head S_i and S_j*
3. *for each Cluster Head (CH)*
4. *S_i wishes to send its sensed data to CH*
5. $if\ \left(d_{S_i-to-CH_{S_i}} < d_{S_i-to-S_j}\right)$
6. *S_i transmits data to CH*
7. ***Else***
8. *S_i transmits data to S_j (S_j is a Relay node)*
9. *S_j transmits data to CH*
10. *End if*
11. *End for*
12. *End for*
13. *End for.*

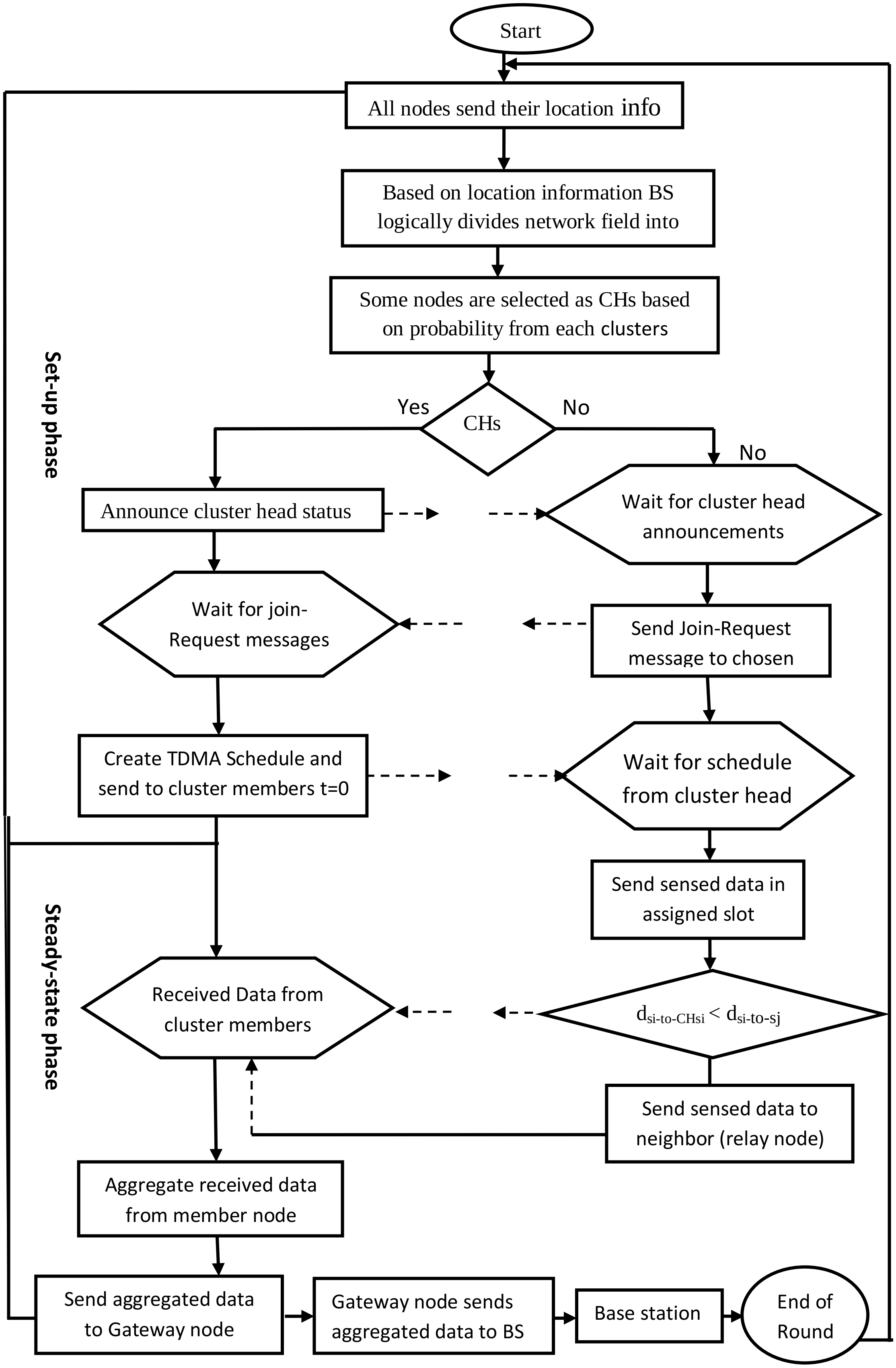
In the intra-cluster algorithm above; $d_{S_i-to-CH_{S_i}}$represent the distance between sensor node S_i and cluster head CH_{S_i}, $d_{S_i-to-S_j}$ is the distance between sensor node S_i and its neighbor S_j.

3.3.2.2 Inter-cluster communication

LEACH [12] assumes that cluster members communicate via a single hop with CHs, and then CHs gather the information collected from cluster members and send it to the BS directly. But during the inter-cluster communication in EN-LEACH, each CH receives the data from its cluster members. When all the data have been received, each CH aggregates the data it has received along with its own data into a single composite message (intra-cluster aggregation). After a CH has created its aggregate message, it forwards the data to its Gateway node and then, the data would be transmitted to the BS via a multi-hop path using the gateways. That is, cluster heads-Gateway nodes-cluster heads…repeatedly until reach the BS. During this process, the other nodes keep sleep to save energy.

