Energy Harvesting Aware Routing for Internet of Things in Smart Cities

Ph.D Thesis

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Final Approval

It is certified that we have examined the thesis report submitted by *Mr. Hassan Zeb*, Reg. No. *143-FBAS/PHDCS/F16*, and it is our judgment that this thesis is of sufficient standard to warrant its acceptance by the International Islamic University, Islamabad, for the Doctor of Philosophy in Computer Science.

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Hassan Zeb

Dedication

To my Family and Teachers.

Hassan Zeb

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To praise **ALLAH**, The Most Beneficent, The Merciful, The Gracious, and the Compassionate, whose abundant blessing and exaltation flourished my thoughts and thrived my ambition to have the treasured fruit of my modest efforts in the form of this manuscript from the blooming spring of blossoming knowledge, words are constrained, and knowledge is limited. I would especially like to appreciate the **Holy Prophet Hazrat Muhammad (SAW)**, who is the world's greatest teacher and an unending reservoir of wisdom and information for humanity. He imparted morals and timeless concepts.

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Publications From Thesis

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2. **Hassan Zeb**, Anwar Ghani, Moneeb Gohar, Abdulrahman Alzahrani, Muhammad Bilal(Senior Member, IEEE), and Daehan Kwak, "Location Centric Energy Harvesting Aware Routing Protocol for IoT In Smart Cities," *IEEE Access*, 11: 102352–102365, 2023. **(IF – 3.9)**

Articles Under-Review

1. **Hassan Zeb**, Anwar Ghani, Muhammad S. Obaidat, Lif Fellow IEEE, Abdulrahman Alzahrani, Salabat Khan, Khalid Mahmood, Sinior Member, IEEE, and Do-Hyeun Kim, "Enhanced Location-Centric Energy Harvesting Aware K-means Clustering for IoT Networks in Smart Cities," *Transactions on Sustainable Computing, IEEE*, 2023. **(IF – 3.9)**

Acronyms

ACO: Ant Colony Optimization

AODV: Ad hoc On-Demand Distance Vector

BS: Base Station

CAGR: Compound Annual Growth Rate

CH: Cluster Head

CM: Cluster Member

EECP: Energy Efficient Clustering Protocol

EH: Energy Harvesting

EHARA: Energy Harvesting Aware Routing Algorithm

EIRP: Effective Isotropic Radiated Power

EVAL: Evaluation

FFA: Firefly Algorithm

GCD: Greatest Common Divisor

HH: Harvesting-Harvesting

ICT: Information and Communication Technologies

IEEABR: Improved Energy Efficient Ant Based Routing Algorithm

IEGGR: Incremental Expansion Greedy Geographic Routing

IoT: Internet of Things

KDE: Kernel Density Estimation

LA: Learning Automata

LCM: Least Common Multiple

LEACH: Low-Energy Adaptive Clustering Hierarchy

MAC: Media Access Control

M2M: Machine-to-Machine

MWSNs: Mobile Wireless Sensor Networks

NCL: Node Congestion Level

OPC: Optimal Placement of Charger

PLR: Packet Loss Ratio

PDR: Packet Delivery Ratio

RF: Radio Frequency

RFID: Radio Frequency IDentification

RSSI: Average Received Signal Strength Indicator

RC: Residual-Consumed
RSC: Radial-Shaped Clustering
RTL: Regional Traffic Load
SMA: SubMiniature version A
SWIPT: Simultaneous Wireless Information and Power Transfer
TTL: Total Traffic Load
WBAN: Wireless Body Area Network
WCD: Wireless Charging Devices
WPCN: Wireless Power Communication Networking
WRI: World Resources Institute
WSN: Wireless Sensor Network
WRSN: Wireless Rechargeable Sensor Network

Abstract

In the swiftly evolving landscape of IoT-based Wireless Sensor Networks (WSNs), deploying individual sensor nodes for data collection in smart city environments has attracted considerable attention. These networks empower monitoring in distant and challenging conditions, but their operation is beset by challenges emanating from the resource limitations intrinsic to sensor nodes. Chief among these challenges is energy preservation, given the constrained battery capacity, data storage, computational speed, and communication range of these nodes. Energy harvesting techniques emerge as a solution to overcome energy limitations and sustain IoT devices in these demanding settings. These methods obviate the necessity for frequent energy component replacements, fostering networks capable of indefinite operation. Radiofrequency (RF) based energy harvesting stands out among various energy harvesting options, making it a primary focus for IoT applications. This thesis offers a comprehensive approach to augmenting energy efficiency and energy harvesting in IoT-based WSNs. The main contributions encompass:

Energy Harvesting Optimization: This study presents real-world indoor experiments utilizing Powercast energy harvesting devices for dipole and patch antennas alongside a moving vehicle equipped with a charger. The experiments encompassed various scenarios, including indoor settings, different distances, and the deployment of directional antennas. An efficient technique is developed to optimize the placement of chargers and IoT devices within this setup, while conclusive results attest to its efficacy.

Energy-Efficient Routing: A simple yet effective energy-efficient routing protocol was proposed, emphasizing efficient link selection based on proximity to the destination node. The protocol integrates distributed neigbbor discovery and routing processes with energy harvesting techniques to enhance network longevity. Experimental outcomes underscore the successful routing, achieving a 0% Packet Loss Rate (PLR) with up to eighty nodes, minimal delays, maximum throughput, and improved energy utilization.

Cluster Formation and Stability: An innovative approach involving cluster formation and the selection of stable cluster heads was introduced. This approach uses a modified K-means algorithm to group nodes into clusters, with cluster selection based on proximity to the destination node. RF energy harvesting is integrated to extend the network's lifespan. Comparative results underscore the model's superiority, achieving a 91% packet delivery ratio with a one second packet interval, 97% with a 0.077-second packet interval, and enhanced throughput.

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Chapter 1

Introduction

The IoT, introduced by Kevin Ashton at Procter & Gamble (P&G) in 1999 [3], plays an important role in daily life. The IoT has emerged as one of the most prominent technologies poised to revolutionize human interactions with the physical world. IoT can be defined as the interconnection of things and sensors to the Internet, enabling the exchange of data and messages for smart control and management [4].

The Machine-to-Machine (M2M) Connections market was worth $35.6 billion in 2022. It is expected that the industry will experience growth, reaching $57.4 billion by 2032, with a projected compound annual growth rate (CAGR) of 5.40% during the forecast period from 2023 to 2032 [1].

Most IoT devices have limited memory and battery life. Frequent battery replacement in harsh areas is difficult and increases operational expenses. Researchers have solved this problem by recharging the battery from renewable energy resources such as solar, wind, vibration, and vebicles and changing the routing protocols from energy-aware to energy harvesting-aware routing protocols. Nevertheless, some resources, such as solar power and variable wind, are not available continuously. Researchers and different charging platforms (WISP, PoWiFi, Powercast, EnOcean) have introduced radio frequency (RF) based energy harvesting, which is clean, green, and continuously availahle. Due to these qualities, a new research area called RF-powered IoT has emerged, offering great potential for researchers to investigate the IoT field more deeply.

The Wireless Rechargeable Sensor Network (WRSN) is one of the most important components of RF-powered IoT devices. WRSNs collect data from a specific region and process necessary information. This work considers that the devices in IoT networks are heterogeneous, with heterogeneity stemming from factors like initial energy, residual energy, link capacity, energy consumption, sensing capacity, and even transmission range.

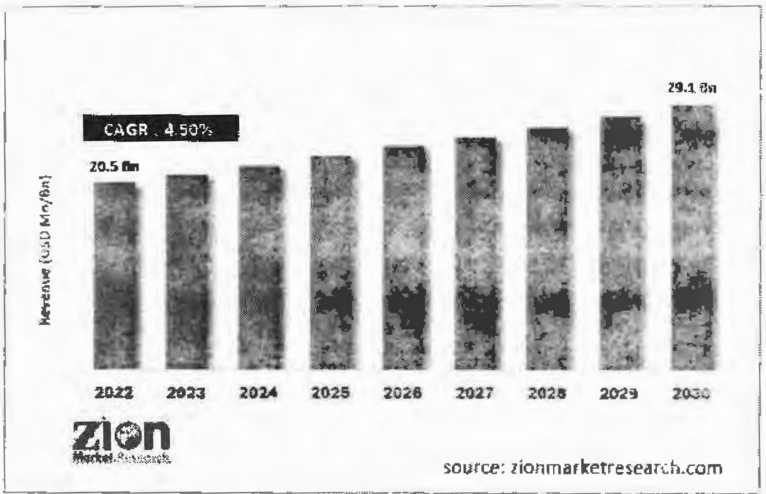

Figure 1.1: Global Machine-to-Machine (M2M) Connections Size [1]

The IoT has many applications, including smart transportation, smart grid, smart home, smart agriculture, logistics, retailing, and environmental monitoring. By leveraging IoT technologies, traditional manufacturing processes can undergo significant changes, leading to a substantial increase in production efficiency.

1.1 Smart Cities

In the coming decades, cities are encountering new challenges emblematic of modern societies. These challenges include population aging, the need for reduced energy consumption and carbon emissions, the pursuit of greater sustainability, and the aspiration for economic growth. Additionally, the size of cities is rapidly expanding due to increased migratory movements. Currently, approximately 50% of the world's population resides in cities, and it is projected that by 2050, this percentage will rise to around 70% [5].

To tackle these challenges, the concept of smart cities has emerged, proposing innovative approaches to development and city management. Although there is no universally accepted definition of a smart city, a definition put forth by the authors of [6] has gained popularity: a city is considered smart when investments in human and social capital, as well as in traditional (transport)

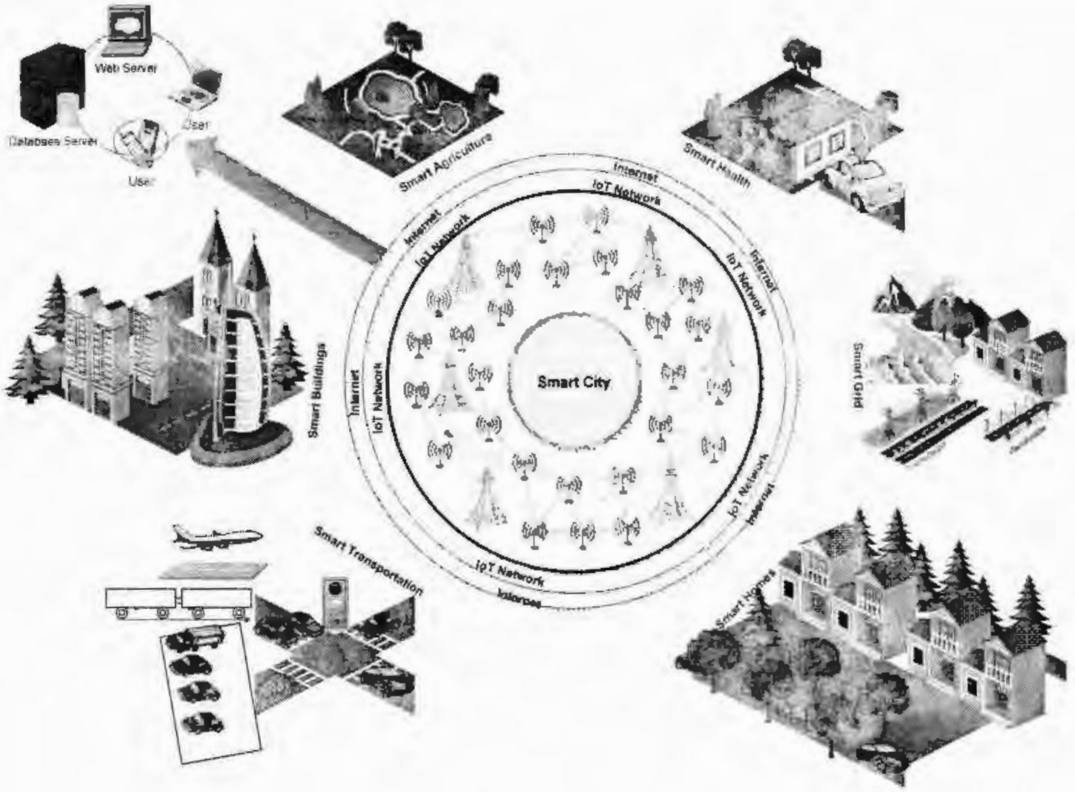

Figure 1.2: Smart City

and modern Information and Communication Technologies (ICT) communication infrastructure, contribute to sustainable economic growth and high quality of life. This is achieved through the wise management of natural resources and the practice of participatory governance. The following are the applications of a smart city:

1.1.1 Smart Home

The growing trend of internet-connected home appliances, such as refrigerators, ovens, and washing machines, offers enhanced user control and real-time status updates via Wi-Fi or Bluetooth. This connectivity extends benefits like convenient management and reliable information. Smart homes leverage IoT for efficient lighting, HVAC control, and enhanced security through cameras, alarms, and motion sensors. Additionally, smart speakers act as interfaces, allowing users to control appliances via voice commands effortlessly. However, these advancements also raise concerns regarding privacy and data security. As interconnected devices increase, robust protection systems must be developed to mitigate potential cybersecurity threats [7].

1.1.2 Smart Health

Leveraging wireless sensors and advanced communication tech, IoT is revolutionizing healthcare with potential benefits across technology, economy, and society [8]. IoT finds applications in glucose monitoring, oxygen levels, rehabilitation, medication, and wheelchair management. RFID tags track medicine production and distribution, ensuring quality. Wearable sensors like blood pressure, temperature, and ECG sensors offer vital data for early diagnosis and real-time monitoring, even extending healthcare to patients' homes for comfort [9]. Start-ups and companies work on IoT medical clouds and databases for data transmission, storage, and presentation. A Chinese firm developed an all-in-one medical platform with cloud-based imaging, 3D processing, and visualization [8]. Further research can enhance healthcare's convenience, affordability, and efficacy.

1.1.3 Smart Agriculture

By 2050, the global population is anticipated to soar to 9.7 billion, a substantial increase of 2 billion people compared to 2019 figures. This projection stems from a 2019 United Nations report. Addressing this swift population growth requires a remarkable 60% surge in food production, according to the World Resources Institute (WRI) estimation. Accomplishing such a substantial boost in food output would demand an additional 593 million hectares of agricultural land to meet the escalated demand [10]. While this entails a considerable land requirement, the IoT is a promising solution. IoT-driven sensing devices are playing a pivotal role across various sectors, particularly in agriculture, where data is seamlessly transmitted through Internet protocols, constituting the realm of the "Internet of Things". The amalgamation of IoT sensor data from Smart Agriculture and Smart City sources is called "smart agriculture," encompassing vital tasks like crop monitoring, disease detection, optimized fertilization schedules, and more [11].

1.1.4 Smart Grid

IoT drives the evolution of the conventional grid into a smart grid, enhancing sustainability, reliability, security, and efficiency through real-time monitoring and intelligent control [12]. This transformation focuses on two key aspects: optimizing energy distribution efficiency and enhancing electricity quality. Advanced photovoltaic and battery technologies enable bidirectional energy flow within the smart grid, necessitating smart power meters to measure and manage energy distribution for users' needs. Real-time energy flow monitoring ensures a consistent, high-quality energy supply, contributing to an uninterrupted power flow in the smart grid [13].

1.1.5 Smart Transportation

Smart transportation involves the monitoring of various modes of travel, including private vehicles like cars, as well as public transportation such as buses and trains. Integrating the IoT technology into individual vehicles is a crucial advancement for the development of autonomous driving systems [14]. In addition, many large cities worldwide have implemented advanced tracking systems for public buses, leading to reduced wait times and improved overall efficiency [15].

1.2 Energy Harvesting

One of the main drawbacks of IoT-based WSN devices is the power supply, which degrades the network's performance. It is difficult to replace the battery in a challenging environment frequently, which can increase operational expenses. The researchers tried to solve this problem and introduce the concept of EH techniques from renewable energy sources such as solar, wind, thermal, RF, etc. The RF energy harvesting technique has obtained the attention of emerging technology platforms, such as Google, WISP, PoWiFi, Powercast, and EnOcean STM 300, due to its clean, green, and freely available nature in continuous form and its introduction of wireless charging devices (WCD). WCD is a suitable choice to prolong the lifetime of IoT-based WSNs to near-perpetual[16]. The Powercast Technology Company [17] offers a comprehensive suite of devices designed for energy harvesting and powering sensor nodes, serving the specific needs of research endeavors. There are four components of the Powercast energy harvesting model: an energy transmitter, a sensor board, an evaluation board, and antennas. The Powercast technology company introduces RF-based energy harvesting WCD to replenish the sensor devices' energy. The Powercast Technology Company has provided energy-harvesting devices that power IoT devices since 2003. It provides a temperature scanning system, a wireless charging grip for the Nintendo joy-con, a power spot, a UHF RFID retail price tag, and development kits. The development kits are used for research and powering IoT devices, which consist of evaluation boards (P1110, P2110), antennas, RF field-detecting light sticks, and sensors. The Powercast P2110-EVAL-01 development kit used in this research is designed for extremely low-power IoT devices. The focus of this work is to study the data received from dipole and patch antennas. The complete kit is based on the following devices:

1.2.1 RF Transmitter

The RF Powercast transmitter omits data and power as RF signals with a unique ID and a 915 MHz frequency. The output power (P_t) is 3 w EIRP with a beam pattern of 60° in vertical polarization, and the frequency range is 915 MHz. The distance for permanent installations of the TX91501B transmitter is eight feet above floor level. The Powercast Company provides the transmitter, which is covered in a black box with fixed output power and settings. The user cannot make changes to the transmitter.

1.2.2 Wireless Sensor Board

The board can measure and transmit light, temperature, humidity data, and external inputs. The sensor board is connected to the evaluation board through a 10-pin connector to obtain the energy from the evaluation board to transmit data. The ID of the sensor nodes can be set from 0 to 7 using ID SELECT switches. The sensor board has a PICkit connector through which the PICkit programmer can be connected.

1.2.3 P2110 Evaluation Board

The evaluation board is responsible for energy harvesting. The board contains the functionality of energy storage JP1 (C3, C4, and C5 jumpers), a 10-pin connector (J2) for wireless sensor board connection, a rectifier to convert the RF energy into DC, an SMA connector for an antenna or RF input (J1), and a visual LED indicator. The sensor board obtains the harvested energy from the evaluation board.

1.2.4 Powercast Antennas

The Powercast development kit comes with two types of antennas: dipole and patch. These antennas are connected to the evaluation board through an SMA connector for the antenna (J1). The dipole antenna has the RF connector at the bottom, and the patch antenna has the RF connector in the middle. The dipole antenna is flat, omnidirectional, and vertically polarized, and the gain power is 1.0 dBi with a 360-degree reception beam pattern. The patch antenna is two-layered, directional, and vertically polarized, and the gain power is 6.1 dBi with a 120-degree reception beam pattern.