Table 3: Algorithm for Inter-cluster communication

1. for each (Layer i)
2. for each Cluster Head (CH_i)
3. for each Gateway node (GN_i)
4. CH received data from Non-cluster head
5. CH aggregate the received data
6. $if\ (i == 1)$
7. CH_i transmits aggregated data to GN_i then
8. GN_i transmits aggregated data to BS
9. ***Else***
10. CH broadcast data to the next Layer CH
11. End if
12. End for
13. End for
14. End for.


Start
All nodes send their location info
Based on location information BS logically divides network field into
Some nodes are selected as CHs based on probability from each clusters
Set-up phase
Yes
CHs
No
No
Announce cluster head status
Wait for cluster head announcements
Wait for join-Request messages
Send Join-Request message to chosen
Create TDMA Schedule and send to cluster members t=0
Wait for schedule from cluster head
Send sensed data in assigned slot
Steady-state phase
Received Data from cluster members
$d_{si\text{-}to\text{-}CHsi} < d_{si\text{-}to\text{-}sj}$
Send sensed data to neighbor (relay node)
Aggregate received data from member node
Send aggregated data to Gateway node
Gateway node sends aggregated data to BS
Base station
End of Round

Chapter Four: Simulation

In this chapter we present the empirical studies to evaluate the performance of the proposed EN-LEACH protocol. We compare the performance of EN-LEACH against LEACH, which is a well known hierarchical routing protocol with high energy efficiency. We chose to use Matlab as simulation environment because it offers all the required tools and utility so we can focus our effort only on the simulation. This chapter also explores the Network model, Assumption about the BS, system energy consumption model.

4.1 Network Model

The network considered in this thesis consists of N solar powered sensor nodes. Each node can use power control to change it transmit power and therefore communication distance. All nodes have the same hardware architecture and are randomly deployed in the field. Each node can harvest energy from the environment without backup chemical battery and can evaluate its short term energy harvesting rate. The shape of the sensing field is assumed to be a square with a side length of L meters. Sensors are logically divided into layers and will be grouped into several clusters. In each cluster there will be *Cluster Head* (CH) that gather and aggregates the information received from the *Cluster Members* (CM). CMs are sensors that are constantly sensing information and sending the sensed information to their CHs in the form of data packets with a certain data rate. Sensors that are elected as CHs will be freed from the information sensing task to reduce their energy consumption; the gateway nodes (GN) will acts as intermediate node which transmits the aggregated data received from CH to the base station.

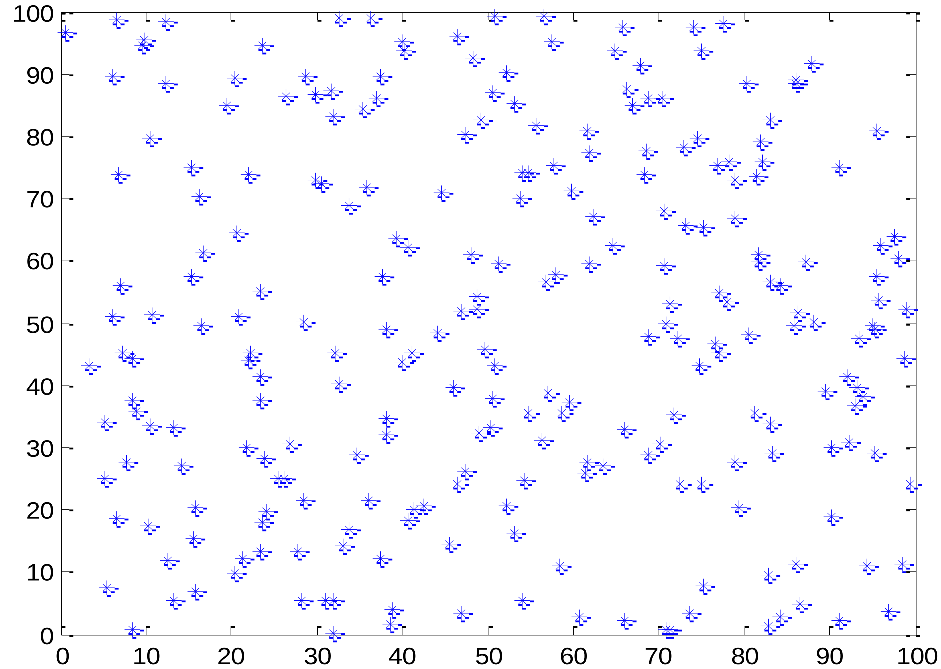


Figure3.2: Random deployment of sensors

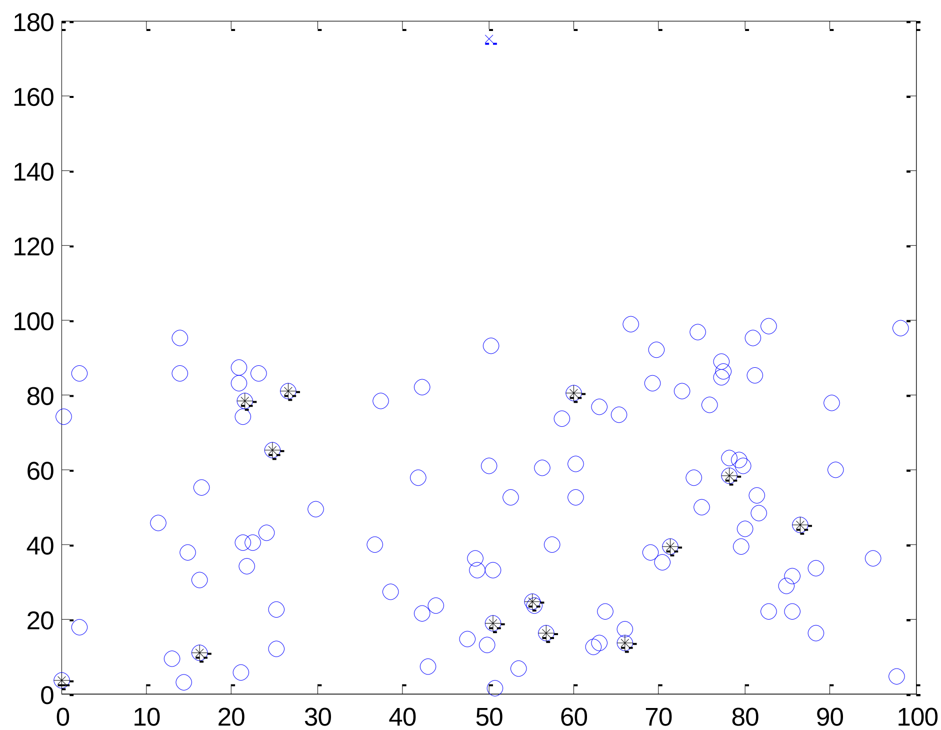


Figure 3.21: Network Model

4.2 Assumptions

In this thesis, we have made some assumption about the BS:

- The base station knows the distance from each node, not the location.
- The base station knows the number of nodes in the network.
- The base station is located far from the sensing field (positioned at point (50, 175)) and is assumed to have unlimited amount of energy and communication resources.
- The end user can have access to data from the sensor network through the BS.
- The BS determined the number of layers in the network by considering the area of the network and the number of nodes.

$$M = \left\lceil \frac{N^2}{2A} \right\rceil \tag{4.0}$$

Equation (4.0) is used by the BS to determine the number of layers, where *M* represents the number of layers, *N* is the number of nodes, and *A* is the area of the network. In this thesis, the total number of nodes in the network is 300 and the area is $(100\text{m})^2$. Then, the number of layers in the network will be $\left\lceil \frac{(300)^2}{(2\times100\times100)} \right\rceil = 5$.

4.3. Energy Harvesting Management

In this thesis, the commonly used solar power is chosen to be the energy harvesting source. Due to the weather condition and the day-night differences, solar energy harvesting system will experience large variances in the harvested energy input at different time instances. In order to monitor the harvested energy dynamically, we divide system time into a number of *Time Slots (t).*The length of each time slot is denoted by *T* minutes. Thus, the total amount of energy harvested in a time slot *t* by a sensor *n* is denoted by $E_{h_n}(t)$. The way to estimate $E_{h_n}(t)$ can be found in [46].

By the definition of Energy Neutral operation, the energy consumed by a sensor should be no more than the amount of energy harvested by its energy harvesting device during a certain period of time. We denote this period of time by N_t, which means the total time slots under consideration. We use the term *Energy Budget* to represent the amount of energy $E_{bgt_n}(t)$ that can be used by the sensor n in a time slot t, without compromising the energy neutrality of the sensor. Whereby the energy budget for each time slot is calculated as:

$$E_{bgt_n} = \frac{1}{N_t} \sum_{n=0}^{N_t} E_{h_n}(t) \tag{2.0}$$

Note that if the energy budget for a time slot is not fully used by the sensor, the unused energy will be rolled over to increase the energy budget of the subsequent time slot. Thus, by the definition of energy neutral state, we have:

$$\sum_{n=0}^{N_t} E_{bgt}(n) \leq \sum_{n=0}^{N_t} E_h(n) \tag{2.1}$$

4.4 System Energy consumption model

The transmission cost is proportional to the distance between the two communicating nodes. Thus, there is a great relationship between energy consumption and transmission distance during the process of data transfer. With the increase of transmission distance, transmitting power decays exponentially. So, in this work we first consider the energy consumption by information transmission. Using a simplified power model discussed in [45, 46] for energy consuming of radio communication. In order to transmit k-bit data between two nodes with distance d, the energy consumption is computed as follows:

$$E_{T_x}(k,d) = \begin{cases} k \times E_{elec} + E_{amp} \times d^2 & , if\ d < d_0 \\ k \times E_{elec} + E_{fs} \times d^4 & , if\ d \geq d_0 \end{cases} \tag{2.2}$$

Where E_{elec} is the base energy required to run the transmitter or receiver electronics; d_0 is the distance threshold. E_{amp} and E_{fs} are the unit energy required for the transmitter amplifier that depends on the distance and the propagation model to approximate the power loss (the free space d^2 or the multipath fading d^4) [45].

$$d_0 = \sqrt{\frac{E_{fs}}{E_{mp}}} \tag{2.3}$$

To receive k-bit data, the radio expends energy [45]:

$$E_{R_x}(k) = k \times E_{elec} \tag{2.4}$$

Therefore, the energy consumption of CH_i for a round is:

$$E_c(CH_i) = \sum_{i=1}^{m} E_{R_x}(k_i) + E_{DA}(k) + E_{T_x}(k_u, d(CH_i, GN_i)) + E_s + E_i \tag{2.5}$$

In this equation, m is the number of cluster member nodes of CH_i; $E_{DA}(k)$ is energy consumption for data aggregation with k bits data. E_s and E_i are the energy consumption in sensing and idle state, respectively and $E_{T_x}(k_u, d(CH_i, GN_i))$ is the energy expend by *CH* in forwarding the aggregated data to the GN_i.