1.3 Motivation

RF-powered IoT networking has garnered significant attention from researchers due to its potential in managing and retrieving data from various devices within smart cities. These cities encompass many devices, including light controllers, smoke detectors, AC controllers, sensors, actuators, and wireless devices. These interconnected devices operate wirelessly, carrying out their designated functions.

Optimizing energy usage while performing various tasks is challenging to effectively extend the lifespan of IoT networks. Regularly replacing batteries for IoT devices can incur substantial costs. Researchers have introduced RF-powered IoT devices to tackle this issue, which harness energy from the surrounding environment. This innovative approach significantly enhances the longevity of IoT networks and propels us closer to a realm of perpetual operation.

However, RF-powered IoT networking does encounter certain problems and obstacles. These encompass the necessity for timely observation and anticipation of energy requirements, which can fluctuate due to extended communication distances, data transfer activities, and computational workloads. Moreover, the depletion of nodes, leading to link disruptions, routing breakdowns, shifts in network structure, and the continuous need for network upkeep, contributes to the existing complexities. Additionally, concerns include the selection of optimal pathways, strategies for efficiently placing chargers, prudent utilization of available bandwidth, the effectiveness of energy harvesting hardware, and the occurrence of delays or time-related latency during the communication processes.

Furthermore, traversing the nearest-farthest nodes from the charger can degrade the harvesting process. This exacerbates one of the most important problems, which involves repeatedly traversing nodes that are not in the direction of the destination node. This results in wasted energy without proper consideration for the packet transmission process. This problem is further intensified in link failures, where traversing non-optimal nodes is repeated incessantly.

The phenomena mentioned above lead to energy wastage at each stage. Therefore, the previously mentioned issues serve as motivation to design routing protocols that are efficient and mindful of energy harvesting for IoT based on EH-WSN.

1.4 Scope of the Research

Path reconstruction and traversal of all nodes by a routing protocol can result in excessive energy wastage and an escalation in communication complexity, leading to delays, elongated routing paths, and heightened topology costs. This research is oriented towards the primary objective of minimizing energy consumption while simultaneously alleviating communication intricacies, including delay, throughput, and packet delivery ratio. The central emphasis of this study is placed on the optimization of topology construction and routing.

Topology construction serves as the foundational infrastructure for efficient routing. During this process, nodes compute essential parameters such as distance and angle, thereby guiding the routing procedure to facilitate streamlined data transmission. Notably, this research excludes considerations about antenna efficiency, frequency allocation, and hardware intricacies. The principal focus remains enhancing energy efficiency and refining communication efficacy through sophisticated topology construction and routing optimization strategies.

1.5 Research Challenges

The researchers have collectively inferred that routing protocols designed with energy-harvesting awareness confront various challenges. These encompass the necessity for timely observation and anticipation of energy requirements, which can fluctuate due to extended communication distances, data transfer activities, and computational workloads. Moreover, the depletion of nodes, leading to link disruptions, routing breakdowns, shifts in network structure, and the continuous need for network upkeep, contribute to the existing complexities. Additionally, concerns encompass the selection of optimal pathways, strategies for placing chargers efficiently, prudent utilization of available bandwidth, the effectiveness of energy harvesting hardware, and the occurrence of delays or time-related latency during the communication processes.

1.6 Problem Statement

Effective routing strategies and strategic placement of chargers are crucial in energy-harvesting-aware routing protocols to extend the network's lifespan. These components mutually reinforce efficient network operations. Nevertheless, both efficient routing strategies and optimal charger placement encounter various shortcomings that could potentially undermine routing efficiency.

These problems can be outlined as follows:

First, One of the main problems in RF-powered IoT-based routing protocols is the balance between harvesting and consuming energy at each sensor node during communication. If the energy harvesting (EH) process yields less energy than the consumed energy, the device rapidly reaches a dead state. This phenomenon leads to the division of the node's energy consumption and harvesting process into three modes: residual-consumed (rc), consumed-harvesting (ch), and harvesting-harvesting (hh). In the residual-consumed mode [18], the battery only performs its normal process and does not harvest energy. In the consumed-harvesting mode [19, 20], the battery performs its normal process and harvests energy. In the harvesting-harvesting mode, the device only harvests energy and performs no other functions. This mode is linked to node failure and leads to the issue of energy utilization management being crucial for routing protocols to optimize initial energy consumption and harvested energy.

The next problem is the farthest-nearest charger problem. If a charger is farthest from the device, it can harvest less energy, and vice versa. This problem can cause a node to be in a dead state.

In existing works [2, 21, 22], if a device containing the patch antenna moves outside the cone, it stops the EH process and enters a dead state. In our work, we are selecting an area for devices, and this area is larger than a cone. Therefore, this work aims to leverage the charger and antenna patterns. The most significant issue in these works was the constant distance between the charger and the device. As the distance between the charger and the devices increased, signal strength decreased, leading to insufficient energy reception. This, in turn, increased communication complexity and node mortality. When these work, select one grid point for the charger, but not all devices are covered by a single charger, leading to an increase in charger deployment costs.

The charging route starting [18, 23] from the BS and ending with the BS is suitable for a dipole antenna. However, for a patch antenna, it only works when it is within the range of a directional charger; otherwise, it does not work.

Second, The selection of intermediate nodes for data forwarding is critical for routing protocols. Some researchers used directional information [24, 25] to the destination node. In contrast, others employed a fitness function incorporating parameters such as energy levels (full, low, etc.), residual energy, shortest distance, smallest angle, etc. [26–28].

Many researchers have employed a hybrid approach; for example, paper [24] utilized direction information with the smallest angle, high energy harvesting, and the smallest distance. Paper [25] incorporated directional information from the source to the destination using distance. Paper [27] considered the closest distance to the destination node and applied the right-hand rule. Paper [26] integrated the shortest distance with energy harvesting rate and maximum residual energy, while paper [28] employed the shortest distance with probabilistic energy harvesting rate and maximum residual energy.

These approaches suffer from several challenges. During the initialization of the protocol, some employ route reconstruction when intermediate nodes fail [25, 26, 28]. Others may harvest less energy and consume more energy, ultimately reaching a dead state [24, 27], and visiting all nodes. Visiting all nodes means that during topology construction/initialization, paths are created by visiting all nodes in all directions, not necessarily in the direction of the destination node. Once the path is established and an intermediate node failure occurs, the system reconstructs the path, again traversing all nodes in all directions. Some approaches increase the diameter of the path [24, 25, 27], leading to increased energy consumption for the overall nodes.

Third, A literature review reveals that some researchers have simultaneously employed data collection and energy transfer [29–34]. Additionally, some have utilized the downlink and uplink concept for data collection and energy transfer [35–37]. However, commercial platforms such as Powercast do not use these techniques; instead, they focus on the recharge or work technique. In this context, "working" refers to the routing process, while "recharge" refers to the charging process. During the charging process, the routing process cannot be done. This phenomenon results in issues like link failure, node failure, dynamic topology challenges, charging latency, communication delays, and topology maintenance. SWIPT-based routing techniques, downlink and uplink techniques, energy-aware, commercial platforms, and energy-harvesting-aware routing use different techniques for efficient link/path/node selection for communication purposes in a network. These techniques include shortest path, channel capacity, energy level, distance, location-based, and energy harvesting rate [26, 28, 38, 39] parameters for efficient link/path/node. During the topology construction or initialization phase, all nodes in all network directions are traversed. So, in this phase, each node participates in the network process even if they don't need to. Consequently, the energy of those nodes which need not be traversed can waste their energy for free.

Furthermore, energy depletion causes many issues like link failure, node failure, dynamic topology, charging latency, communication delays, and topology maintenance. In these cases, a device stops all activities and becomes unavailable for routing activities, leading to routing path breakage. Consequently, the routing algorithm creates a new route as the initial stage [26, 40, 41]. So, in this phase, again, each node participates in the network process even if they don't need to be. Consequently, the energy of those nodes that do not need to be traversed can again waste energy for free.

Therefore, an approach is required that:

- Select links/node/path only in the direction of the destination device.
- Avoid the new route construction.

Fourth, In K-means-based cluster techniques, some authors used dynamic center points, kernel density estimation [42], midpoint method [43], and LEACH-based techniques for cluster head (CH) [44, 45] etc. In path selection, some authors used distance, residual energy, and route traffic parameters [42], and energy [44, 46]. In path selection, all these techniques select the CH blindly to reach the destination node and traverse those nodes which do not need to be traversed, so wastage of extra energy. However, these approaches are susceptible to CH failure, link failure, route maintenance, and route reconstruction, which can result in increased energy consumption. Therefore, an approach is required that:

- Creates and selects clusters only in the direction of the destination device,
- Avoids new route construction in case of CH failure.

All these problems are interconnected, with the solution to one often leading to the solution of another. Therefore, motivation arises to address these issues. This thesis introduces an innovative framework for optimizing energy-harvesting-aware routing protocols. By strategically managing route reconstruction and intelligently guiding device behavior during recharge or dead states, the presented approach aims to enhance network stability, efficiency, and sustainability. Moreover, an optimal charger placement strategy helps to prolong network lifetime. This seamless integration of energy harvesting and routing activities ensures smoother transitions while minimizing energy wastage.

Based on the above observations, the following research questions are to be addressed:

- How to effectively determine the best placement of a charger to resolve the dilemma of charging the nearest and farthest nodes? How can an optimal charging tour be formulated to identify the best charger positions and uncover the charging areas or points that remain within the charger's line of sight from any location as the charger moves?

- How can an energy harvesting aware location-based routing algorithm be developed that guides node traversal within directions to the destination node?
- How can an energy harvesting aware location-based clustering routing algorithm be devised to select the closest CH to the destination node location?

1.7 Aims and Objectives

The main aim of this thesis is to address the key challenges of energy harvesting-aware routing protocols, such as optimal charger placement, the Farthest-Nearest node from charger problem, optimal route/link selection for data transmission, and selecting the closest cluster to the destination node and making it near perpetual.

The proposed research comprises a set of objectives that will lay the foundation for realizing the overarching goal of the presented work, outlined as follows:

Objective 1: To incorporate an optimal charger placement strategy into energy-harvesting-aware routing protocols, utilizing real-world testbeds to enhance node energy harvesting efficiency and address the Farthest-Nearest Problem related to node-to-charger distance.

Objective 2: Develop an energy harvesting aware routing protocol that optimally considers node locations/angles during path/link selection, aiming to minimize packet transmissions, avoid extra node traversals, and avoid path reconstruction.

Objective 3: Develop an energy harvesting aware cluster-based routing protocol that optimally considers destination node locations during CH selection, aiming to minimize packet transmissions and node traversals and avoid path reconstruction.

Objective 4: In General, create routing protocols for IoT networks that minimize energy consumption at the individual node and network-wide levels.

1.8 Research Contribution

The main contribution of this thesis can be summarized as:

- To propose a technique for optimal charger placement in the IoT-based networks that efficiently charge the devices and make the network near perpetual. This technique incorporates circular charger points for charger and fixed device points for IoT devices to make possible near-perpetual network operations.

- To propose a simple EH-aware routing protocol that only traverses those nodes that become in the direction of the destination node. This can be achieved through selecting efficient links among neighbor nodes based on closest angles.
- To propose a modified K-means algorithm-based clustering protocol that only selects the CH in the direction of the destination node. This can be achieved by dividing the nodes into clusters according to their angles.

1.9 Thesis Organization

Chapter-1: Chapter 1 briefly introduces the IoT in smart cities, IoT-based Wireless Sensor Networks, and Energy Harvesting. Discuss the motivation of the thesis, the scope of the research, and the research challenges. Also, discuss the problem statements, research questions aims of the thesis, and contributions.

Chapter-2: In this section discusses the Literature on the energy harvesting routing protocols, optimal placement of chargers, and clustering techniques. Also, the limitations of the existing work are described and tried to solve in this work.

Chapter-3: In chapter-3 explains the methodology of the thesis and proposed system model. It also discusses the parameters of the thesis, which can be compared with the existing schemes and Schemes Scenarios of the thesis.

Chapter-4: In this chapter of the thesis presents the first accepted scheme article of the thesis briefly. In this article, the main focus is on finding optimal points for charger placement and device placement. The presented work shows a great impact on charging devices.

Chapter-5: In this thesis's chapter, present the second scheme article of the thesis briefly. In this work, the main focus is on finding an optimal link for sending data to the sink/base node. The results obtained by using the NS-3 simulator and presented work show a great impact on current works.

Chapter-6: This chapter of the thesis briefly presents the third scheme article of the thesis, which is in progress. In this work, the main focus is on selecting the optimal CH for data transmission towards the destination node. The results were obtained by using the NS-3 simulator, and there was evidence that the presented work performed better than existing works.

Chapter-7: In this chapter, a discussion is made on the effectiveness of this thesis in the routing protocols techniques.

Chapter-8: This is the last section of the thesis, which briefly discusses the Conclusion and Future Work of the thesis.

The chapter-flow chart of the study is shown in Fig. 1.3

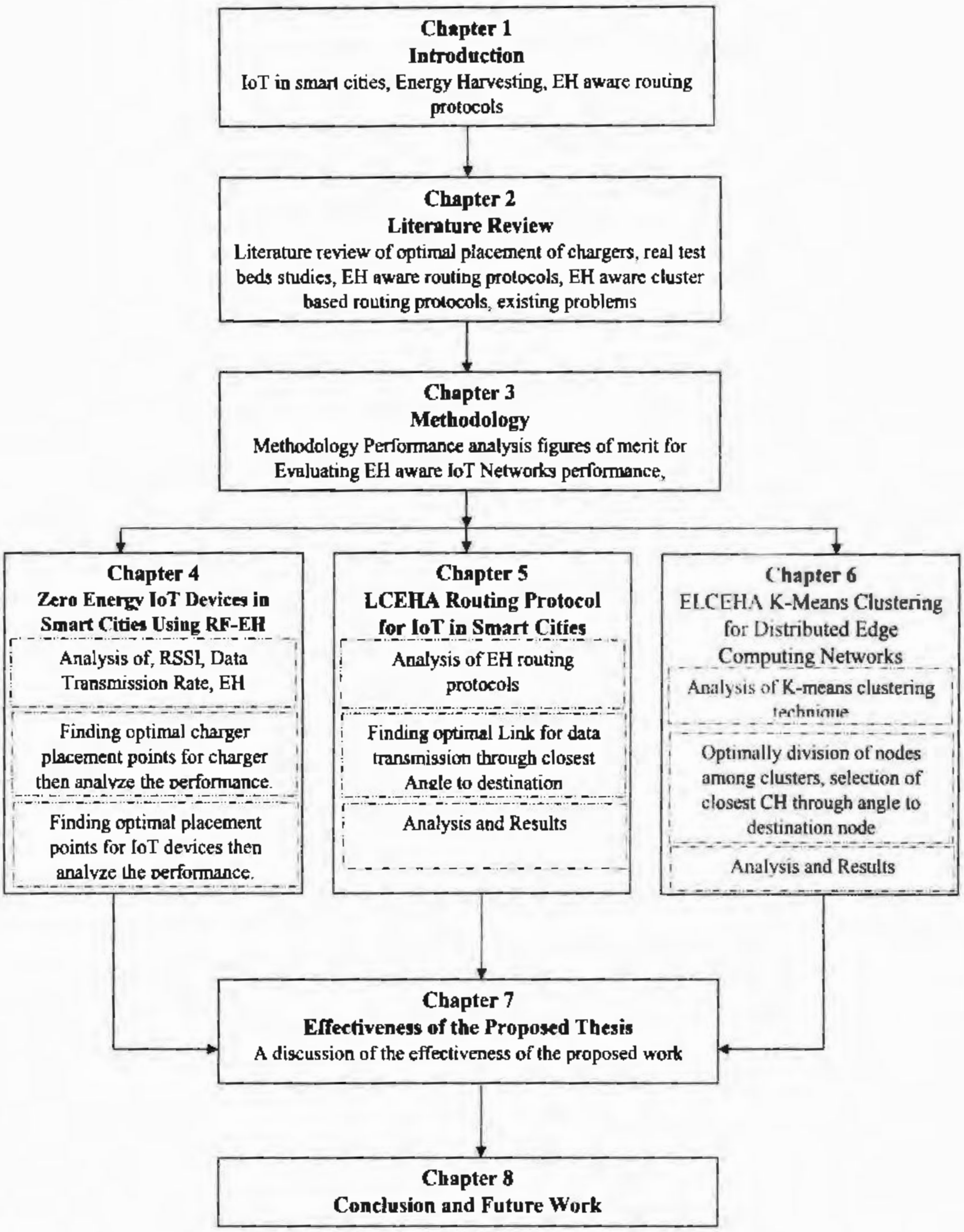

Figure 1.3: Chapter-wise Flow Chart for Study

Chapter 2

Literature Review

IoT-based WSN is a collection of sensor nodes and other devices that monitor a given area for specific purposes. Each sensor node can sense the environment and send the data to the BS or sink. Each sensor node has a battery or capacitor to store energy, a wireless transceiver, a processing unit, and memory for processing tasks. Battery life is one of the main research topics for researchers because battery replacement is a challenging task in harsh areas. To cope with the challenges, researchers have introduced energy harvesting from RF, solar, sound, wind, etc., to recharge the battery/capacitor of a sensor node [47]. Following this line, the researchers introduce energy harvesting-aware routing protocols. According to [47], the main goal of IoT-based energy harvesting-WSN protocols is not to focus on energy but to use the variable energy to support QoS requirements. This paper presents some energy harvesting-WSN protocols that use RF-energy harvesting for IoT-based WSNs. Energy harvesting- WSN is not a limited area of research. From the extensive literature review, the RF-energy harvesting for WSNs can be divided into the following categories:

2.1 Wireless Power Communication Networking (WPCN)

WPCN is an RF-energy harvesting-based communication network that uses the uplink and downlink concept for wireless energy transmission (WET) and wireless information transmission (WIT). The basic idea of WPCN is as follows: each node harvests energy from RF and transmits this energy wirelessly to other nodes using the downlink. Other nodes utilize the collected energy to transmit data to the destination through the uplink. The study of authors [36] presented an effective data collection algorithm for WPCN-based WSNs. In the algorithm, WPCN nodes harvest their energy from RF and store it in capacitors/batteries. The downlink is used for WET, and the uplink is used for WIT simultaneously. The authors assume a one-hop star topology in which sensor nodes surround the sink node, and the sensor nodes harvest their energy from the sink node. The sink node collects the sensed data from the nodes using the uplink and sends wireless energy to one hop node using the downlink. The authors investigate the throughput of the node during the collection of sense data to the sink per unit of time. MAC is a layer two protocol for connecting nodes to access a transmission line. Much research has been conducted to develop MAC protocols for energy harvesting-WSNs. The authors of [35, 37, 40] presented the Slotted ALOHA (S-ALOHA) based protocol and claimed that this is the first work to apply the S-ALOHA in energy harvesting-WSNs for WPCN. S-ALOHA has time slots; each node waits for a time slot and sends the data during the time slot. Otherwise, it waits for the beginning of the next time slot. energy harvesting S-ALOHA can be described as follows: each node harvests the energy from the RF energy harvester, and when a slot is accessed, it transmits the data. In [35, 40], the authors proposed the harvest-until-access technique, where nodes harvest energy continuously until a slot is accessed and then send the packet. In [37], the same authors proposed another scheme for the harvest-or-access technique.