The energy consumption of a Gateway node is:

$$E_c(GN_i) = E_{T_x}\big(k_j, d(GN_i, BS)\big) + E_{R_x}(k_i) \tag{2.6}$$

where $E_{T_x}\big(k_j, d(GN_i, BS)\big)$ is the energy expended by GN in forwarding the CH aggregated data to BS.

The energy consumption of a cluster member node j in cluster i^{th} for a round [46] is:

$$E_c(j) = E_{T_x}(k_j, d(j, CH_i)) + E_{R_x}(k_i) + E_s \tag{2.7}$$

Chapter Five: Simulation Results

In this section, we simulate the performance of the EN-LEACH algorithms in terms of the energy consumption of CH, Energy neutrality, Total amount of packets received and the throughput of the network in Matlab. The results obtain in terms of three metric: energy consumption of CHs, Energy neutrality, Total amount of packet received and throughput of EH- WSN are represented in form of graphs. We assume that 300 energy harvesting sensor nodes are randomly deployed over 100 x 100 m square area sensor field and the whole network is divided into five layers (n=5). The BS located at (50, 175).

5.1 Analysis metrics for simulation runs

The common metric to evaluate the performance of a routing protocol is to calculate the throughput in WSNs. But to perpetual operated EH-WSNs, we also should emphasize the percentage of available nodes in the whole network nodes. The more available nodes at the same time, the more information about sensed object, thus brings the observer more details, deep and comprehensive understanding of the sensed object. Therefore, maximizing the number of available nodes under given workload and environmental constrain should be the major task for perpetual operated EH-WSNs. The parameters used in the simulations are shown in Table 1.

Table 4: Simulation Parameters

Parameters	**Values**
Network field	100m x 100 m
BS Location	(50, 175)
E_{elec}	50nJ/bit
E_{fs}	10pJ/bit/m^2
$Ea_{mp.}$	0.0013 pj/bit/m^4
E_D	5nJ/bit/signal
d_o	87m
$E_{bgt.}$	54joule
Packet size (K)	4000bits
Layers(n)	5
Number of node	300
μ_{max}	0.008J/hour
T	3600seconds
N_t	24timeslot

5.2 Performance evaluation of proposed algorithm

In this section, we compared the performance of our proposed routing protocol (EN-LEACH) with the well known traditional hierarchical routing protocol LEACH in terms of the energy consumption of CHs, Total amount of packets received, Energy neutrality and throughput.

5.2.1 Energy consumption of cluster heads (CHs) Analysis

The performance of EN-LEACH is compared with the traditional LEACH protocol in terms of energy consumption of cluster head and is shown in fig. 3.3. With the use of gateway nodes for data transmission from cluster heads to the sink, the energy consumption of the network is decreased. This is due to the gain of the energy dissipated by cluster heads to the base station.

From the graph it is clear that EN-LEACH can achieve twice the energy savings than LEACH protocol. Figure [3.3] shows graphs that illustrate the energy consumption of CH with respect to the number of clusters and the total number of rounds. As expected, the energy consumption is reduced when the number of clusters is increased. The energy consumed by CHs for each round in EN-LEACH with respect to the increased in number of clusters is much lower than that in LEACH. This is due to fact that in LEACH, CHs transmit their data direct to the BS. Therefore, the energy consumption is much higher. In EN-LEACH, CHs sends their data to GNs and next GNs transmit the data to BS through multihop communication (inter-cluster communication) so a significant amount of energy is saved.

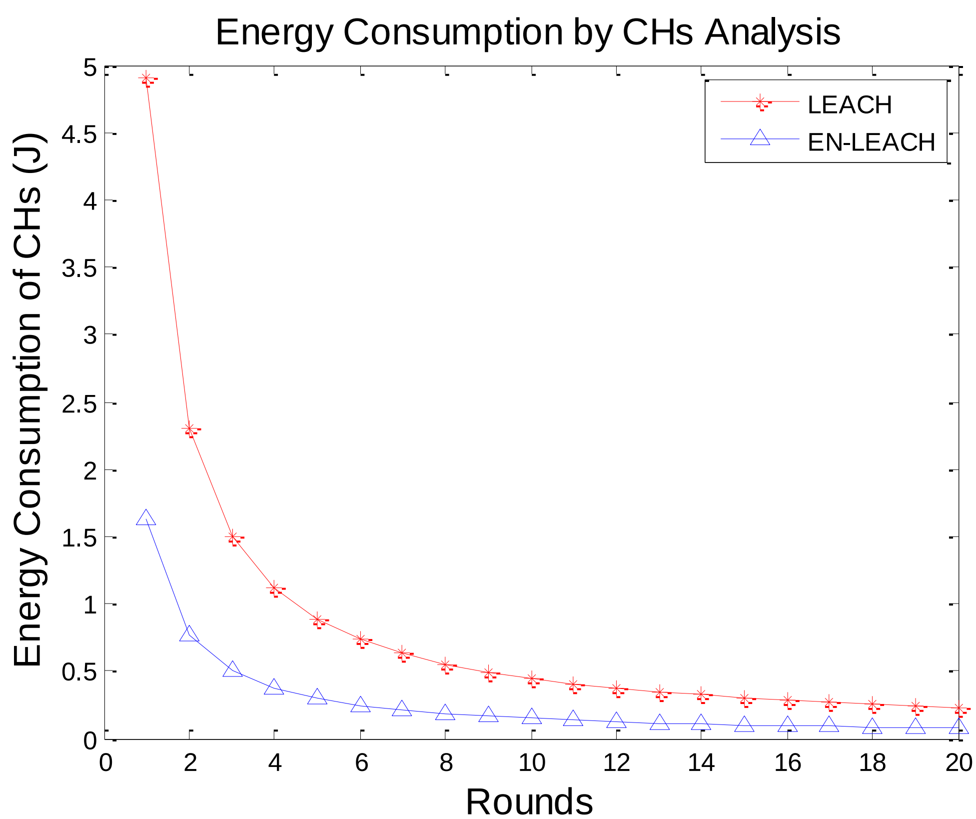


Figure 3.3: Energy Consumption by CHs

5.2.2 Energy Neutrality Test

Simulations are carried out to test the energy neutrality of the proposed EN-LEACH and LEACH. We measure the energy neutrality of a network by the Duration of Cluster Failure (DCF). DCF is calculated by the amount of time a CH in a cluster is dead before the next cluster head rotation. A dead CH will result in cluster failure since no information can be relayed to the base station. Thus, the DCF is a good measure of energy neutrality and a DCF of zero means that the network is energy neutral.

In LEACH protocol, CH use direct communication to reach the BS and the problem of unbalanced energy consumption among CH arises. CH farther away from the BS have heavier energy burden due to the long-haul communication links. Consequently, they will die earlier and results in cluster failure. The DCF under LEACH will be affected by the unbalanced energy consumption among CHs and the amount of information bits k that a CM transmits per second, as the CH will die faster with a higher k. We recorded the total DCF for all clusters in the network for one time slot where the number of clusters m varies from 1 to 13. We can see from Figure [3.4] that the EN-LEACH successfully ensures the energy neutrality of the network (with a zero DCF), which means information can be delivered to the base station consistently without interruption. This is because EN-LEACH uses gateways as intermediate node between CH to balance the energy consumption. EN-LEACH also can automatically adjust the information transmission rate (as compared with the fixed k for LEACH) so that the CHs will not transmit more information than the amount that they can handle. Under LEACH, DCF decreases as the number of clusters in the network increases. This is due to the fact that the traffic load on the CH is smaller as there will be a fewer number of CMs inside each cluster.

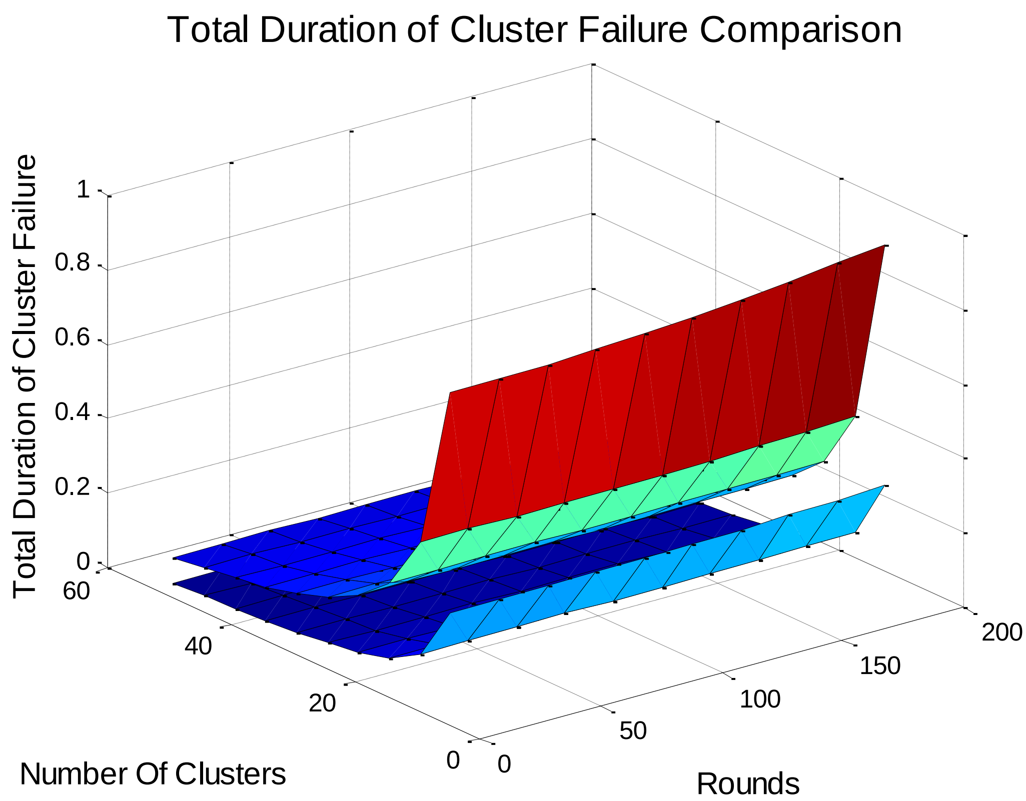


Figure 3.4: Total Duration of Cluster Failure Comparison

5.2.3 Throughput

Throughput indicates the average transmission rate of data packets from sensor nodes to the base station. Figure [3.5] shows the comparison in term of number of packets received at BS over rounds. The simulation results show that the throughput for LEACH is extremely low as compared to EN-LEACH. BS will receive more packets in the proposed scenarios. From simulation results in Figure [3.5], it is observed that the throughput of EN-LEACH is 5times better than LEACH. Significant difference in throughput of our proposed schemes with LEACH is because of providing full coverage for the most of the time to network (i.e. stability period is larger). For simulations, nodes begin with limited initial energy. Once a node runs out of energy, it is considered as dead and no longer transmits or receives data.