2.2 Simultaneous Wireless Information and Power Transfer

The first paper in (SWIPT) was [32], as claimed by [30]. SWIPT uses a single transmission line for information and energy harvesting. In SWIPT, information decoding (ID) and energy harvesting are performed on each node. Some papers related to SWIPT are reviewed and discussed. Ref. [30] presented an energy-aware routing algorithm for RF-based energy harvesting-WSN based on the SWIPT technique. SWIPT uses a relay node to transmit data and power to nodes simultaneously. The relay node decodes and forwards the data between nodes. Some researchers adopt the amplify-and-forward technique instead of the decode-and-forward. The authors introduced the energy and information allocation problem, and then they presented an energy-aware SWIPT routing algorithm called ESWIPTR. The protocol is improved to a distributed synchronous proactive version and an asynchronous proactive table-driven version. The basic routing algorithm is based on an energy equation called E_{cost}. ESWIPTR finds the minimum energy cost path for routing through a routing function. The author also presents a distributed version of ESWIPTR using the distributed Bellman-Ford protocol.

The author considered a WSN with sensor nodes; each sensor was equipped with a single antenna. The data flows between the source and destination nodes. Two transmission modes are used between any two (i, j) nodes: information transmission (IT) and simultaneous wireless information and power transfer (SWIPT). The IT is used when the sensor's battery is full, and SWIPT is used when the battery's energy is less than the minimum energy requirement. The author addressed three problems in this work: routing, information, and energy allocation. In decode and forward (DF) protocols, the receiver node first decodes the information and forwards it to the next node. Therefore, successful decoding is essential for DF protocols. The author presented a decode as follows:

$$\gamma_{ij}^{SWIPT} = p_{ij}|h_{ij}|^2 P_{ij}/(\sigma_{ij}^2 + \eta_{ij}^2) \geq R_{min} \tag{2.1}$$

Where P_{ij} is the sender node sending power, p_{ij} is the power splitting value, h_{ij} is the channel gain, σ_{ij} is the power of a signal, R_{min} is the required SNR requirement, and n_{ij} is the antenna noise. The forward equation is as follows:

$$E_{ij}^{eh} = \epsilon(1 - p_{ij})(|h_{ij}|^2 P_{ij} + \sigma_{ij}^2) \geq P_{cj} \tag{2.2}$$

P_{cj} is the energy harvesting power requirement for forwarding the information to the next hop node.

$$P_{cj} = P_{ji} if r_{ji} = 1 \tag{2.3}$$

P_{ji} is the power cast for forwarding to the neighbor/next node, and r_{ji} is the link state (active = 1, not active = 0). The authors' main objective in routing was to find the minimum cost link.

The author presented two types of routing algorithms, i.e., centralized and distributed. The routing algorithm is based on the concept that a node with low energy selects the next node for routing. The presented routing algorithms, ESWIPTR, are based on Eqs. (1)-(3). A Dijkstra-based centralized routing algorithm was used in this work. The Dijkstra algorithm first checks the shortest path between the neighbor nodes and selects the node with the shortest or closest path to the destination. Like the Dijkstra algorithm, the authors first examine the path with the minimum energy from the source to the destination node and allocate resources. The minimum energy can be calculated through the Ecost equation. The authors also presented the distributed version of the ESWIPTR algorithm using the distributed BellmanFord protocol. The algorithms are evaluated by convergence rate, the impact of the node density, minimum energy requirements for packet forwarding, and the impact of the barrier. The authors presented another paper [31] for interference-aware routing. Interference occurs when one-directional link affects other directional links or uplink affects downlinks in cellular networks. [48] Presented another SWIPT based RF-energy harvesting WSNs with amplify-and-forward relay nodes. [33] Presented a selection cooperation protocol with feedback from destination to source node. [34] Presented a cluster-based SWIPT protocol.

2.3 Polling-based

[49] Presents a polling-based MAC protocol for energy harvesting. The sink fires a packet to nodes containing a contention probability instead of ID. Nodes in the network decide through this packet whether to transmit their packet or not. The contention probability is based on the number of nodes, current energy harvesting rat, and packet collision. The contention probability increases when other sensor nodes respond and decreases when a collision occurs. The polling-based MAC protocol for energy harvesting uses the charge-and-spending harvesting strategy. It first accumulates enough energy and then goes into the receiving state to listen and receive the polling packet. The author used three parameters for the performance of the given protocol: throughput, fairness, and inter-arrival time. Throughput was used to receive the packet at the sink node successfully. Fairness is used to achieve a balanced degree of the network. The fairness F and inter-arrival time T equations are as follows:

$$F = \frac{\left(\sum_{i=1}^{n} R_i\right)^2}{n\left(\sum_{i=1}^{n} R_i^2\right)} \tag{2.4}$$

$$T = \frac{\sum_{i=1}^{n} \frac{1}{R_i}}{n} \tag{2.5}$$

Where R_i represents the rate of data packets received from sensor $i, andn$ is the number of total nodes.

2.4 Optimal Placement of Charger

Tang et al.[18] addressed charging and routing challenges in a network using a mobile device on the shortest travel path. Considering their energy conditions, a prioritization method is employed to charge critical nodes. Routing considered node state and energy supply strategy, selecting forwarder nodes based on energy consumption and estimated recharge time. However, some challenges arose: charging time hindered routing performance, the prioritization method struggled with numerous critical nodes, and topology changes were not accounted for. Moreover, the problems of limited data buffer capacity and long transmission delay are identified [50].

Tomar et al. [51] presented an OPC solution. He divides the IoT network into area of interest (AoI) using fuzzy logic, and then BS assigns the charger to the divided regions. The AoI process can be described as drawing a base axis line from the BS, intersecting the rectangular network horizontally. It divides the region into four quadrants. Each node will calculate its angular distance from the base axis line. Traffic load is also included in the AoI process. The author used the regional traffic load (RTL) and total traffic load (TTL) of the network. Each AoI has at least one charger. The author considered any standard routing algorithm to find the network's traffic load but did not give a solution. The mobile charger (MC) entertains the charging request through fuzzy logic about which next node to charge. In Fuzzy logic, the charger checks the remaining energy, maximum distance, etc.

Ding et al. [52] solve the OPC problem from two different aspects: first, to develop a strategy of charger placement to minimize the deployment cast, and second, to maximize the overall charging levels of the network. The OPC problems of Ding et al. can be summarized as follows: given a set of rechargeable IoT devices and a set of locations, the purpose is to place the chargers (Omni or directional) in suitable locations that minimize the total cost of deployment of chargers. Ding et al. solve the problem of OPC but do not consider the distance between the farthest node and the charger, which can harvest less energy than the nearest node.

The PSCD algorithm [21] by Chen et al. is designed to address the Wireless Charger Deployment Optimization (WCDO) problem using a Particle Swarm Optimization (PSO) approach. Each charger is modeled as a particle, and each particle will store the particle position and antenna direction with a fitness function. The fitness function considers the charging distance and angle for each sensor node the charger covers. Local and global optimum are used to find the best location locally and globally. For local optimum, store the best fitness value, corresponding position, and antenna direction seen so far. Store the best global fitness value, corresponding position, and antenna direction across all particles for the global optimum. Deploy a charger based on the global optimum position and antenna direction.

Jiang et al. [53] presented two types of algorithms, Greedy Cone Covering (GCC) and Adaptive Cone Covering (ACC), for selecting the optimal placement of chargers and the optimal area for device placement. They utilized a cuboid model to deploy chargers and devices, with grid points on the top and lower parts of the cuboid used for devices. GCC and ACC algorithms have two phases: cone generation and cone selection.

Cones are generated by taking each grid point as the apex. The algorithm starts by creating a half sphere (HS) centered at each grid point in the deployment area. The HS is a three-dimensional region that covers sensor nodes within its boundary. Within the generated HS, the algorithm calculates the set of sensor nodes (SS) that fall within the half sphere's coverage. For each pair, the following steps are performed. Vector Generation: For a selected pair of nodes, the algorithm calculates a vector representing the direction from the grid point (apex of the cone) to the midpoint between the two nodes. Multiple vectors are generated for multiple nodes in HS. Using the calculated vector, a cone can contain an apex point (the point from where it starts), a direction, an effective charging distance, and an effective charging angle.

Cone Selection: The algorithm generates candidate cones at this stage. Now, the algorithm selects the best cone. The cone that covers the most devices will be selected for charger placement. Therefore, the apex of the selected cone becomes the charger point.

The Genetic Particle Swarm Optimization Charger Deployment (GPSOCD) [22] is introduced, combining Particle Swarm Optimization (PSO) and a genetic algorithm (GA). In PSO, each particle holds velocity movement direction, updated rule information, and inertia weight. The update rule involves iteratively adjusting particle velocity based on its historical best position (local best) and the overall best position of the entire swarm (global best). The inertia weight reflects a particle's previous velocity, with a higher inertia rate encouraging larger movements for global exploration and a lower rate focusing on local search in known good areas.

The GA functions as a fitness function, selecting velocity, update rule, and inertia weight parameters to create new chromosomes with improved parameter values.

The PSCD [2] algorithm is designed to address the Wireless Charger Deployment Optimization (WCDO) problem using a Particle Swarm Optimization (PSO) approach. In this algorithm, each charger is modeled as a particle, and each particle stores the particle position and antenna direction along with a fitness function. The fitness function considers the charging distance and angle for each sensor node the charger covers. Local and global optimum are used to find the best location locally and globally. The algorithm stores the best fitness value, corresponding position, and antenna direction for the local optimum. It stores the best global fitness value, corresponding position, and antenna direction across all particles for the global optimum.

The algorithm uses the global optimum position and antenna direction to deploy a charger.

IPSCD is a modified version of PSCD in which only the step where the charger is placed through the global position is modified. The modification involves selecting the best global position again from the available global positions.

Xu et al. [23] aimed to optimize charger placement for efficient device charging, incorporating directional antennas for energy transmission. They addressed two challenges: determining docking spots and charging orientations for devices to achieve complete charging coverage. Docking spots refer to specific locations where the charger's direction vector and angle are not aligned with the charging device. The second challenge involves planning the moving path of a DCV (Device Charging Vehicle) to ensure no sensors run out of energy during the charging cycle. The solution focuses on finding docking points with optimal charger orientation and angle, creating a charger tour starting and ending at the BS (Base Station). In the case of network topology changes, the process repeats, which becomes costly. Concentrate on a specific area to charge specific devices efficiently.

2.5 EH Aware Location/Angle Based Protocols

Nguyen et al. [26] introduced the energy harvesting Aware Routing Algorithm (EHARA), which considers the nodes' battery level and divides it into three categories: maximum, minimum, and low. The underlying concept of this protocol is to select the link with the minimum cost and the node with the minimum cost when a source node intends to transmit a data packet to a destination node. The minimum cost link is determined based on factors such as the link distance and the energy harvesting process. However, this approach has an issue when it initiates a new route creation procedure in case of route failure. Moreover, there is a possibility of long routes existing.

Gong et al. [38] introduced an on-demand energy harvesting-aware routing approach for Wireless Sensor Networks (WSNs) focusing on finding an optimal route based on the least transmission cost determined by considering various factors such as the transmission range, estimation of transmission cost from the current node (m^{th} node) to its next hop, the average number of retries, the minimum required radio transmission power, circuit processing power, receiving power of the next node, time required to deliver a packet, and energy harvesting considerations. The energy consumption rate is high as more messages dissipate. Moreover, it creates a new path after link breakage.

Yallappa [28] presented an energy harvesting aware protocol using two parameters, distance and maximum current energy, to calculate the fitness for an optimal path between source and destination nodes. However, the prediction model of node energy harvesting is weak.

In [54], the authors introduced a MAC protocol that leverages RF energy harvesting to charge the battery of sensor nodes. Once the nodes are fully charged, they initiate data collection and transmission activities. To prevent packet collisions, the protocol incorporates the concept of back-off time to avoid collisions. However, the challenge is predicting a node's waiting time to harvest energy and start working.

Authors in [39] presented a scheduling mechanism for operational states of sensor nodes that involves switching between recharge and work states. Considering the dynamic topology resulting from these state transitions, the author proposed a solution for single-hop and multi-hop scenarios, where routing path selection is based on channel capacity and energy level. However, the proposal suffers from the lack of traversal of additional nodes, handling the addition of new nodes, and limited scalability in large-scale networks.

The authors in [55] improved the R-MPRT algorithm using the residual energy of each node instead of the energy harvesting rate to determine its cost function. This modification likely aimed to optimize the algorithm's performance and efficiency when dealing with energy management in wireless networks or similar systems. The proposal still suffers from extra node traversing with the broadcasting mechanism.

In [56], the author introduces an energy-aware routing protocol EAQ-AODV employing Q-learning for CH selection and incorporates parameters like residual energy, common channel, number of hops, licensed channel, communication range, and trust factor to establish optimal routing paths. Using Q-learning, the protocol learns from past experiences to make informed decisions. One challenge of this proposal is frequent updates and overhead during network changes.

The article in [57] introduces a heuristic angular clustering framework for securing statistical data aggregation in sensor networks to address energy and scalability issues in wireless sensor networks through a complex deployment structure called radial-shaped clustering (RSC). RSC divides the network area into virtual concentric rings, and each ring is further divided into sectors called clusters. The node closest to the midpoint is selected as the CH, and data from each sector are aggregated and forwarded to the sink node using angular inclination routing. The paper does not address the extensive communication overhead associated with cluster data aggregation and routing. In large-scalc sensor networks, excessive overhead might lead to inefficiencies.

The authors in [58] presented a novel approach using Voronoi diagrams and Delaunay Triangles for energy-efficient path selection to forward the data. For optimal path selection, a source node identifies the destination node's Voronoi cell and its own, then selects the next hop from the common Delaunay Triangle. This geometric approach reduces communication overhead and conserves energy, making it an efficient and promising solution for geographic routing in wireless sensor networks. However, the proposal suffers from scalability, route maintenance, and border node-related problems.

Redjimi et al. [59] presented a location-based IEGGR (Incremental Expansion Greedy Geographic Routing) for solving the local minima problem. The main idea behind IEGGR is to construct a local sub-graph for each node, known as the Routing Area, by including neighbors closer to the base station than the source node. The nodes in this area participate in a Minimal Spanning Tree (MST) calculation using Prim's algorithm. When a node encounters a void (no neighbor closer to the base station), it widens its local sub-graph area to an angle to form the Recovery Area. The trade-off between widening the recovery area to avoid voids and keeping it small to conserve energy and reduce delays must be carefully considered. This problem causes high energy consumption and end-to-end transmission delay.

In [50], the author claims that existing studies on energy harvesting-WSN fail to adequately address the relationship between energy state and data buffer constraints. Consequently, they do not effectively resolve energy efficiency issues and long delays. The author proposes a novel routing protocol based on a greedy strategy for energy-efficient energy harvesting- WSN considering the energy harvesting, energy classification factors, and energy consumption to identify each node's energy state accurately. In this method, the intermediate node closest to the destination node is selected, possibly leading to long routes and more energy wastage. Moreover, the border node problem has not been solved: when the same nodes closest to the destination are in the forward transmission region, the algorithm does not specify which one will be selected.

[60] Presented a routing protocol for energy harvesting-WSN. In this work, he used the Improved Energy Efficient Ant Based Routing Algorithm (IEEABR) for harvesting RF energy and managing the harvested and available energy for wireless sensor networks. He first discusses the RF power density, storage of the harvested power, calculation of the received power, and power management in the energy harvesting-WSN protocol. IEEABR technique used for routing. The author of this paper used the Friis equation [61], which is used for a situation where the distance between two nodes or antennas is known, and this equation is discussed in [61] in detail. [26] Presented an energy harvesting-aware routing protocol.

In [62], the author proposed Fuzzy logic-based adaptive duty cycling for sustainability in energy harvesting sensor actor networks. The harvesting model forecasts the amount of energy that can be collected from a renewable energy source and also estimates the remaining available energy for the future by incorporating the predicted harvesting energy, an energy consumption model, and the current residual energy. However, the paper does not provide a solution for determining the nearest or farthest node to harvest energy. This means that a node closer to the energy harvester may harvest more energy than a node farther away.

The authors in [63] highlight challenges in energy harvesting for IoT applications, particularly the limited lifetime of IoT networks due to power deficits in nodes and the need for appropriate positioning of RF-energy transmitters for sufficient energy transfer. The proposed solution is a network-aware RF-energy transmitter positioning scheme that considers energy-hole information, data routing information, and node-connectivity information to optimize transmitter placement and address energy-hole issues. Similarly, the authors in [64] focused on improving the performance of IoT systems by combining cognitive radio (CR), energy harvesting, and back-scatter communication (BC) technologies. The objective is to achieve high throughput on various channels by proposing a novel hybrid communication scheme.

The author of [65] introduces an angle-based approach for routing path selection. Their work can be divided into Greedy Delivery and Bypass Delivery. In the Greedy Delivery method, a node broadcasts an RTS message to find the better candidate for delivering data to the destination. In the Bypass Delivery method, the node enters bypass mode if no candidate is found using Greedy Delivery. It broadcasts an RTS message with its location and destination and bypass mode information to its neighbors. Each neighbor calculates a deflection angle to determine its candidacy and sets a timer for broadcasting the CTS message. The node selects the neighbor with the minimum angle towards the destination as the forwarder to relay its data packet. A significant portion of the data packets are sent in broadcast mode, which leads to various issues. These problems include delays in transmitting the packets, higher energy consumption, a higher likelihood of losing packets during transmission, and longer routes to reach their intended destinations.

The research by Kumar et al. [66] shares similarities with the proposed approach in this article. However, there is a difference in optimal link selection. The authors employed a region-based approach for sending initialization packets in their study. While they did not delve into the selection of forwarding regions, they utilized a triangulation region to forward the initialization packet. All nodes would forward the packet within this region by choosing nodes in increasing order of their angles. However, a concern arises when a node lacks neighbors, which may lead to a dead end. Additionally, unnecessary traversal of nodes may occur, resulting in extra energy wastage, as these nodes may not be in the direction of the destination node.