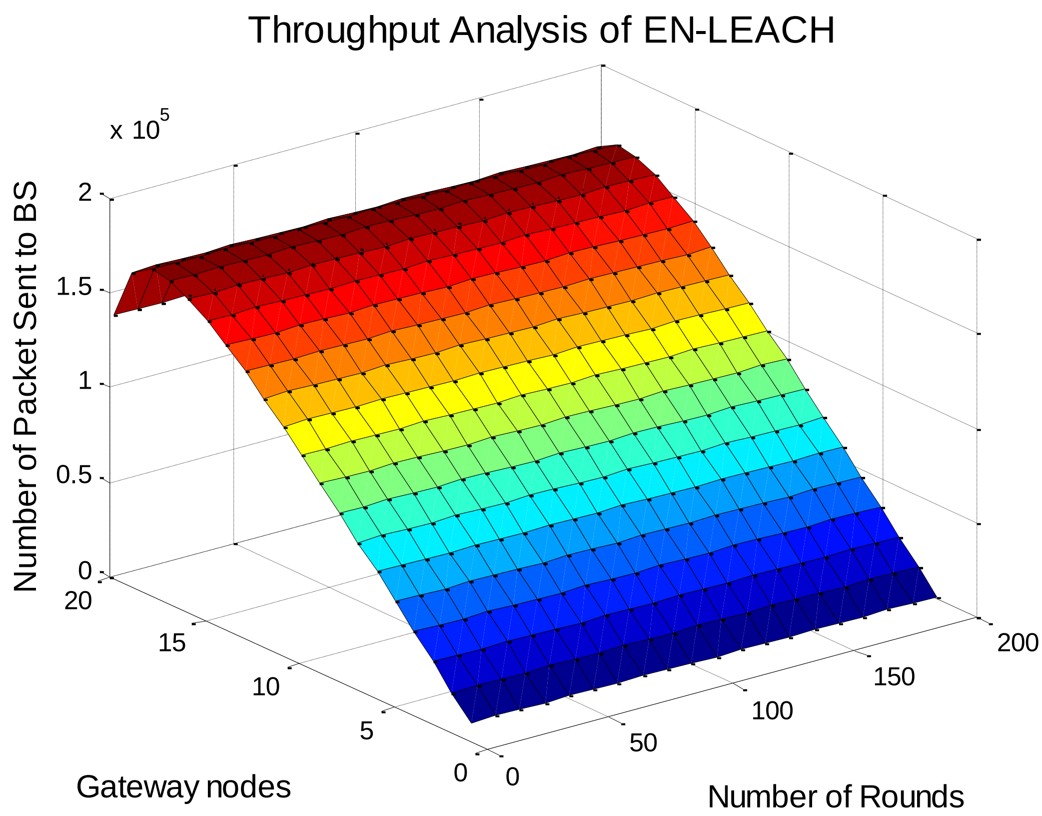


Figure 3.5: Throughput analysis of EN-LEACH

5.3. Result analysis

From our simulations, we observed the followings:

- Using gateway and cluster head, it saves excessive energy consumption for long distance transmission, increased energy utilization of the entire network.
- EN-LEACH can achieve twice the energy savings than LEACH protocol.
- EN-LEACH outperforms LEACH due to balanced energy dissipation of individual node throughout the network and maintains the network in an energy neutral state.
- Energy dissipation is balanced between non-cluster head nodes and CH nodes in the EN-LEACH compared to LEACH protocol.
- Balancing the energy consumption, reduced the phenomenon of rapid death of the cluster head caused by excessive energy consumption, also preventing the situation of instability period caused by one cluster head failure to work, ensure the network wide energy neutrality.

Chapter Six: Conclusions and Future Work

Routing in sensor networks is very challenging due to several characteristics that distinguish them from traditional communications and wireless ad-hoc networks since several restrictions, e.g., limited energy supply, computing power, and bandwidth of the wireless links connecting sensor nodes. The major difference between the WSN and the traditional wireless network is that sensors are very sensitive to energy consumption. Introducing clustering into the networks topology has the goal of reducing the number of message that need to be delivered to the sink in large-scale WSNs and the recent emergence of Energy harvesting technology have made it possible for sensor node to have infinite amount of energy, hence, the sensor in the network can be in a energy neutral state.

In this thesis, an Energy neutral LEACH routing protocol has been proposed for energy harvesting WSN. The network model based on energy harvesting is being developed. The mathematical formulae for choosing the cluster head are provided. The model developed is simulated in MATLAB. The simulation results of energy consumption of cluster heads, total duration of cluster failure and throughput are provided. It has been observed that the energy consumed by CHs for each round in EN-LEACH is much lower than that in LEACH. For example, after the 50 rounds, the LEACH consumed the about 42% of the initial energy while in EN-LEACH is about 15%. It has been also observed that EN-LEACH can successfully prevent cluster failure by ensuring the network wide energy neutral status. It can also provide improved network data throughput with consistent delivery. Since EN-LEACH requires less number of cluster formations, it also has a lower control message overhead as compared with traditional clustering protocols such as LEACH. Finally, it is concluded that the performance of EN-LEACH is better than LEACH.