Khan et al. [63] presented an energy harvesting-aware routing protocol for an IoT-based wireless body area network (WBAN). The author solved the topology construction and routing problems. In the sensor deployment phase, the author used a beacon message through which each node calculates its distance, hope count, and residual energy of the nodes. In the topology construction process, the author used two packets, hello and reply. During the topology construction process, the author tried to find the information about neighbor nodes and store it in the routing table. The best forwarder node is selected among neighbor nodes in the routing process. The best forwarder node has the qualities of maximum residual energy, shortest path, total energy (TE), distance (d), hop count (HC), link efficiency (LE), and node congestion level (NCL). So, three packets are used in the whole network: beacon, hello, reply, and data packets. This paper has some problems, such as link/node failure not being considered, long roots exist, and the farthest-shortest problem not being considered. Routing in the direction of the destination node is not considered.

The Authors of [25] presented an energy harvesting-based routing protocol. He used the learning automata (LA) to solve discrete energy harvesting and energy consumption balancing problems. In LA, current action has been taken from the previous action. The author divides his technique into two steps: the initial network step and the routing steps. The author constructs the topology using an initial packet and replies to packet-type messages in the initial network step. The ack and data packet type messages are used in the routing steps. In the initial network step, when a source node wants to send data to the destination node, it generates the initial packet and broadcasts it to neighbor nodes. When the destination node receives the initial packet, it converges to the reply packet; hence, the source node can get the information of the destination node. During the initial step, each node calculates the residual energy and the energy harvesting probability. After getting the necessary information from the initial step (neighbor node information, etc.), the data packet is broadcast to the neighbor nodes using LA. In this paper, the mismatch problem exists. Also, the author does not consider routing to a specific location.

Ilyas et al. [67] presented a trust-based routing protocol for an IoT-based sensor network. The author presented a routing algorithm that collects data from the smart environment, smart homes, smart health, smart agriculture, and smart grids in a smart city environment. The author tried to reduce the control packets during network communication. The presented solution was cluster-based, in which the author divided the nodes into CH, a cluster gateway (CG), and a cluster member (CM). The IoT devices are fixedly deployed in a target area. The author used two phases for network operations: initialization and routing. A reply and ack packet collect necessary information for routing among neighbor nodes in initialization. Besides these packets, inter-cluster packets are also exchanged by CH and CG, such as joint requests, broadcasting of CG roles, etc. The data packets are sent through an efficient link regarding harvesting energy rate, initial energy, distance, etc. One of the main limitations of this approach is the number of message transmissions in inter-cluster and intra-cluster. Link/node failure not considered. Traverse extra nodes during routing. [27] Employ the minimum distance and the required energy for sending and receiving packets, considering the energy harvesting rate. In situations where no minimum distance is specified, apply the right-hand rule. It's important to note that implementing the right-hand rule may increase the path diameter.

2.6 Cluster Based

In this research [68], the author presented a modified version of the K-means algorithm called Mk-means. This work aims to select the CH to minimize the energy consumption within IoT-based WSNs. Several techniques have been used to reduce the energy consumption of the nodes, including the firefly algorithm (FFA), which used the optimal path selection from CH to the base station for optimal route construction. For constructing an optimal path for clusters, the author used distance, residual energy, and route traffic parameters as fitness functions. This approach leads to efficient data transmission between inter and intra-cluster architecture. The approach efficiently reduces the energy consumption of individual nodes. This work does not consider link failures, and as a result, the approach leads to a minimum Packet Delivery Ratio (PDR) and throughput compared to the work presented in Chapter 6

This research [42] introduces an enhanced clustering algorithm called IS-k-means for balanced energy consumption in WSNs. It combines clustering by fast search and finding of density peaks (CFSFDP) and kernel density estimation (KDE) to improve the selection of initial cluster centers. The soft-k-means algorithm reassigns nodes at cluster boundaries, ensuring a fair distribution of nodes per cluster. Multi-CH are introduced to promote energy balance within clusters, reducing individual node burden. Extensive simulations validate the algorithm's effectiveness, especially in small-scale WSNs with single-hop transmission.

The work of [43] based on K-means clustering protocol is presented called Energy Efficient Clustering Protocol based on K-means (EECPK-means). This work deals with the load of CHs in WSNs. The author used the midpoint method to enhance the initial selection of centroids in the K-means algorithm. This results in more balance in cluster creations.

The author of [44] introduces an enhanced version of the LEACH protocol incorporating the K-means clustering to improve the CH selection process. This method focuses on creating symmetrical clusters to reduce the distance between nodes and sink. The author considers the sink node's location when it is located far away in the network. In the CH selection process, a node is selected as CH that requires less energy to manage the cluster members and optimizes the overall energy consumption within the network.

The research of [45] introduces K-means clustering combined with the LEACH protocol [69]. The CHs are selected using LEACH protocols, while the K-means protocol approach generates the clusters. The results showed that it consumed less energy than LEACH. There is the possibility of re-clustering, which leads to extra energy consumption during cluster creation and the CH selection process.

The study of authors [70] is based on combining k-means and Gaussian elimination methods for minimizing the energy consumption in wireless sensor networks (WSNs) and prolonging the network operation time.

In the study of the authors [71] presented a modified k-means clustering algorithm that takes into account two important factors: the distance between CHs and their member nodes and the remaining energy levels of the nodes. The objective was to reduce overall energy consumption and maximize network lifetime.

The work of [72] found optimal paths in a mobile ad-hoc network (MANET) using a new K-means clustering algorithm. The author tried to solve the traditional clustering limitations, such as permanent CH, fixed cluster members, and fixed networks. This approach selected an optimal route from the source to the destination node and ensured the packet reached the destination node. The clusters and CHs are dynamically changed.

The study of [73] authors is based on combining fuzzy c-means clustering and particle swarm optimization (FCM-PSO) methods that reduce energy consumption and minimize network disconnects. This approach used communication constraints and membership probability during CHs and cluster node selection.

The work of [74] is based on cluster formation and selection of stable CH in WSN. The cluster formation process used a modified K-means algorithm with a different centroids selection method. In the centroids selection process, the geographic area of the network and the spatial distribution of nodes are considered. The selection of CH is based on a weighted multi-criteria acceptability formula that considers multiple criteria such as energy consumption, mobility, node degree, and packet drop ratio. The weighted approach ensures a balanced and efficient distribution of CHs. The main objective of this work is to increase the performance and reliability of the IoT-based WSN. There are route maintenance problems, and extra energy nodes are wasted.

The authors of [46] presented a proactive MANET routing protocol that relies on nodes' energy levels and movement patterns. The author combined three techniques, K-means clustering, AODV, and Ant Colony Optimization (ACO) in the presented work. In the K-means clustering, the node energy consumption level is stored, and this information is used for AODV routing, which ACO further enhances to optimize the routing decision. This protocol aims to improve energy efficiency per node and consequently increase the overall energy performance of MANETs. Route Reconstruction in case of CH failure. The wastage of extra energy nodes problem exists.

The work of [75] is based on a modified K-means algorithm (Modified K-Means++) with improved LEACH called MKPP-LEACH. The MKPP-LEACH incorporates the modified K-Means++ algorithm with the original LEACH [69], which takes into account three main factors: the furthest distance between SN and BS in the selection of centroids, the distance as an additional parameter in determining the cluster center, residual energy when selecting CHs for overall protocol. The author aims to minimize the energy consumption in the CHs selection and cluster creation process.

Haq et al. [76] presented a cluster-based energy harvesting-aware routing protocol, which addresses the problem of energy efficiency and communication reliability. The author describes three phases of the presented solution: deployment phase, initialization phase, and CH formation phase. In the deployment phase, the BS broadcasts a message to wake all the nodes. In the initialization phase, two packets, hello and reply, are used to collect the necessary information. In the CH formation phase, three messages are used for inter-cluster and intra-cluster communication. The drawback of this approach is more message exchange between inter-cluster and intra-cluster communication of nodes.

The work of [77] proposes a novel routing protocol, LPLL-LEACH, addressing energy imbalance and extended packet forwarding time in low-energy adaptive clustering hierarchy (LEACH). LPLL-LEACH optimizes energy usage by calculating the optimal number of CHs and redefining CH election thresholds based on multiple factors. Ordinary nodes select clusters using a cost function, and a forwarding function determines the optimal next hop CH for data transmission. Ordinary nodes are allowed direct communication with the base station (BS). LPLL-LEACH employs a hybrid CSMA-TDMA mechanism to minimize latency, enhance data transmission efficiency and reduce time delays.

The study of [78] addresses the challenge of load balancing and optimal CH selection with minimal energy consumption. The proposed approach utilizes an unsupervised machine learning algorithm, specifically the k-means algorithm, to form clusters. Additionally, a fuzzy-based approach is employed for CH selection. Simulation results demonstrate the effectiveness of the proposed method, showcasing improvements in energy usage and minimizing the delay in identifying CHs.

The work of [79] introduces the Energy-Aware Cluster-based Routing (EACR-LEACH) protocol for Wireless Sensor Networks (WSN) in the context of the Internet of Things (IoT). An essential aspect of clustering protocols in WSN-based IoT is the selection of the CH. EACR-LEACH addresses this by employing routing metrics, specifically Residual Energy (RER), Number of Neighbors (NoN), Distance between Sensor Node and Sink (Distance), and Number of Times Node Acts as CH (NTNACH), to determine the most suitable CH.

The paper of [80] proposes a hybrid clustering method, KPSO, integrating K-Means clustering and Particle Swarm Optimization (PSO) to enhance Wireless Sensor Networks (WSNs) performance. The effectiveness of KPSO is compared with traditional techniques, including Mod-LEACH and K-means clustering.

Addressing the challenge of limited sensor energy in Wireless Sensor Networks (WSN), This [81] study focuses on optimizing the data transmission path through routing. The commonly used Low Energy Adaptive Clustering Hierarchy (LEACH) protocol minimizes energy consumption by clustering nodes. However, it faces energy issues with increasing data transmission due to random clustering, which causes node distribution imbalance. The proposed enhancement, LEACH-KMe, integrates the K-Means algorithm, and simulations show it surpasses conventional LEACH in achieving a more even node distribution, lower energy consumption, fewer dead nodes, and increased numbers of alive nodes and residual energy.

The work of [82] presents a dynamic K-means clustering algorithm for wireless sensor networks, focusing on energy efficiency. It adapts cluster numbers based on active nodes, selects CHs using fuzzy inference, and utilizes machine learning to reduce transmitted data for optimized energy use. Simulation results highlight DKFM's superior performance in data reception, active nodes, and energy depletion across different network densities. The algorithm effectively extends the network lifetime, showcasing its robustness in diverse scenarios.

The work [83] addresses the challenge of improving network lifetime and throughput and reducing energy consumption in wireless sensor networks. It proposes a solution, KM-MWOA, integrating K-means clustering to organize sensor nodes and a modified whale optimization algorithm for efficient packet transmission. K-means clustering optimizes data transmission by grouping nodes with a single CH, while MWOA selects energy-efficient and least-delayed paths between CH and the base station. This approach minimizes intra-cluster communication, enhancing energy efficiency and overall network performance.

2.7 Research Gaps

In the literature review, different types of problems arise. Some problems are related to each other, such as energy consumption and routing [48], energy harvesting and routing [35, 39], battery charging [49, 60], and energy management and routing [6]. Some problems are solved without routing, such as the placement of chargers [38, 48, 49]. In the bellow table below, some problems are identified in this research.

Table 2.1: Analysis of Related Studies.

S.No	Literature	Approach	Limitations
1	M. Nguyen et al. [26], 2018	The optimal link selection by considering distance, battery levels	It initiates a new route creation procedure in case of route failure. Moreover, there is a possibility of long routes existing.
2	Li et al. [39], 2018	The optimal link selection by Channel capacity and energy level	The traversing of extra nodes problem and how to tackle joining new nodes.
3	Bozorgi et al. [20], 2017	Energy harvesting clustering by selecting CH with a high energy level and high energy harvesting rate	Used route requests repeatedly to establish a route between nodes in case of link/node failure. Also, data sending is done randomly, not at a specific location, traversing all nodes and ultimately causing extra energy wastage.
5	Tomar et al. [51], 2020	Presented an optimal placement of charger strategy to charge the nodes	The author used next to charge paradigm to charge the nodes by their request, causing a problem such as more requests and more charging delays.
6	Ding et al. [52], 2020	Solve the OPC problem from two different aspects, first to develop a strategy of charger placement to minimize the deployment cast, and second, to maximize the overall charging levels of the network.	do not consider the distance between the farthest node and the charger, which can harvest less energy than the nearest node.

Table 2.1 – continued from previous page

S.NO	Author/Year	Approach	Limitations
7	Tang et al. [18], 2018	Solve the OPC problem by mobile charger moving in the shortest path and select the link of a node with high energy, estimated time to replenish energy, and energy consumption rate to forward the data	The charging time degrades the performance of the routing process. Link/device failure (topology changes) not considered.
8	Zhilin et al. [41], 2020	Moving charger is used to charge the critical in terms of energy nodes and TOPSIS technique for link selection	One of the main problems in this paper is how to deal with the situation when more nodes reach a critical situation. Also, network topology maintenance is not considered.
9	Khan et al. [84], 2018	Presented an energy harvesting-aware routing protocol for IoT-based wireless body area network (WBAN).	The optimal link selection by considering maximum residual energy, shortest path, total energy (TE), and hop count (HC).
10	Ilyas et al. [67], 2020	Energy harvesting Clustering	More message transmission in initialization phase,Inter-cluster and intra-cluster
11	Haq et al. [76], 2020	Presented cluster-based energy harvesting aware routing protocol	More message transmission in the initialization phase, Inter-cluster and intra-cluster communication.
12	Mahboubet al. [45], 2017	Presented modified K-means cluster-based routing protocol	There is the possibility of re-clustering, which leads to extra energy consumption during cluster creation and the CH selection process.

Table 2.1 – continued from previous page

S.NO	Author/Year	Approach	Limitations
13	Jiang et al. [53], 2016	The article proposed optimal charger placement strategy.	The main issue in this scheme is that the nodes degrade the EH process as the charger height increases, So we still need to overcome the farthest-nearest charger placement problem. It could be better for dense networks.
14	Gupta et al. [74], 2021	The author presented a modified K-means algorithm. Centroids are selected through node position, and CH is selected through energy consumption, mobility, node degree, and packet drop ratio.	Route maintenance and wastage of extra energy nodes problems exist.
15	Kumar et al. [46], 2019	The author presented a modified K-means combined with AODV, and Ant Colony Optimization (ACO) techniques.	Route Reconstruction in case of CH failure. The problem of wastage of extra energy nodes exists.
16	Mukti et al. [75], 2022	The author presented a modified K-means combined with LEACH	There is the possibility of re-clustering, which leads to extra energy consumption during cluster creation and the CH selection process.
17	Joseph et al. [68], 2023	The author presented a modified K-means algorithm called Mkmean with firefly algorithm (FFA) for optimal link selection.	This work does not consider link failures, and as a result, the approach leads to a minimum Packet Delivery Ratio (PDR) and throughput compared to the work presented in Chapter 6

2.8 Synthesise of Literature

This literature synthesis integrates findings from twelve recent studies on improving energy efficiency in Wireless Sensor Networks (WSNs). The reviewed studies encompass various strategies, including energy harvesting technologies, efficient charger deployment, adaptive routing algorithms, and optimized clustering and routing protocols. By examining these approaches, this synthesis aims to identify key themes, patterns, and relationships that contribute to understanding how energy efficiency can be achieved and sustained in WSNs.

The synthesis is organized into three main themes: Energy Harvesting and Charger Deployment, Routing Algorithms and Energy Efficiency, and Network Performance and IoT Applications. Each theme highlights significant advancements and insights derived from the collective research, providing a comprehensive overview of this field's current state of knowledge. This structured approach underscores the importance of multifaceted solutions for enhancing energy efficiency in WSNs and sets the stage for future research and development efforts. The themes discussed are as follows:

2.8.1 Theme 1: Energy Harvesting and Charger Deployment

Energy Harvesting Technology Studies consistently show that energy harvesting technology significantly improves the lifetime of WSNs (J.-R. Jiang et al., 2016; M. Khelifi et al., 2021). Energy harvesting enables WSNs to harness energy from their surroundings, reducing reliance on battery power and enhancing network sustainability. For instance, solar energy harvesting has been successfully integrated into WSNs to improve network performance and reduce maintenance costs. The integration of energy harvesting technology has been shown to improve network performance, reduce maintenance costs, and enable the deployment of WSNs in a wider range of applications.

Efficient Charger Deployment: Deployment strategies, such as particle swarm optimization (PSO), enhance network sustainability by optimizing the placement and efficiency of wireless chargers (J.-R. Jiang et al., 2021). Efficient charger deployment ensures energy is transferred efficiently, reducing energy waste and enhancing network performance. For example, optimizing charger placement has been shown to reduce energy consumption by up to 30%. The development of advanced deployment strategies has been instrumental in improving the overall energy efficiency of WSNs.

Mobile Directional Charging: Optimizing charging efficiency and maintaining perpetual sensor network operation through mobile directional charging enhances energy efficiency (X. Xu et al., 2019). Mobile directional charging enables wireless chargers to move within the network, optimizing energy transfer and reducing energy waste. This approach has been shown to improve network performance, enhance energy efficiency, and reduce maintenance costs. For instance, mobile directional charging has improved network lifetime by up to 50% .

2.8.2 Theme 2: Routing Algorithms and Energy Efficiency

Distributed Routing Algorithms: Research has shown that distributed energy-harvesting-aware routing algorithms are highly effective in adapting to dynamic network conditions and optimizing energy efficiency, leading to improved network performance and reduced energy consumption (T. D. Nguyen et al., 2018).

Learning Automata-Based Approaches: Learning automata-based approaches have been demonstrated to improve routing decisions in discrete energy harvesting mobile WSNs, resulting in better energy utilization and enhanced network reliability (S. Hao et al., 2019).

Physarum-Inspired Routing Protocols: Physarum-inspired routing protocols have been developed to enhance energy efficiency in energy harvesting WSNs by mimicking the foraging behavior of the slime mold Physarum polycephalum, resulting in improved network performance and reduced energy consumption (W. Tang et al., 2018).

2.8.3 Theme 3: Network Performance and IoT Applications

IoT Application Requirements: Studies have highlighted the importance of considering the specific requirements of IoT applications when designing routing protocols to ensure reliable performance and efficient energy use (K. P. Yallappa and A. A. Naik, 2022).

Energy Harvesting Protocols: Energy harvesting protocols such as EH-GPSR (Energy Harvesting Geographic Perimeter Stateless Routing) have been developed to enhance network lifetime and stability, ensuring reliable execution of IoT applications and improving overall network performance (M. Khelifi et al., 2021).

Clustering Algorithms Clustering algorithms like modified k-means and the AODV (Ad hoc On-Demand Distance Vector) routing protocol have been shown to improve network performance and energy efficiency in WSNs, enabling the deployment of IoT applications (A. Gupta et al., 2021; B. A. Kumar et al., 2019).

Modified k-Means Firefly Optimization: The modified k-means firefly optimization technique has been developed to enhance network lifetime and energy efficiency in WSNs, improving performance and reliability for IoT applications (A. J. Joseph et al., 2023).

Chapter 3

Methodology

This thesis delves into several research challenges related to the given research questions. The first question focuses on finding the optimal charger placement to address the dilemma of charging nodes near and far from the charger. Additionally, it aims to formulate an efficient charging tour to identify the best charger positions and uncover charging areas that remain within the charger's line of sight as it moves. The second question aims to develop a location-based routing algorithm aware of energy harvesting, guiding nodes toward their destination while considering their energy needs. Lastly, the third question seeks to create an energy-aware location-based clustering routing algorithm to choose the closest CH to the destination node's location.

The thesis encompasses three primary research strategies. First, it leverages practical knowledge gained from real-world projects to assess the capabilities of modern technologies and their tangible benefits. These projects, discussed in Chapter 4, involve real test beds for research purposes. Next, it utilizes a flat network approach to devise an energy-efficient routing protocol for IoT Wireless Sensor Networks (WSNs). This approach tackles challenges such as improving packet delivery, reducing energy consumption, optimizing throughput, and minimizing delays. Furthermore, the thesis adopts a cluster-based network approach, as explained in Chapter 6, to design an energy-aware routing protocol for IoT-based WSNs, focusing on enhancing packet delivery, minimizing energy usage, and optimizing throughput. Importantly, the challenges encountered during these projects underscore the limitations of existing methods and provide valuable insights for effectively shaping these methodologies.

3.1 System Model

This section provides a concise and general overview of the model utilized in this research from various perspectives. The system model can be modeled as a graph G = (V, E), where V represents the rechargeable nodes, and E represents the links between two nodes. The notation for the wireless link between nodes i and $j \in V$ is denoted as e(i, j). Each sensor node can sense the given area and upload the sensed data to the sink node. Additionally, each node can recharge from a renewable energy source. Many energy harvesting techniques, such as solar, thermal, and flow-based, have been introduced. However, the RF-based energy harvesting technique has garnered tremendous attention from researchers due to its easy availability (from TV, radio, and Wireless frequencies). The nodes are powered by energy-harvesting circuits, which harvest energy regularly. There are three components of the energy harvesting model: the energy source (RF, solar, thermal), the energy harvesting hardware (*Powercast* TX91501 *Powercast* Transmitter, P2110 receiver), and the energy storage devices. [8, 36]. The energy harvesting hardware is responsible for transforming energy into electricity and storing it in the storage device (batteries, capacitors).

3.1.1 Real test Beds Model

As discussed above in the research question, the system model for The thesis used a real test-bed scheme to implement the first proposed schemes. In this tests-beds scheme, the thesis used Powercast Technology Company (Pittsburgh-PA-USA), which provided devices for this research and practical test-beds. The devices and their specification are tabulated as follows:

The designed testbed model uses the P2110-EVAL-01 energy harvesting development kit, which contains components in the above table. A small toy vehicle is used for the transmitter to make it mobile, and it starts working by blinking the blue light. Also, the toy is used to make the sensor mobile. After starting the TX 91501 transmitter, the antennas are connected to the evaluation board. After the evaluation board, the wireless sensor board was plugged into the evaluation board. Next, the hyper-terminal is installed on the laptop and connected to the access point to the laptop through a USB cable. After installation of the hyper-terminal emulator, it can be opened to start the step-by-step installation process. In the installation process, it is named "Powercast," and click the "ok" button. Another dialogue required region, area code, and connection port. Enter Pakistan, 46000, and COM16, and click the "OK" button. Another screen opened basic information such as bits rate, parity, and flow control. The bit rate can only be set to 19200; click the "ok" button. A blank screen appeared, but after clicking switch PB1 on the access point board, the emulator started

Table 3.1: Powercast Item Descriptions

Item Name	Item ID	Description
P2110 Evaluation Board	P2110-EVB	Evaluation board with SMA connector for antennas and a 10-pin connector for the Wireless Sensor Board.
Dipole Antenna		915 MHz omnidirectional antenna with 360-degree reception and 1dBi gain.
Patch Antenna		915 MHz directional antenna with 120-degree reception and 6.1 dBi gain.
Power and Data Transmitter	TX 91501-3W-ID	915 MHz transmitter sending power and data signals with a unique ID.
Wireless Sensor Board	WSN-EVAL-01	Measures temperature, humidity, light, and external input. Captures transmitter ID.
Access Point	WSN-AP-01	Acts as an access point, receiving data from the wireless sensor board.
PICkit™ 4 programmer/debugger	PG164130	USB for programming and updating code on the wireless sensor board.

working and showed the built-in message of the Powercast Company. The points on the ground are made in circular form with the help of scotch tape. The circular points are away from one another at a distance of one foot and are identified by numbers. So, two circular points are drawn one foot away from each other. The circular shape is used to move the charger, and the circular points are used to get data from these specific points. The charger is equipped with a vehicle toy and uses a small wire to make it movable. The charger moves in an anti-clock direction and is fitted on the toy vehicle so it cannot lose the 60-degree direction. The presented observation is based on antennas, patches, and dipoles.

3.1.2 Flat Network Model

The thesis used extensive simulation to implement the second proposed scheme. The simulation was performed using a 100×100m area as shown in Fig. 5.1 in the NS3 environment. For tracing energy consumption during simulations, a `BasicEnergySource` object with an initial energy of 1.2 Joules is installed on each node, and the remaining energy is monitored throughout the simulation. Additionally, a `WifiRadioEnergyModel` was installed on each node to examine WiFi radio energy consumption. WiFi radios consume energy during packet transmission, so the transmit current, receive current, and idle current are set to 2 mA, two mA, and 0.27 mA, respectively. A `BasicEnergyHarvester` object used for energy harvesting was also installed with parameters `harvestingUpdateInterval` set to 1 and `HarvestablePower` ranging from 0.0 to 0.1. Table 6.1 represents the detailed simulation parameters. In the designed simulation scenarios, only one sink and multiple nodes exist.

3.1.3 Hierarchical Model

The thesis utilized extensive simulation to implement the third proposed scheme. Simulations were conducted using a 100 × 100 m and a 900 × 700 m square area, as illustrated in Fig. 5.1. The 100 × 100 m area simulation was employed to validate the designed approach across various distance parameters, while the 900 × 700 m area simulation was utilized for comparison with other works. Energy-related aspects were closely monitored during the simulations. Each node had a `BasicEnergySource` component with an initial energy of 1.2 Joules, allowing the observation of energy consumption over time. Additionally, each node was equipped with a `WifiRadioEnergyModel` to analyze energy usage during WiFi radio operations. This model accounted for energy consumption during packet transmission, with specified current values for transmission, reception, and idle states. Furthermore, an `BasicEnergyHarvester` was integrated into the nodes for energy harvesting purposes, with parameters like update interval and harvestable power range set accordingly.

3.2 Performance Metrics

In this study, several performance metrics have been defined to evaluate the effectiveness of the simulation scenarios. These metrics help us assess the network's performance and efficiency under different conditions.

3.2.1 Received Power

This metric is crucial in evaluating the effectiveness of wireless systems, especially in practical testing environments. It pertains to the distinct methods employed in dipole and patch antennas to capture incoming signals and transform them into direct current (DC). Additionally, the separation between the charger and nodes is a critical factor. In wireless sensor networks (WSNs), achieving optimal energy efficiency is fundamental when transmitting data from a source node to a destination node.

3.2.2 Energy Consumption

Energy consumption is a crucial metric that measures the total energy utilized by all nodes involved in data delivery during the simulation. It reflects the network's energy usage patterns and helps us understand energy utilization efficiency.

3.2.3 Packet Loss Ratio

The Packet Loss Ratio (PLR) quantifies the proportion of lost packets compared to the total number of packets sent during the simulation. It provides insights into the network's reliability and robustness in handling data transmission.

3.2.4 Throughput

Throughput measures the amount of data that can be successfully transmitted or processed over the network within a specific time frame. It indicates the data transmission capacity of the network and is calculated using the following formula:

$$Throughput = \frac{\sum rxBytes \times 8}{TotalTime \times 1000000.0} \tag{3.1}$$

3.2.5 Packet Latency Time

Packet Latency Time refers to the time a packet travels from the source node to the destination node. It helps us understand the delay experienced hy data packets during transmission.

The formula for calculating Packet Latency Time is as follows:

$$Delay = \left(\frac{\sum Delaysum}{\sum txPacket} \right) \tag{3.2}$$

The unit of measurement for the Packet Latency Time is milliseconds (ms).

In the context of varying distance parameters, the optimal spacing between nodes plays a crucial role in the efficiency of communication and data transfer within routing protocols. Maintaining the right node distance ensures smoother information flow, leading to enhanced routing protocol performance and efficient energy harvesting. When node distances exceed recommended thresholds, routing protocol efficiency diminishes, affecting multiple performance metrics.

The impact of increased node distances extends beyond a single performance metric, influencing aspects like data transmission speed, latency reduction, and network responsiveness. This section explores different distance parameters and analyzes how they affect performance metrics.

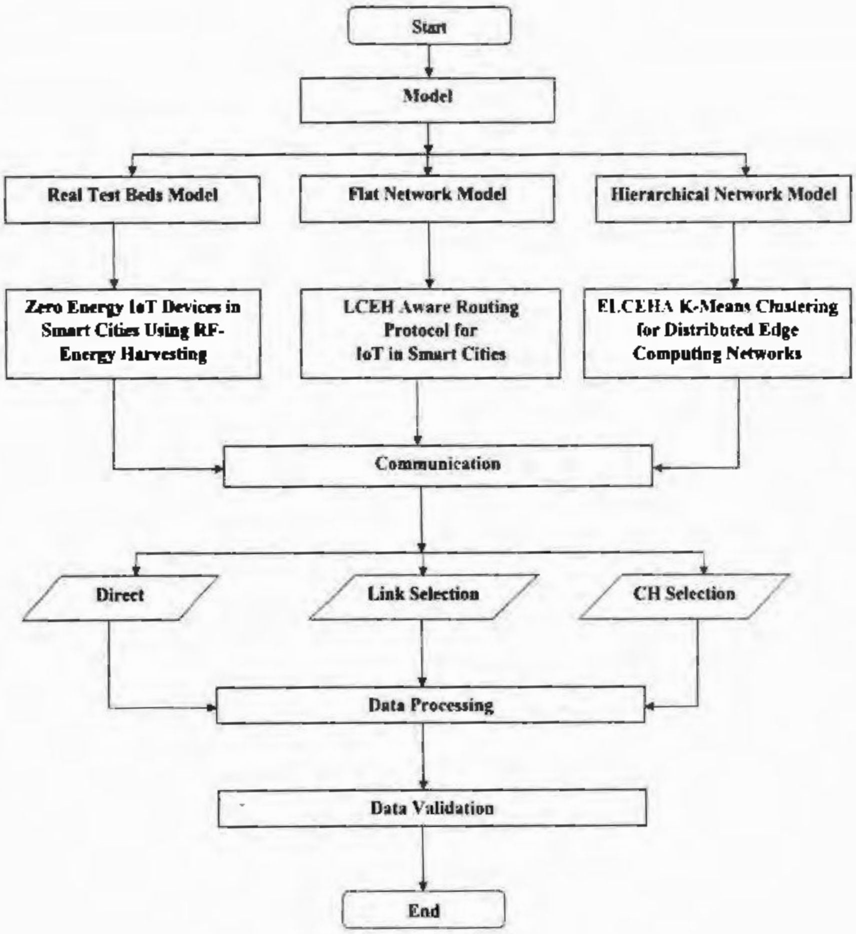

Figure 3.1: System Model

Chapter 4

Zero Energy IoT Devices in Smart Cities Using RF Energy Harvesting

The IoT-based wireless sensor network comprises physical devices deployed within a designated area of interest. According to recent research, 2025 witnessed an astonishing proliferation of more than 75 billion IoT devices, encompassing sensors, actuators, wireless devices, smart meters, lighting systems, and more, distributed globally [85]. These devices found utility across various domains, including but not limited to smart health, smart grids, smart cities, and smart environments [47, 86].

In the context of smart environments, WSNs play a pivotal role by gathering data about various physical conditions like temperature, humidity, light levels, and acceleration, among others. This collected data is transmitted collaboratively through the WSN to a central data station for further analysis and inspection. The evolution of semiconductor technology has captivated the interest of researchers and technology companies, leading to the creation of user-friendly, energy-efficient, and cost-effective devices tailored to the requirements of IoT-based WSNs. One of the primary drawbacks associated with IoT-based WSN devices revolves around their power supply, which significantly impacts network performance. The frequent battery replacement required in harsh environments poses a challenge and contributes to heightened operational expenses [60, 87]. In response to this challenge, researchers have sought solutions and introduced the concept of energy harvesting techniques from renewable sources such as solar, wind, thermal, and RF [87]. The RF energy harvesting technique has garnered attention from emerging technology platforms, including Google, WISP, PoWiFi, Powercast, and EnOcean STM 300 [87]. This technique is favored due to its environmentally friendly, sustainable, and readily available nature in a continuous form and its introduction of WCDs. WCDs offer a viable option for significantly extending the lifespan of IoT-based WSNs, effectively moving towards perpetual operation.

In previous studies, data collection and energy transfer were achieved through wireless power communication networking (WPCN) and simultaneous wireless information and power transfer (SWIPT). WPCN employs the uplink for wireless information transfer (WIT) and the downlink for wireless energy transfer (WET) [36]. On the other hand, SWIPT assumes simultaneous data collection and energy transfer operation. However, notable commercial wireless charging technology platforms, such as Powercast [88] and WISP [89], diverge from the WPCN or SWIPT concepts. These platforms utilize capacitors for energy buffering due to their environmentally friendly nature, longer lifespans, higher recharge cycles, broader voltage and current ranges, cost-effectiveness [90], and superior performance at low temperatures compared to batteries [86]. The Powercast platform employs a recharge-then-transmit procedure, temporarily suspending the sensor node's functionality and energy harvesting (recharging) during this phase. The sensor node remains idle until it accumulates the required energy, at which point it resumes normal operations. This alternating between idle and active states introduces dynamism to the network topology, leading to challenges including dynamic topology, charging and communication latency, and the farthest-nearest node problem.

The farthest-nearest node problem is a crucial issue in the context of charging IoT devices. This problem implies that nodes closer to the charger can harvest more energy than nodes farther away. As the charger moves from nearest to farthest nodes, it consequently alters the transmission speed of sensed data from rapid to sluggish. These factors result in the sensor node entering an idle state. Once the necessary time has elapsed, the sensor node becomes active and resumes regular operations. The alternating states of idleness and activity of the sensor nodes contribute to the dynamic nature of the network topology. Consequently, this dynamism raises various issues, including dynamic topology shifts, charging latency, communication latency, and the farthest-nearest node dilemma. These challenges have prompted the quest for an optimal charging strategy that ensures the charger's optimal placement.

As shown in previously conducted practical experiments, nodes located near the charger show faster energy harvesting, leading to quick transmission of sensed data. Conversely, nodes farther away from the charger experience prolonged data transmission times. Hence, the distance emerges as a critical factor influencing the charging process.

The primary objective of this report is to formulate a strategy for the strategic positioning of chargers and sensors, ensuring uninterrupted energy supply to the sensor boards while averting the idle state.

While previous methodologies have demonstrated the potential to prolong the lifespan of zero-powered energy devices, the main focus remains on scenarios involving a single charger and multiple sensor boards. This focus stems from the constraint of possessing only one Powercast RF energy transmitter and two sensor boards. This work aims to address and overcome the following challenges:

1. The Powercast energy transmitter operates at a central frequency of 815 MHz, emitting power signals with 3W EIRP. The transmitter's antenna boasts a 60° horizontal and 60° vertical beam pattern. Consequently, sensor placement is constrained along this direction, as deviating from it would hinder the charging and data transmission process, potentially causing the sensor to enter the idle state.

2. The evaluation board captures this transmitted power via patch and dipole antennas, converting it into DC through a capacitor-regulated voltage output of up to 5.25 V. The output current can reach 50 mA, facilitating the charging of a 50 mF capacitor. The patch and dipole antennas possess gain powers of 6.1 dBi and one dBi, respectively. The patch antenna's beam pattern spans 122° horizontally and 68° vertically, whereas the dipole antenna has a 360° beam pattern. Consequently, the placement of the patch antenna is constrained to 122° horizontally and 68° vertically to ensure power reception. Deviating from these angles would hinder power reception, potentially leading the sensor to an idle state.

3. The distance between the charger and sensor plays a pivotal role, with received signal strength inversely proportional to the square of the transmission distance. As a result, a distance constraint is imposed to maintain proximity between the charger and sensor.

Researchers have explored diverse techniques to ensure an uninterrupted energy supply to mitigate the issue of devices entering the idle state. These techniques include single/multiple mobile charger placements, single/multiple fixed charger placements, set covers, and probabilistic charger placements. However, these approaches have challenges, including cost and charging time considerations. The proposed study focuses on a single mobile charger and fixed sensors scenario. Particular emphasis will be on:

1. Investigating the impact of a moving charger on data reception from sensors.

2. Evaluating the speed of the mobile charger.
3. Analyzing the directional aspect (theta) of the mobile charger.

4.1 System Model

In this thesis, The Powercast Technology Company provided devices are employed for both research and practical testbeds. The Powercast energy harvesting model comprises four essential components: an Energy Transmitter, Sensor boards, an evaluation board, and antennas. Powercast Technology Company has pioneered RF-based energy harvesting WCDs designed to replenish energy for sensor devices. Since 2003, Powercast Technology Company has been at the forefront of delivering energy harvesting solutions that power IoT devices. Their product range includes a temperature scanning system, wireless charging grip for Nintendo Joy-Con controllers, PowerSpot technology, UHF RFID Retail Price Tags, and development kits. These development kits serve a dual purpose: aiding research endeavors and powering IoT devices. The kits contain evaluation boards (P1110, P2110), antennas, RF field-detecting light sticks, and sensors. Specifically, the P2110-EVAL-01 development kit has been selected for this research work, tailored for use with highly low-power IoT devices.