We have seen in this work that the energy efficiency is a very important issue for the networks especially for WSNs which are characterized by limited battery capabilities. The complexity and reliance of corporate operations on WSNs require the use of energy-efficient routing techniques and protocols, which will guarantee the network connectivity and routing of information with the less required energy. Energy efficient protocols have been developed for WSNs and are classified as *flat, hierarchical, query-based, coherent and non- coherent based, negotiation-based, location-based, mobile agent-based, multipath-based, QoS-based*. The flat protocols may be an ideal solution for a small network with fixed nodes. However, in a large network they become infeasible because of link and processing overhead. The hierarchical protocols try to solve this problem and to produce scalable and efficient solutions. They divide the network into clusters and to efficiently maintain the energy consumption of sensor nodes and perform data aggregation and fusion in order to decrease the number of transmitted messages to the sink. The clusters are formatted based on the energy reserve of sensors and sensor's proximity to the cluster head. Thus, hierarchical protocols are suitable for sensor networks with heavy load and wide coverage area. On the other hand, the location based protocols may be useful for high dynamic networks as they do not need a state in routers nor in packet header and does not cause flood in the search. They use location information in order to calculate the distance among nodes, thus minimizing the energy consumption and extend the lifetime of the network.

We covers the fundamental aspects of EH-WSNs, ranging from the architecture of EH-WSN node and of its energy subsystem to protocols for maximizing workload and also ensuring energy neutrality, MAC and routing, passing through models for predicting energy availability. With the advancement on energy harvesting techniques, and the development of small factor harvester for many different energy sources, EH-WSNs are poised to become the technology of choice for the most of applications that require network functionalities for years or even decades (perpetual operation).

We have also discussed how energy harvesting can be used for powering sensor networks. In addition to supplementing the energy supply in battery powered systems, energy harvesting can enable a new mode of operation, namely the energy neutral mode in which the system uses only as much energy as is available from the environment.

6.1 Future Work

In this thesis we have shown that our proposed routing protocol can maintain the sensor network in an energy neutral state such that the energy consume by a sensor node is not more than the energy it can harvest. Our simulations show that using gateway saves excessive energy consumption for long distance transmission, increased energy utilization of the entire network. EN-LEACH can achieve twice the energy savings than LEACH protocol and outperforms LEACH due to balanced energy dissipation of individual node throughout the network and maintains the network in an energy neutral state. Also balancing the energy consumption, reduced the phenomenon of rapid death of the cluster head caused by excessive energy consumption, also preventing the situation of instability period caused by one cluster head failure to work, ensure the network wide energy neutrality. In the future we will continue our work to employs more than one gateway node within each cluster and the second gateway node will take turn when the first is dead.

Appendix A

MATLAB Source Code

Random deployment of sensor node code

```
%%%%Random deployment of Sensor nodes%%%%%%%
non=250;
threshold=120;
linput=300;
rounds=400;
M=input('input M=');
nodey=linput*rand(1,non);
nodex=linput*rand(1,non);
fid = fopen('AliveNodes.txt','w');
nodeEN=[];
for i=1:length(nodey)
   nodeEN(i) = 200;
end
length(nodey);
length(nodex);
length(nodeEN);
plot(nodex,nodey,'b*')
```

Network model code

```
clc, clear all, close all

numNodes = 300; % number of nodes

p = 0.1;

netArch  = newNetwork(100, 100, 50, 175);

nodeArch = newNodes(netArch, numNodes);

roundArch = newRound();

plot1

par = struct;

for r = 1:roundArch.numRound;  r;

   clusterModel = newCluster(netArch, nodeArch, 'EN-LEACH', r, p);

   clusterModel = dissEnergyCH(clusterModel, roundArch);

   clusterModel = dissEnergyNonCH(clusterModel, roundArch);

   nodeArch     = clusterModel.nodeArch; % new node architecture after select CHs
```

```
    par = plotResults(clusterModel, r, par);
    if nodeArch.numDead == nodeArch.numNode
        break
    end
end
```

Energy consumption of CH code

```
%%%%%%%simulation parameters%%%%%%%%%%
Eamp=0.0013*10^-12;
Efs=10*10^-12;
Eelec=50*10^-9;
EDA=5*10^-9;
n=300; M=100; d=100; l=4000; Nf =10000;
[k]= (1:1:20);
m=1;
%%%%%%%%%%%end of parameters%%%%%%%%%
E_CH_elect=l.*(Eelec.*((n./k)-m+1)+Efs*d^2);
Enon_CH_elect=l.*(Eelec.*(1+k)+Efs*d^2);
E_CH_frame=l.*(((n./k)-m+1)*EDA+Eamp*d^4+((n./k)-m+1)*Eelec);
Enon_CH_frame=l.*(Eelec+Efs*((M^2)./((2*3.14159).*k)));
E_CH_data=(1./((n./k)-m+1)).*(Nf./k).*E_CH_frame;
Enon_CH_data=(((n./k)-m)./((n./k)-m+1)).*(Nf./k).*Enon_CH_frame;
E_CH_iter=E_CH_elect+E_CH_data;
Enon_ch_iter=Enon_CH_elect+Enon_CH_data;
Eround=(E_CH_iter/m)+(((n./(k*m))-1).*Enon_ch_iter)./((n./k)-m);
plot(k,Eround,'r-*');
hold on
m=3;
E_CH_elect=l.*(Eelec.*((n./k)-m+1)+Efs*d^2);
Enon_CH_elect=l.*(Eelec.*(1+k)+Efs*d^2);
E_CH_frame=l.*(((n./k)-m+1)*EDA+Eamp*d^4+((n./k)-m+1)*Eelec);
```

```
Enon_CH_frame=l.*(Eelec+Efs*((M^2)./((2*3.14159).*k)));
E_CH_data=(1./((n./k)-m+1)).*(Nf./k).*E_CH_frame;
Enon_CH_data=(((n./k)-m)./((n./k)-m+1)).*(Nf./k).*Enon_CH_frame;
E_CH_iter=E_CH_elect+E_CH_data;
Enon_ch_iter=Enon_CH_elect+Enon_CH_data;
Eround=(E_CH_iter/m)+(((n./(k*m))-1).*Enon_ch_iter)./((n./k)-m);
plot(k,Eround,'-^');
xlabel('Rounds', 'FontSize',14)
ylabel('Energy Consumption of CHs (J)', 'FontSize',14)
title('Energy Consumption by CHs Analysis','FontSize',14)
legend('LEACH','EN-LEACH')
```

Total Duration of Cluster failure code

```
%%% initial parameters%%%%%%
Eamp=0.0013*10^-12;
Efs=10*10^-12;
Eelec=50*10^-9;
EDA=5*10^-9;
n=1000; k=50; d=100; l=4000; Nf =10000; m=1;
[M,k]=meshgrid(1:20:200,5:5:50);
Ech_elect=l.*(Eelec.*(n./k)+EDA.*((n./k)-1)+Efs*d^2);
Enon_ch_elect=l.*(Eelec.*(1+k) + (k*EDA)+Efs.*((M.*M)./((2*3.14159).*k)));
Enon_ch_frame=l.*(Eelec+Efs.*((M.^2)./((2*3.14159).*k)));
Ech_frame=l.*(((n./k)-m)*EDA+(emp*d^4)+((n./k)-m+1)*Eelec);
f1=1./(k.*((n./k)-m+1)); f2=((n./k)-m)./(k.*((n./k)-m+1));
Ech_data=f1.*Nf.*Ech_frame;
Enon_ch_data=f2.*Nf.*Enon_ch_frame;
Ech_iter=Ech_elect+Ech_data;
Enon_ch_iter=Enon_ch_elect+Enon_ch_data;
Estart=(Ech_iter./m)+((n./(k.*m))-1).*(Enon_ch_iter./((n./k)-m));
surf(M,k,Estart);
```

```
hold on
m=3;
Ech_elect=l.*(Eelec.*(n./k)+EDA.*((n./k)-1)+efs*d^2);
Enon_ch_elect=l.*(Eelec.*(1+k)+(k*EDA)+efs.*((M.*M)./((2*3.14159).*k)));
Enon_ch_frame=l.*(Eelec+efs.*((M.^2)./((2*3.14159).*k)));
Ech_frame=l.*(((n./k)-m)*EDA+(emp*d^4)+((n./k)-m+1)*Eelec);
f1=1./(k.*((n./k)-m+1)); f2=((n./k)-m)./(k.*((n./k)-m+1));
Ech_data=f1.*Nf.*Ech_frame;
Enon_ch_data=f2.*Nf.*Enon_ch_frame;
Ech_iter=Ech_elect+Ech_data;
Enon_ch_iter=Enon_ch_elect+Enon_ch_data;
Estart=(Ech_iter./m)+((n./(k.*m))-1).*(Enon_ch_iter./((n./k)-m));
surf(M,k,Estart);
xlabel('Rounds', 'FontSize',12)
ylabel('Number Of Clusters', 'FontSize',12)
zlabel('Total Duration of Cluster Failure','FontSize',12)
title('Total Duration of Cluster Failure Comparison','FontSize',14)
```

Throughput Analysis of EN-LEACH code

```
%   Input:
%       initEnergy  Initial energy of each node
%       transEnergy Enery for transferring of each bit (ETX)
%       recEnergy   Enery for receiving of each bit (ETX)
%       fsEnergy    Energy of free space model
%       mpEnergy    Energy of multi path model
%       aggrEnergy  Data aggregation energy
%Energy Model (all values in Joules)
%Initial Energy
Eo = 2;
%Eelec=Etx=Erx
ETX=50*0.000000001;
ERX=50*0.000000001;
```

```
%Transmit Amplifier types
efs=10*10^-12;
eamp=0.0013*10^-12;
Eelec=50*10^-9;
%Data Aggregation Energy
EDA=5*10^-9;
%Energy budget
Ebgt=54;
%maximum number of rounds
rmax=200;
%Computation of do
do=sqrt(Efs/Emp)
%%%%%%%%%%%% END OF PARAMETERS %%%%
n=1000; k=50; d=100; l=4000; r=250*10^3; Estart=0.1;
[M,m]=meshgrid(1:10:200,1:1:20);
Ech_elect=l.*(Eelec*(n/k)+Ebf*((n/k)-1)+efs*d^2);
Enon_ch_elect=l.*(Eelec*(1+k)+(k*Ebf)+efs.*((M.*M)/(2*3.14159*k)));
Ech_frame=l.*(((n/k)-m)*Ebf+(eamp*d^4)+((n/k)-m+1)*Eelec);
Enon_ch_frame=l*(Eelec+efs.*((M.^2)/(2*3.14159*k)));
f1=1./(((n/k)-m+1)*k); f2=((n/k)-m)./(((n/k)-m+1)*k);
p1=((m.*Estart)-Ech_elect-Enon_ch_elect);
p2=(f1.*Ech_frame)+(f2.*Enon_ch_frame);
Nf=p1./p2;
surf(M,m,Nf);
xlabel('Number of Rounds', 'FontSize',12)
ylabel('Gateway nodes', 'FontSize',12)
zlabel('Number of Packet Sent to BS','FontSize',12)
title('Throughput Analysis of EN-LEACH','FontSize',14)
```

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