The main research focus centers on examining data received from dipole and patch antennas. The main objective is to elucidate the relationship between various factors, including distance, Received Signal Strength Indicator (RSSI), capacitor recharge time, the impact of angle on packet transmission time and energy harvesting, and packet routing to the access point. The subsequent devices constitute the core of designed testbeds:

1. RF Transmitter: The RF Powercast transmitter emits data and power as RF signals at a unique ID and 915 MHz frequency. The output power (Pt) is 3 W EIRP with a beam pattern of 60° in vertical polarization, operating within the frequency range of 915 MHz. The TX91501B should be mounted eight feet above the floor level for permanent installations. The transmitter provided by Powercast Company is enclosed in a black box and comes with fixed output power and settings without the possibility of user modifications.
2. Wireless Sensor Board: This board can measure and transmit light, temperature, humidity data, and external inputs. To obtain energy from the evaluation board for data transmission, the sensor board is connected to the evaluation board through a 10-pin connector. The ID SELECT switches can set the sensor nodes' IDs from 0 to 7. Additionally, the sensor board

features a PICkit connector that facilitates connection with the PICkit programmer.

3. P2110 Evaluation Board: The evaluation board is responsible for energy harvesting. It incorporates energy storage functionality through JP1 (C3, C4, C5 jumpers), a 10-pin connector (J2) for connecting the wireless sensor board, a rectifier to convert RF energy into DC, an SMA connector (J1) for antenna or RF input, and a visual LED indicator. The harvested energy is transferred from the evaluation board to the sensor board.

4. Powercast Antennas: The Powercast development kit includes two types of antennas: Dipole and Patch. These antennas connect to the evaluation board through an SMA connector for the antenna (J1). The Dipole antenna features an RF connector at the bottom and offers flat, omnidirectional, and vertically polarized characteristics. It has a gain power of 1.0 dBi with a 360° reception beam pattern. In contrast, the Patch antenna is two-layered, directional, and vertically polarized, providing a gain power of 6.1 dBi and a beam pattern for 120° reception.

5. Vehicle for Transmitter: The energy transmitter has a mobile vehicle to charge the devices in a circular path.

The Powercast wireless charging and sensing platform devices are utilized in this testbed. The energy recharging model often employs Friis' free space equation 4.1.

$$P_r = G_t G_r \Big(\frac{\lambda}{4\pi(d+\beta)}\Big)^2 P_t \tag{4.1}$$

Where P_t is the transmitted power, P_r is the received power, $G_t$is the transmitter antenna gain power, G_r is the receiver antenna received power, d is the T-R-Separation distance in meters, and λ is the wavelength in meters. Gain power is based on the aperture of the antenna.

He et al. [91] improve this equation by considering that the polarization loss in power transfer and signal power should be rectified and converted to electrical energy before it can be used.

$$P_r = \frac{G_t G_r \eta}{L_p}\Big(\frac{\lambda}{4\pi(d+\beta)}\Big)^2 P_t \tag{4.2}$$

L_p represents polarization loss,η is rectifier efficiency, and β is a parameter to adjust the Friis free space equation for short-distance transmission. Formally, the proposed model can be described as letting M_k be the set of chargers, and v_k be the set of nodes, then the charging model based on equation 4.2 as follows:

$$P_r = \frac{\alpha P_t(M_k)}{(\| v_k - M_k \| + \beta)^2} \tag{4.3}$$

where $\| v_k - M_k \|$ represent the distance between node v_k and charger M_k, P_t represent the transmission power of charger M_k, $\alpha = \frac{G_t G_r \eta}{L_p}(\frac{\lambda}{4\pi})^2$.

The charger and devices have directional antennas for the directional charging model. The angle of the charger and devices will be kept in mind. Let $\overleftarrow{\varnothing_{mk}}$ be the directional vector of the charger (i.e. charger angle Θ_{mk}) and $\overleftarrow{\phi_{mk}}$ be the directional vector of the device (device angle Θ_{vk}) then equation 4.3 can be written for the directional model as follows:

$$P_r(M_k, v_k) = \frac{\alpha P_t(M_k)}{(\| v_k - M_k \| + \beta)^2} \begin{cases} \| v_k - M_k \| \leq D \\ \frac{\overrightarrow{\|v_k - M_k\|} \cdot \overrightarrow{\phi_{mk}}}{\|v_k - M_k\|} \geq cos(\frac{\Theta_{vk}}{2}) \\ \frac{\overrightarrow{\|M_k - v_k\|} \cdot \overrightarrow{\phi_{mk}}}{\|v_k - M_k\|} \geq cos(\frac{\Theta_{mk}}{2}) \end{cases} \tag{4.4}$$

Let M_k^r be the maximum transmitter range of energy transmitter and v_k^r be the maximum transmission range of the device. Since the energy transmitter has a 0 to sixty degree angle, the dipole has 0 to 360, and the patch has a 0° to 120° range, then Eq. 4.4 can be written for the dipole antenna as follows:

$$P_r = \frac{\alpha P_t(M_k)}{(\| v_k - M_k \| + \beta)^2} \begin{cases} \| v_k - M_k\| \leq M_k^r \\ \frac{\overrightarrow{\|v_k - M_k\|} \cdot \overrightarrow{\phi_{mk}}}{\|v_k - M_k\|} \geq cos(\frac{\Theta_{vk}}{2}) \text{where } 0 \leq \Theta_{vk} \leq 2\pi \\ \frac{\overrightarrow{\|M_k - v_k\|} \cdot \overrightarrow{\phi_{mk}}}{\|v_k - M_k\|} \geq cos(\frac{\Theta_{mk}}{2}) \text{where } 0^\circ \leq \Theta_{mk} \leq 60^\circ \end{cases} \tag{4.5}$$

Equation 4.4 can be written for the patch antenna as follows:

$$P_r(M_k, v_k) = \frac{\alpha P_t(M_k)}{(\| v_k - M_k \| + \beta)^2} \begin{cases} \| v_k - M_k \| \leq M_k^r \\ \frac{\overrightarrow{\|v_k - M_k\|} \cdot \overrightarrow{\phi_{mk}}}{\|v_k - M_k\|} \geq cos(\frac{\Theta_{vk}}{2}) \text{where } 0^\circ \leq \Theta_{vk} \leq 120^\circ \\ \frac{\overrightarrow{\|M_k - v_k\|} \cdot \overrightarrow{\phi_{mk}}}{\|v_k - M_k\|} \geq cos(\frac{\Theta_{mk}}{2}) \text{where } 0^\circ \leq \Theta_{mk} \leq 60^\circ \end{cases} \tag{4.6}$$

The maximum transmission power received at nod v_k from charger M_k can be calculated as, from equation 4.3, the nearest-farthest problem can be calculated as:

$$P_r = \frac{\alpha P_t(M_k)}{(\| v_k - M_k \| + \beta)^2} if 0 \leq \| v_k - M_k \| \leq M_k^r \quad (4.7)$$

In the proposed model, the charger's position is changed to assess different distances from the energy transmitter while keeping the energy transmitter's position fixed. During the experiment, the received power and the time taken for incoming data at distances ranging from one to three meters in outdoor and indoor environments are examined.

4.2 Proposed Scheme

The Powercast P2110-EVAL-01 development kit is used for energy harvesting in the presented testbed model. Power Transmitter TX 91501-3W-ID (transmitter) transmits the power, P2110 Evaluation Board P2110-EVB (receiver) receives this power, Wireless Sensor Board WSN¬EVAL-01 plugin with P2110 Evaluation Board P2110-EVB sends the sensed data to access point, and hyper terminal is used to show the sensed data on computer/laptop screen. Transmitter TX 91501-3W-ID is responsible for transmitting the energy signal to P2110 Evaluation Board P2110-EVB. The evaluation board obtains the energy signal, converts it to DC, and recharges the supercapacitor. Then, the harvested energy is used for sending data by the wireless sensor board. In fixed chargers and devices, it degrades the sensing and communication process if the charger goes farthest from the evaluation board. So, a technique is needed to cover the farthest and nearest problem. To solve this problem, the energy transmitter is equipped with a moving toy to make it a mobile charger. The movement will occur to keep in mind predefined constraints, not going away from the maximum transmission range of the energy transmitter and not crossing a sixty degree area (beam pattern). The sixty degree area means the beam pattern of the transmitter, which has sixty degree widths and sixty degree heights. For simplicity, sixty degree areas will be used. To fulfill these constraints, the proposed solution will be present. The solution is based on two sub-problems: optimal charging tour to find optimal positions for a charger and discovering the charging area or points that are under the eye of the charger from any point when the charger moves.

It is understood that the charger transmits energy in a fixed directional manner, covering a sixty degree angle. The main concern is establishing a consistent area comprising points that fall within the trajectory of energy transmission as the charger moves. Failing to achieve this would result in the charging device never receiving energy while the charger is in motion, rendering it ineffective.

To avert such a scenario, the main objective is to identify a fixed area or set of points for the charging device to receive energy from the moving charger continuously.

A specific region will be used to address this challenge where the charging device can obtain energy from the charger in all positions during its movement. Notably, two types of antennas will be utilized: a patch antenna and a dipole antenna, each possessing distinct receiving patterns. The dipole antenna offers omnidirectional reception with a 360° energy pattern, while the patch antenna's reception is directional, confined to a 120° energy pattern. For simplicity, a 360° coverage area for the dipole antenna is adopted, and a 120° coverage area for the patch antenna.

Incorporating Powercast's technology, the Friis equation is employed for energy calculations. To facilitate this, an online calculator is available, provided in the form of a ".xls" file [55], enabling us to ascertain the received energy. For instance, at a distance of 1 meter, the received energy is 8.11; at 2 meters, it reduces to 2.030, and so forth.

Currently, the conducted testbeds are based on two sensors and one charger, so fixed points are created for sensors when the charger is moving.

The Powercast transmitter emits energy directionally within a sixty degree area. The evaluation board receives this signal and converts it into DC power. If the orientation of the evaluation board aligns with the transmitter's direction, energy harvesting becomes attainable. Consequently, all processes stand at a standstill, resulting in an inactive scenario.

Furthermore, Powercast specifies a transmitter range of up to 80 feet [50]. This implies that the farthest node can be positioned at a maximum distance of 80 feet from the transmitter. Thus, the viable range spans from 0 to 80 feet. This situation gives rise to two distinct challenges for the energy transmitter: distance and range. If the distance exceeds 80 feet, the receiving antenna (device) cannot access energy. Similarly, if the evaluation board lies beyond the sixty degree coverage area, the receiving antenna cannot harvest energy.

A comprehensive solution is required to effectively address these issues and establish a network with near-perpetual energy availability.

4.3 Problem Identification

Powercast energy transmitters emit energy directionally within a sixty degree spread, while the dipole and patch antennae receive this energy across 360° and 120°, respectively. In prior experiments conducted by us, the charger was positioned statically and the sensing device dynamically. Distances ranging from one to five feet were utilized to assess energy harvesting and the data-sending process. Additionally, the experiments are conducted at distances of one to three meters. Notably, as the sensor device moved away from the charger, energy harvesting and subsequent data transmission declined. This phenomenon is termed the nearest-farthest charger problem and substantiates the principle that received signal strength is inversely proportional to the square of the transmission distance [92].

The subsequent issue pertains to Powercast devices. The energy transmitter's emissions are directional rather than omnidirectional. Moreover, the dipole antenna exhibits a 360° reception angle, whereas the patch antenna possesses a 120° reception angle. Consequently, finding a distance that optimally accommodates the efficient operation of all devices presents a challenge. For instance, were the charger omnidirectional, the notion of distance would be negligible, allowing for the proximity of charging devices to the charger.

Powercast evaluation board and charger devices rely on continuous energy supply due to their lack of onboard batteries. The previous experimental setup revealed that these energy-dependent devices require a consistent energy source for functionality. Any alteration in the energy transmitter's direction at any time would render the evaluation board inoperative.

Hence, a technique is needed to address the nearest-farthest problem effectively.

4.4 Proposed Solution

The P2110-EVAL-01 energy harvesting development kit in the testbed model comprises various components. A small vehicle toy is used for the transmitter to introduce mobility, indicated by the blinking blue light. This toy was also used to mobilize the sensor. Upon activating the TX 91501 transmitter, the antennas are connected to the evaluation board. Subsequently, the wireless sensor board is connected to the evaluation board. Further steps involved the installation of a hyper-terminal emulator on a laptop and securing the access point to the laptop via a USB cable. Following the emulator installation, a step-by-step setup process is initiated, naming it "Powercast" and proceeding with the specified region (Pakistan), area code (46000), and connection port (COM16). Additional settings included bit rate, parity, and flow control, with the bit rate set to 19200. After these configurations, the emulator displayed a blank screen, which appeared upon toggling switch PB1 on the access point board. This action triggered the display of Powercast

Company's built-in message.

Circular points were demarcated on the ground using scotch tape for data collection. These points were numbered and positioned one feet apart, facilitating testing. A charger mounted on a toy vehicle was maneuvered along the circular path in an anti-clockwise manner, ensuring it maintained the sixty degree direction. The observations in this work were based on both patch and dipole antennas. The experimental setup encompassed indoor real test beds to address the stated problems.

While these issues are not novel, researchers have endeavored to resolve them. A mobile charger offers a viable solution for device charging. However, specific problems and solutions of this work distinguish the presented approach from prior research. It is essential to differentiate between omnidirectional and directional phenomena. The relationship between chargers and charging devices determines their directional attributes. Existing solutions tend to tackle these challenges in a generalized context. However, the directional-directional phenomena are concerned, excluding the dipole antenna.

So, a technique tailored to directional devices that can effectively address the three problems above is needed. The proposed solution can be divided into two phases: the charger movement phase, aimed at identifying the optimal charging tour by determining the best positions for the charger, and the second phase, focusing on establishing the optimal charging/sensor/evaluation board points or areas.

When the charger is positioned at point one, the angle theta is sixty degrees, and the maximum transmission distance aligns with the Powercast 35903 specification of 80 feet [50]. The energy transmission follows a circular pattern, as depicted in Fig. 4.1, with points positioned at one-feet intervals. This arrangement results in uniformly spaced lines intersecting the circle.

Consider two straight lines intersecting each other, $a_1x + b_1y + c_1$ and $a_2x + b_2y + c_2$, the following equation is used:

$$P_{(x,y)} = \frac{b_1c_2 - b_2c_1}{a_1b_2 - a_2b_1}, \frac{c_1a_2 - c_2a_1}{a_1b_2 - a_2b_1} \tag{4.8}$$

After finding the intersection points, we can calculate the area enclosed by these points using the shoelace formula [93] with the following equation:

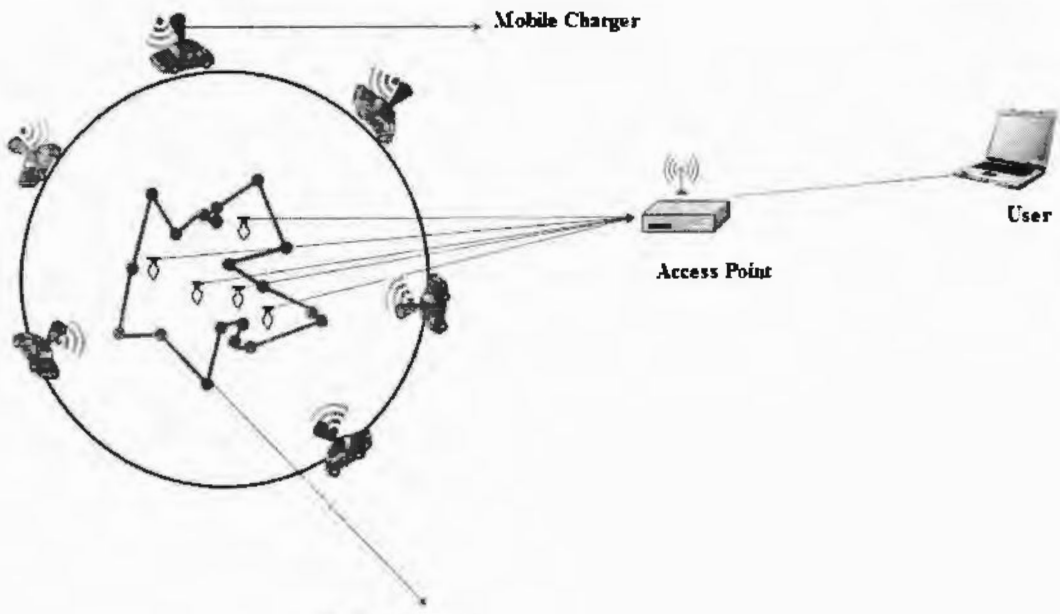

Figure 4.1: Circular Charger Model.

$$S_f = \frac{1}{2}\left|\sum_{i=1}^{n-1}(x_i y_{i+1} + x_n y_1) - \sum_{i=1}^{n-1}(x_{i+1} y_i + x_1 y_n)\right| \tag{4.9}$$

Where n is the number of vertices of the constructed points as per equation 4.8. For the first summation, x_i is the x-coordinate of the i-th vertex, y_{i+1} is the y-coordinate of the next vertex, x_n is the x-coordinate of the last vertex, and y_1 is the y-coordinate of the first vertex (1st vertex). For the second summation, x_{i+1} is the x-coordinate of the next vertex, y_i is the y-coordinate of the i-th vertex, x_1 is the x-coordinate of the first vertex, and y_n is the y-coordinate of the last vertex.

4.4.1 Optimal Charging Tour to Find Optimal Position for Single Charger

Fig. 4.1 illustrates the presented charger placement strategy, wherein the charger moves along a circular path, supplying energy to the evaluation board for scavenging. The movement of the charger is synchronized with the transmitter angle, ensuring that the charger's "eye" remains positioned optimally.

4.4.2 Optimal Points/Area for Sensor Devices

When the charger is located at point one, the angle theta measures sixty degrees, and the maximum transmission distance depends on the charger's ability to send signals, with Powercast 35903 offering an 80-feet range. As depicted in Fig. 4.1, the charger transmits energy in a circular pattern, with the points one feet apart. This arrangement results in uniformly spaced lines intersecting the circle.

Upon reaching point two, as the transmitter emits energy, it intersects the preceding lines at various points, as demonstrated in Fig. 4.2. The main objective is to identify these intersection points.

Suppose the lines intersect at points p_{s1} and p_{s2}. In this case, the location of these intersection points can be determined using intersection formulas [94]. By employing these formulas, one can ascertain the precise intersection points desired. The region between these intersection points is the optimal area, with the points representing optimal positions for deploying the charging devices. We can use the equation 4.9 to find the area of the constructed region.

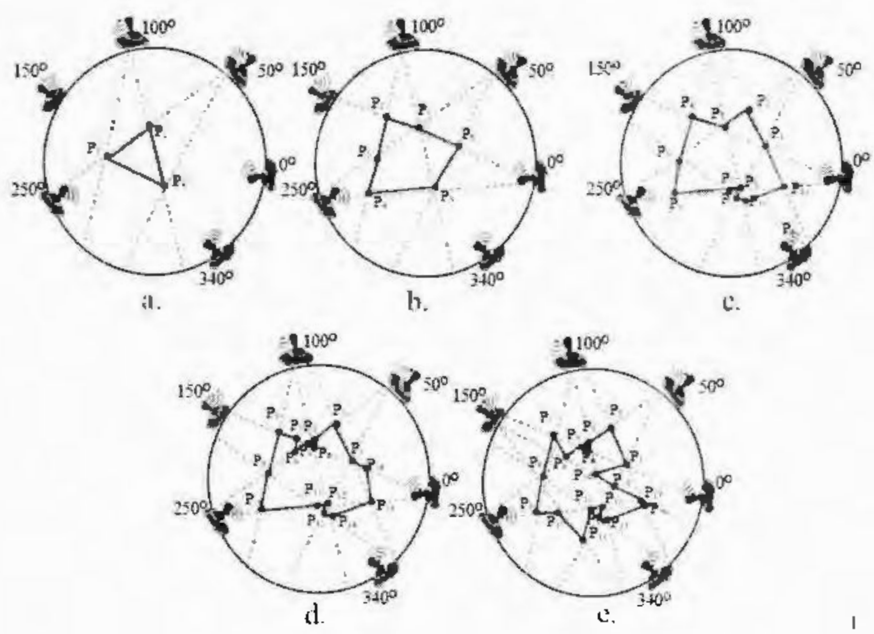

Figure 4.2: Optimal Points Algorithm Phases.

In this work, two algorithms are introduced to address the solution. Algorithm 1 is devised with the dipole antenna range as its focal point, whereas Algorithm 2 is tailored to the patch antenna

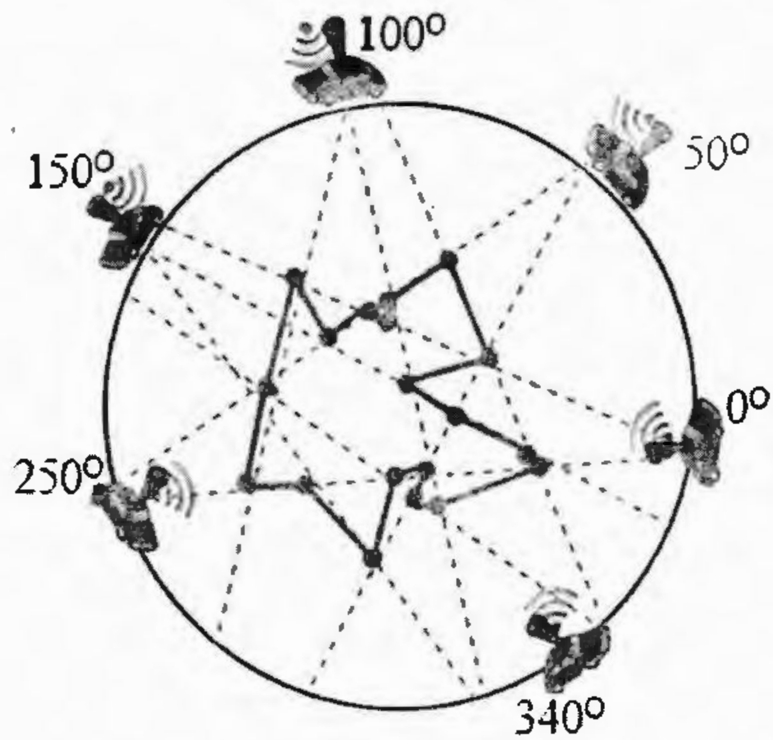

Figure 4.3: Sensor Device Placement for Dipole Antenna.

range. The primary objective centers on identifying the optimal placement points for the charger and the sensor while adhering to the sixty-degree constraints of the transmitter's emission.

In the context of Algorithm 1, a cone starts from the charger point, and only the cone's two left and right side lines are considered. When the charger reaches a location, the lines intersect at each point. The primary purpose is to find the intersection points, denoted as I_p, and the corresponding areas discovered through these intersections are represented as A_i. We can determine the optimal area for device placement by employing these two methods. On the other hand, in Algorithm 2, the angle of the patch antenna is considered as 120°. This angle encompasses the inherent 120° patch range and additional coverage facilitated by the charger's range. This observation arises from the finding that the patch antenna can leverage the charger's range to extend the charging range, making 120° become $120^{\circ} + \epsilon$, where ϵ is used to exploit the benefits of the charger antenna direction. $120^{\circ} + \epsilon$ increases the device placement area.

The following section describes the experimental setup and the conduct of the experiments accord-

Algorithm 1 Charger Placement Strategy for Dipole Antenna

Input: Set of Devices s_i where $i = \{1, 2, 3, \ldots, n\}$, charger Points C_p where $p = \{1, 2, 3, \ldots, 360°\}$, and Distance $d_k = 1$ feet
Output: Optimal area A_i for device placement through the intersection points (I_P).
$I_P \leftarrow \emptyset$, $C_p \leftarrow \emptyset$, $A_i \leftarrow \emptyset$
if $C_{pi} \neq \emptyset$ **then**
  for each point $C_{P_i} \in C_P$ **do**
    Start moving the charger from point C_{Pi+1} to 360° points.
    Two lines starting from C_{P_i} are intersected by C_{Pi+1} lines.
    for $j = i$ to n lines **do**
      Represent line L_j as: $L_j : a_j x + b_j y + c_j = 0$
      Represent line L_{j+1} as: $L_{j+1} : a_{j+1} x + b_{j+1} y + c_{i+1} = 0$
      At C_{Pi+1}, lines L_j and L_{j+1} intersect each other.
      $I_{Pi+j} \leftarrow \left(\frac{b_i c_j - b_j c_i}{a_i b_j - a_j b_i}, \frac{c_i a_j - c_j a_i}{a_i b_j - a_j b_i}\right)$
    end for
    $A_i = A_i \cup \leftarrow I_{Pi+j}$
  end for
end if
return A_i

Algorithm 2 Charger Placement Strategy for Patch Antenna

Input: Set of Devices s_i where $i = \{1, 2, 3, \ldots, n\}$, charger Points C_p where $p = \{1, 2, 3, \ldots, 120°\}$, and Distance $d_k = 1$ feet
Output: Optimal area A_i for device placement through the intersection points (I_P).
$I_P \leftarrow \emptyset$, $C_\theta \leftarrow \emptyset$, $A_i \leftarrow \emptyset$
if $C_{pi} \neq \emptyset$ **then**
  for each point $C_{P_i} \in C_P$ **do**
    Start moving the charger from point C_{Pi+1} to 120° points.
    Two lines starting from C_{P_i} are intersected by C_{Pi+1} lines.
    for $j = i$ to n lines **do**
      Represent line L_j as: $L_j : a_j x + b_j y + c_j = 0$
      Represent line L_{j+1} as: $L_{j+1} : a_{j+1} x + b_{j+1} y + c_{i+1} = 0$
      At C_{Pi+1}, lines L_j and L_{j+1} intersect each other.
      $I_{Pi+j} \leftarrow \left(\frac{b_i c_j - b_j c_i}{a_i b_j - a_j b_i}, \frac{c_i a_j - c_j a_i}{a_i b_j - a_j b_i}\right)$
    end for
    $A_i = A_i \cup \leftarrow I_{Pi+j}$
  end for
end if
return A_i

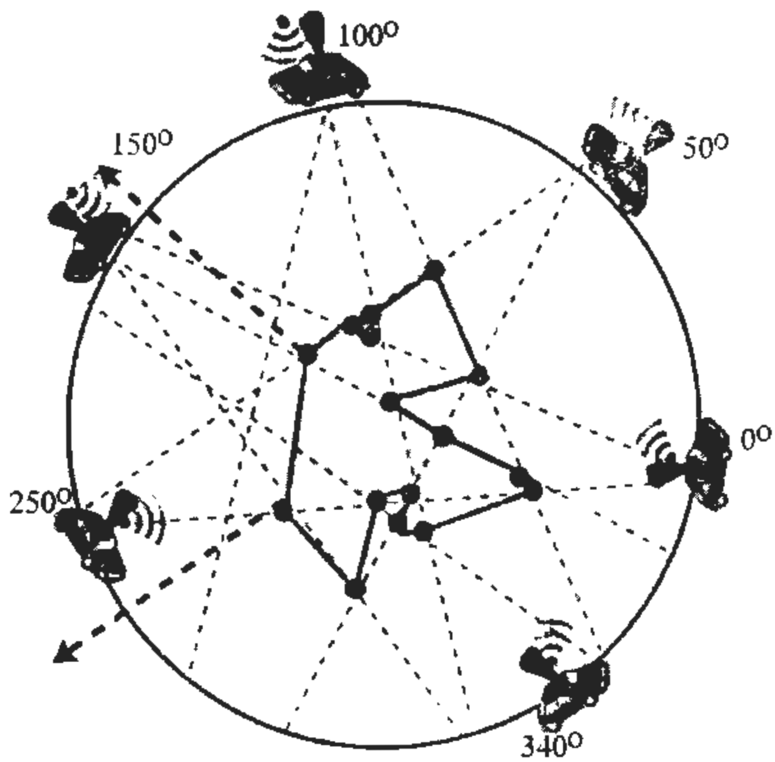

Figure 4.4: Sensor Device Placement for Patch Antenna.

ing to these algorithms.

4.4.3 Experimental Setup with Dipole Antenna

The dipole antenna boasts a 360° reception angle, enabling it to gather energy from the charger without any directional limitations. In contrast, the patch antenna's reception is confined to a 120° angle. Therefore, while the charger is in motion, the sensor device can harness energy from all directions owing to the dipole antenna's characteristics. Meticulously gathered receiving data has been presented in table 4.1 to support the given observations.

As illustrated in Fig. 4.4, the experimental data in Table 4.1 conclusively validates that the indicated points/area represent optimal positions for sensor placement. Moreover, the circular trajectory depicted in the figure signifies the optimal path for the charger, ensuring a continuous energy supply to the sensors.

Table 4.1: Dipole Antenna Sensed Data

Angle	RSSI (dBm)	Temperature (C°)	Humidity (%)	Light (lm)	External
	3.18	70.1	47	33	1683
	4.14	70.1	47	44	1673
	3.79	70.1	47	48	1680
	3.79	70.1	47	40	1677
50°	3.47	70.1	47	33	1682
	3.32	70.1	47	48	1677
	3.47	70.1	47	40	1679
	3.47	70.1	47	44	1677
	3.79	70.1	47	44	1683
	3.66	70.1	47	48	1680
	4.46	70.1	47	40	1674
	5.60	70.1	47	37	1678
	4.31	70.1	47	40	1683
	4.46	70.1	47	29	1677
150°	4.31	70.1	47	48	1678
	4.14	70.1	47	37	1679
	3.79	70.1	47	29	1677
	4.14	70.1	47	40	1680
	4.46	70.1	47	29	1678
	7.73	69.7	47	29	1690
	7.05	69.7	47	33	1679
	6.62	69.7	46	29	1690
	7.94	69.7	47	40	1683
250°	7.48	69.7	46	48	1683
	7.05	69.7	47	40	1679
	7.28	69.7	47	37	1679
	7.28	69.7	47	44	1687
	7.73	69.7	47	48	1679
	5.4	69.9	46	40	1678
	6.62	69.9	47	48	1681
	5.6	69.9	46	40	1680
	5.78	69.9	46	44	1681
360°	5.21	69.9	47	51	1678
	5.4	69.7	47	44	1681
	4.84	69.9	47	37	1674
	5.21	69.9	46	48	1674
	4.84	69.7	46	29	1683

4.4.4 Experimental Setup with Patch Antenna

The patch antenna's reception angle spans 120°. The experiment shows that the patch antenna operates optimally within the range of 120°+ϵ degrees, where ϵ incorporates certain benefits from the charger's angle. Charging devices effectively receive energy within this angle, but issues arise when the charger changes direction. In such cases, the charging device becomes unresponsive, causing the energy harvesting and data transmission processes to degrade to zero. The experimental data is presented in Table 4.2 to substantiate the findings of the proposed approach.

Referring to Fig. 4.1, the table illustrates that as the charger's direction shifts from zero dgree to 250°, energy harvesting and data transmission processes experience degradation. Conversely, when the charger's direction aligns with 240°, the energy harvesting and data transmission processes regain strength. Based on these comprehensive experimental observations, It can be confidently asserted that the points/area indicated in Fig. 4.3 are optimal for positioning sensors. Additionally, points ranging from 340° to 100° stand as optimal charger tour points or pathways, assuring an uninterrupted energy supply to sensors. For further clarity, please consult Table 4.2. To enhance comprehension, supplementary figures are included (4.5, 4.6, 4.7, 4.8, 4.9, 4.10) illustrating the sensed data of the patch antenna.

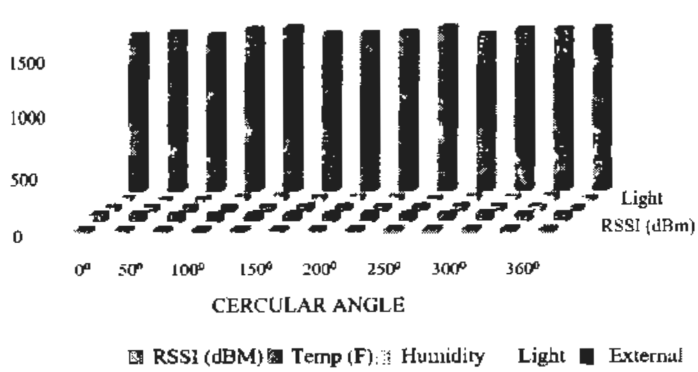

Figure 4.5: 0° Sense Data from Patch Antenna.

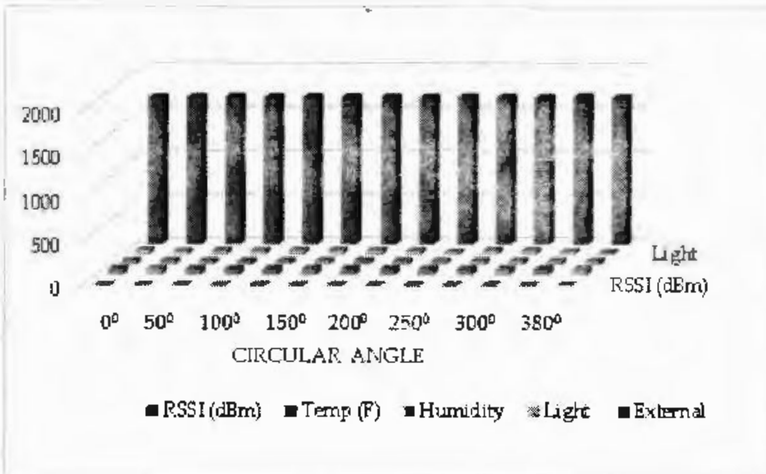

Figure 4.6: 50° Sense Data from Patch Antenna.

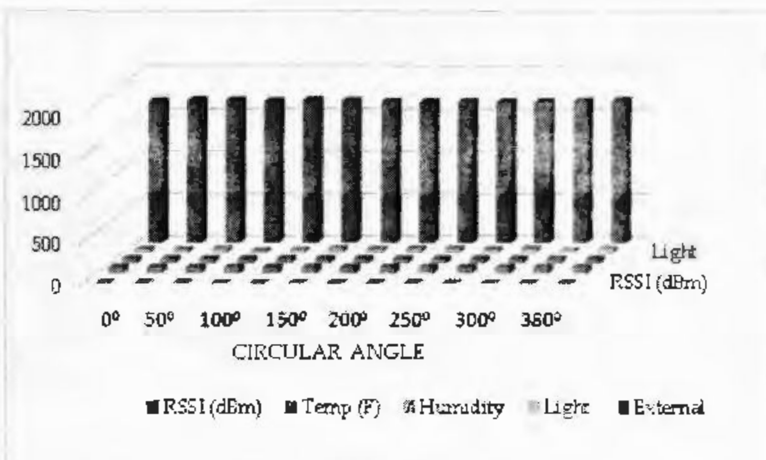

Figure 4.7: 100° Sense Data from Patch Antenna.

Table 4.2: Patch Antenna Sensed Data

Angle	RSSI (dBm)	Temperature (C°)	Humidity (%)	Light (lm)	External
0°	33.88	70.5	46	37	1331
	33.88	70.5	46	25	1352
	32.73	70.5	46	29	1325
	31.92	70.5	46	48	1382

Continued on next page

Table 4.2 – continued from previous page

Angle	RSSI (dBm)	Temperature (C°)	Humidity (%)	Light (lm)	External
	32.73	70.5	46	51	1393
	31.92	70.5	47	40	1343
	31.92	70.5	46	44	1346
	32.73	70.5	46	40	1358
	30.13	70.5	46	29	1393
	30.13	70.5	47	48	1340
50°	12.11	70.5	47	48	1686
	12.97	70.5	47	40	1687
	10.45	70.5	47	48	1695
	11.86	70.5	47	44	1687
	12.11	70.5	47	48	1690
	10.45	70.5	47	48	1690
	12.71	70.5	47	51	1690
	12.11	70.5	47	44	1686
	12.97	70.5	47	29	1692
	11.27	70.5	47	51	1690
100°	3.18	70	48	40	1670
	3.66	70	47	37	1678
	1.74	70	48	48	1676
	3.96	70	48	22	1669
	3.96	70	47	29	1678
	3.66	70	48	48	1673
	3.96	70	47	40	1665
	3.47	70	48	48	1662
	3.32	70	48	48	1666
	3.66	70	48	40	1663
150°	0.6	70.5	48	51	1584
	0.52	70.5	47	48	1594
	0.49	70.5	48	29	1594
250°	0.86	70.7	48	51	1581
	0.67	70.7	47	48	1574

Continued on next page

Table 4.2 – continued from previous page

Angle	RSSI (dBm)	Temperature (C°)	Humidity (%)	Light (lm)	External
	0.74	70.7	48	29	1584
340°	11.86	70.7	47	37	1696
	12.71	70.7	47	55	1693
	12.42	70.7	47	51	1698
	12.11	70.7	47	48	1693
	11.53	70.7	47	51	1689
	11.86	70.7	47	44	1685
	12.11	70.7	47	48	1689
	12.97	70.7	47	33	1701
	11.53	70.7	47	29	1695
	13.3	70.7	47	51	1698

Analysis of Data in Dipole Antenna The dipole antenna's design permits it to receive data from all directions due to its 360° reception capability. Interestingly, a notable phenomenon occurs when the sensor devices are positioned beneath the charger device: the time differential (dT) between received packets increases. This temporal distinction results in the sensor devices acquiring enhanced power for data transmission.

4.4.5 Analysis of RSSI of Patch Antenna in Mobile Environment

To introduce mobility, the chargers are mounted on moving vehicles. Additionally, the sensor with the patch antenna is positioned on the ground for the experiment. Remarkably, the sensor effectively transmitted data to the access point. To comprehensively showcase the sensed data collected from sensors spanning 100 to 360°, Table 4.3 can be utilized.

4.4.6 RSSI of Patch Antenna During Circular Tour of The Charger

In this section, the focus shifts toward detailing the movement of the charger along circular points and acquiring the Received Signal Strength Indication (RSSI) data for the patch antenna. Initiating the movement at 100°, the progression gradually extended to 360°. Notably, the RSSI values exhibit strong performance ranging from 100 to 280°. However, degradation becomes apparent after reaching 280°, as demonstrated in Table 4.4.

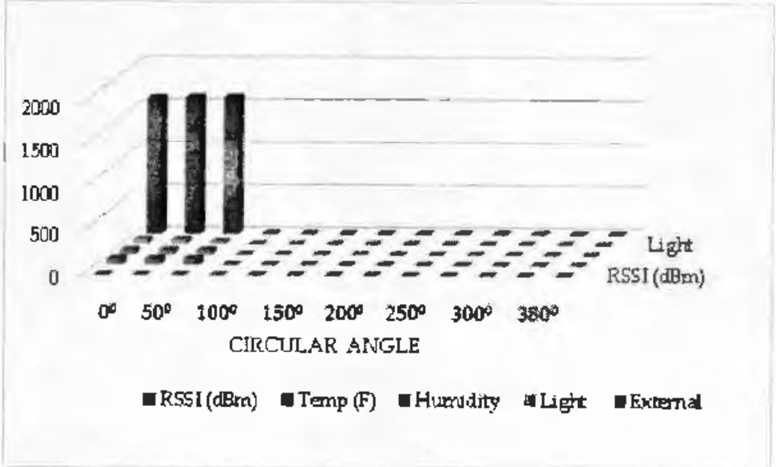

Figure 4.8: 150° Sense Data from Patch Antenna.

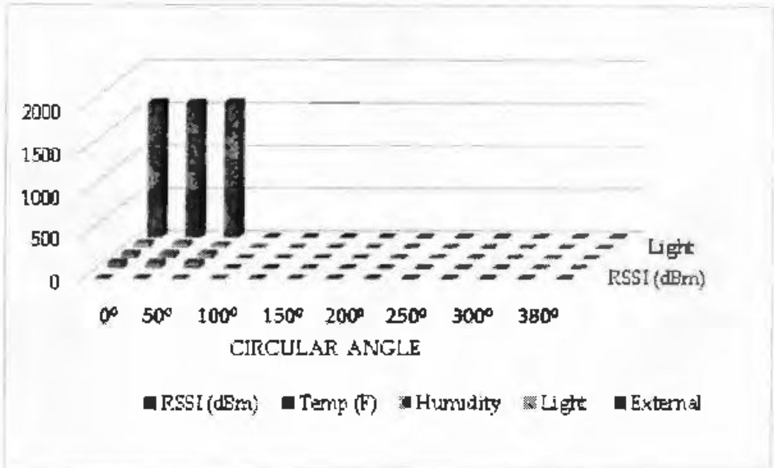

Figure 4.9: 250° Sense Data from Patch Antenna.

4.5 Results

The conducted experimentation has been meticulously aligned with the stipulated requirements of this work. Circular points were strategically chosen to validate the accuracy of the presented problem identification. The determination of optimal points was based on packet transmission dynamics. For instance, in Fig. 4.1, when the point corresponds to 200°, the sensor device exhibits rapid packet transmission due to ample energy reception. However, as the charger shifts to zero degrees, the pace of packet transmission decelerates. Powercast refers to this phenomenon as the

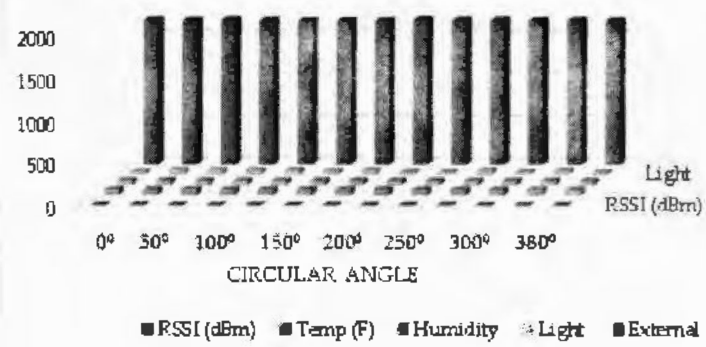

Figure 4.10: 340° Sense Data from Patch Antenna.

Table 4.3: Data Sensed in Mobile Environment.

Pkt No	DT	RSSI	Temp	Humidity	Light	External
1	0	12.71	71.2	48	29	1670
2	1	12.97	71.2	48	33	1666
3	0	11.53	71.2	48	48	1667
4	0	14.19	71.2	48	40	1667
5	1	13.58	71.2	48	37	1667
6	0	14	71.2	48	51	1664
7	0	12.11	71.2	48	37	1656
8	1	12.11	71.2	48	29	1670
9	0	11.86	71.2	48	48	1670
10	0	8.41	71.4	48	33	1654
11	0	7.94	71.4	48	29	1648
12	0	6.82	71.4	48	37	1651
13	1	6.82	71.4	48	40	1646
14	0	3.66	71.4	48	33	1646
15	2	3.32	71.4	48	29	1624
16	1	3.79	71.4	48	40	1633
17	1	1.63	71.4	48	22	1628
18	2	1.85	17.4	47	51	1611
19	1	0.95	71.4	47	51	1611
20	9	0.31	71.2	47	33	1534

"Time Differential" (dT) between received packets. Optimal points yield a high dT, whereas sub-

Table 4.4: Data Sensed in a Mobile Environment for the Patch Antenna.

100–150°	151–200°	201–250°	251–300°	301–360°
11.02	24.1	50	47.64	8.89
13.3	31.12	50	43.05	10.45
15.17	31.92	50	41.98	8.41
16.48	39.9	50	41.98	7.73
17.45	43.05	45.39	41.98	5.4
19.59	36.9	44.16	38.9	4.31
22.49	44.16	47.64	36.9	3.91
19.59	47.64	46.45	35.89	3.96
22.49	44.16	43.05	32.73	4.31
25	47.64	44.16	9.91	4.84
25	49.66	43.05	8.89	5.01
25.82	50	44.16	8.18	2.61
26.61	50	43.05	9.68	0.24
24.1	50	46.45	9.16	0.43

optimal points result in a lower dT.

In this section, the obtained results are graphed for detailed analysis. Fig. 4.11 compares with the work presented in [2], focusing on RSSI values across various angles and distances. The approach in [2] involved fixed sensor device positions and a stationary charger on the ground, leading to the emergence of the nearest-farthest problem. The graph effectively demonstrates the superiority of the presented work. In the figure, "J_1,J_2,J_3" signifies the work of [2], while "H_1,H_2,H_3" represents the presented work.

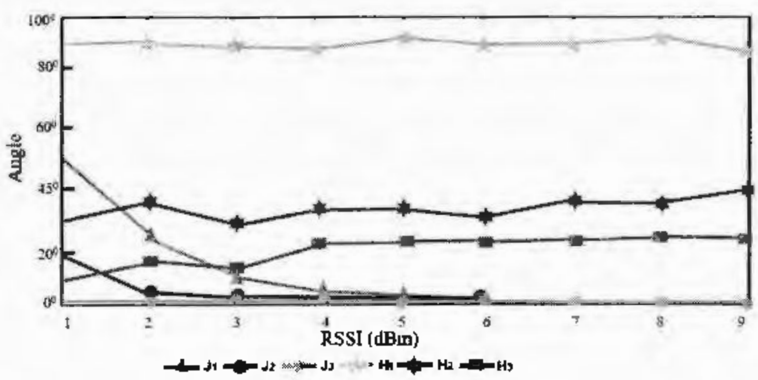

Figure 4.11: RSSI Comparison with [2]

Fig. 4.12 is constructed based on the RSSI data received by the patch antenna placed at various

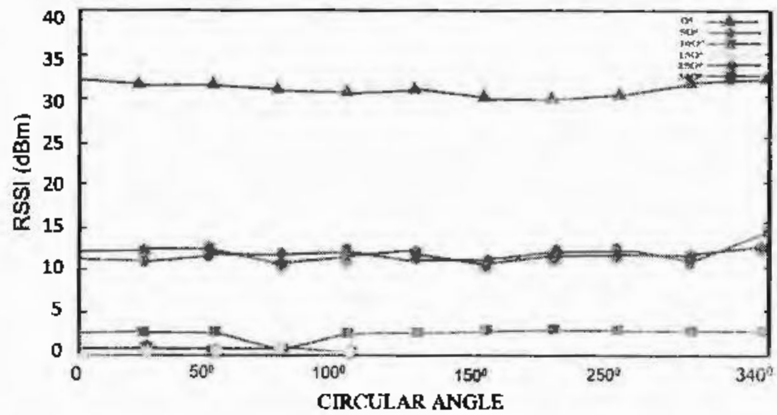

Figure 4.12: Patch Antenna RSSI.

points following the defined requirements of this work. These points encompass the full range from zero to 360°. Points one to four signify RSSI measurements within the 120° range, while points five to six lie beyond this range.

The synergy between the presented optimal sensor points and the optimal charger points is evident in the graph. When the charger aligns with designated optimal points, successful energy transmission occurs, enabling optimal energy harvesting for the sensors. Conversely, deviations from prescribed points lead to a degradation in received signal strength. Notably, no sensor becomes inactive or enters a dead state when the charger follows the constructed optimal path, effectively transmitting energy to the sensors' optimal positions.

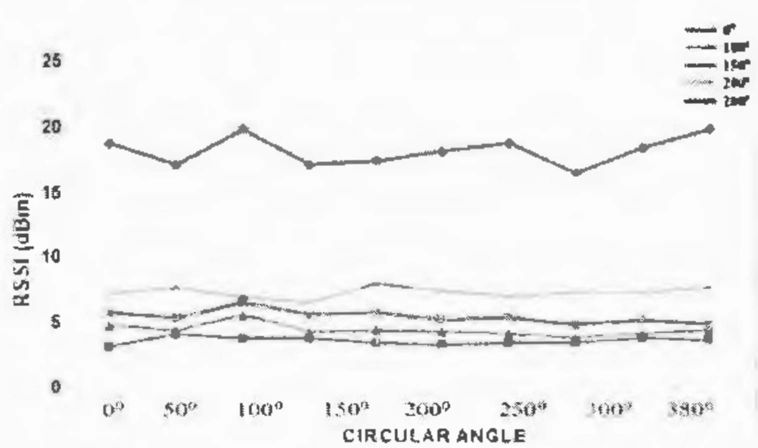

Figure 4.13: Dipole Antenna RSSI.

Fig. 4.13 visually represents the RSSI measurements obtained from a dipole antenna. Notably, the dipole antenna performs better when positioned at constructed optimal points, consistently receiving energy from the charger at a sixty-degree angle. Notably, none of the sensors encounter inactivity as the charger follows the optimal path.

4.5.1 RSSI of patch antenna during circular tour

Fig. 4.14 portrays the RSSI data collected during the charger's circular tour with continuous motion. This experiment involved stationary sensor devices equipped with patch antennas (bearing a 120° beam pattern) while the charger remained mobile (as illustrated in Fig. 4.1). A critical observation emerged: as the charger altered its direction, the sensor device's energy scavenging capabilities experienced degradation. Conversely, energy scavenging was notably enhanced when the charger and sensor device were directly in sight. For instance, in Fig. 4.14, data1 and data5 do not align in the line of sight, while data2, data3, and data4 do. At data3, the sensor device achieved 100% energy scavenging efficiency from the charger. Based on these results, it is evident that the configuration depicted in Fig. 4.3 offers an effective solution for optimal sensor device placement.

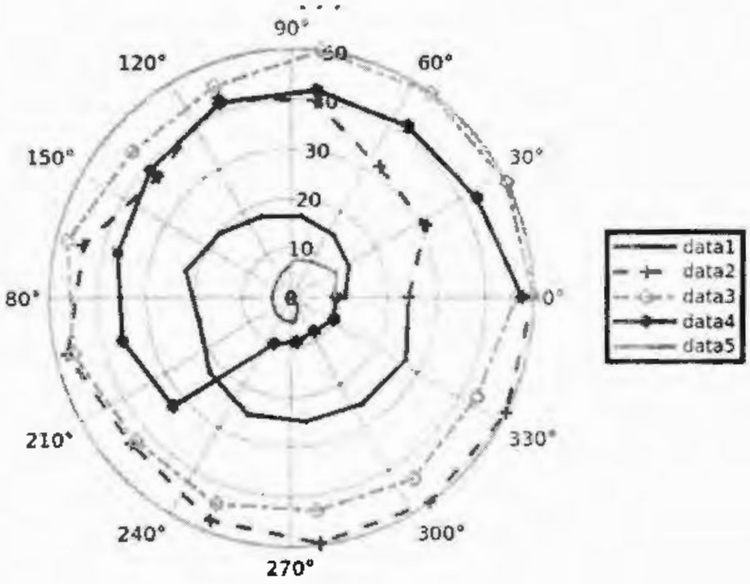

Figure 4.14: Patch Antenna RSSI in Circular Tour

4.5.2 RSSI of dipole antenna during circular tour

Fig. 4.15 is derived from the RSSI data collected while the charger undertook a circular tour. Given the dipole antenna's capacity to receive energy from all directions, the discussed observations support the placement indicated in Fig. 4.4 as the optimal location for the sensor device.

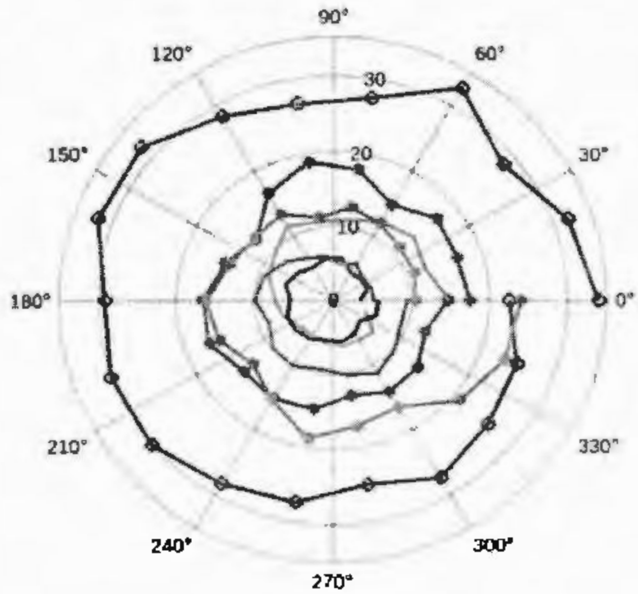

Figure 4.15: Dipole Antenna RSSI in Circular Tour

4.6 Contributions

The main contributions of this chapter are as follows:

- **Gain Proficiency in Energy Harvesting Devices:** This involves delving into the world of physical energy harvesting devices, comprehensively understanding sensors, energy harvesters, energy transmitters, and antennas, and staying up-to-date with the latest advancements in IoT devices and energy harvesting concepts.
- **Explore Charger Placement Techniques:** Investigate various methods for strategically placing chargers to ensure effective and efficient device charging.
- **Analyze Sensor Data and Antenna Types:** Study the Received Signal Strength Indication (RSSI), data transmitted by sensors, the significance of patch and dipole antennas, and make

observations about different physical arrangements.

- **Develop an Optimal Charger Tour Algorithm:** Create a well-designed algorithm that optimizes the tour taken by chargers to maximize the efficiency of device charging.
- **Design an Optimal Strategy for IoT Device Placement:** Devise a strategy for placing IoT devices in ways that maximize energy harvesting potential at any given time.

The contribution of this chapter is the first article Titled: "Zero Energy IoT Devices in Smart Cities Using RF Energy Harvesting," Accepted in the Journal of MDPI Electronics 2023.

4.7 Chapter summary

In this chapter, the main focus lies in addressing the challenge of determining optimal points for charger placement and identifying the optimal area for sensor device deployment. The conducted experiments have underscored that as devices move away from chargers, the energy scavenging process experiences degradation, potentially leading to a deadlocked state. To prevent devices from entering this state, a mobile charger technique was introduced that charges devices and establishes optimal positions for chargers and sensor devices. During mobile charging, observations also highlighted that alterations in the directional antenna's angle result in energy scavenging degradation. To tackle these concerns, two algorithms were developed catering to directional and omnidirectional antennae, offering approximate solutions to the presented problem. These algorithms factor in coverage and energy requirements.

In the proposed algorithms, chargers are rendered mobile while sensor devices remain stationary. The charger's movements are strategically regulated to specific angles, ensuring that each sensor device optimizes its energy harvesting potential. The promising outcomes of this technique are showcased through rigorous testing of these scenarios. It is important to note that while this solution is tailored for a 2D environment, it doesn't extend seamlessly to a 3D setting. The future endeavors involve expanding this work to encompass 3D environments. Additionally, it is intended to leverage standard simulation tools for comparative analysis against other state-of-the-art solutions. Moreover, the insights from this work will be integrated into routing protocols, further enhancing its applicability.

Chapter 5

Location Centric Energy Harvesting Aware Routing Protocol for IoT In Smart Cities

The Internet of IoT has gained significant attention in recent years, with researchers predicting that the industry will consist of around 29.7 billion devices by 2027 [95]. IoT has brought about a revolution in our daily lives, offering immense convenience to humanity [96]. However, many IoT devices need more support due to their sensors' limited battery and memory capacities. This limitation results in challenges such as insufficient sensor lifespan, network failures, and high operational costs. To overcome these issues, energy harvesting has emerged as a solution for low-power electronic devices and sensors. Sensors can recharge their batteries by harnessing energy from solar, thermal, wind power, and even RF. RF-based energy harvesting, in particular, is advantageous due to its continuous availability from various sources such as TV, radio, and wireless frequencies. It has given rise to a new research area known as RF-powered IoT, which holds great potential for applications like smart tracking, structural health monitoring, and wearable devices [47, 97–100].

Energy efficiency is critical for IoT devices to ensure uninterrupted network operations. This includes tasks like transmitting sensed data and maintaining routes. When a node's energy is depleted, it ceases all activities, including forwarding packets, maintaining routes, and traversing long routes. Implementing energy harvesting techniques and optimizing route selection processes are beneficial to improve energy efficiency. By minimizing the involvement of nodes in the routing process, energy consumption can be significantly reduced. This approach aims to maximize energy conservation and extend the operational lifespan of IoT devices [16].

Energy harvesting is a promising technique with great potential for extending the network lifespan in challenging deployment areas where installing IoT devices is difficult. With energy harvesting, nodes can utilize renewable energy from the environment, such as solar, wind, thermal, and RF sources. RF energy harvesting, in particular, offers a solution for zero-energy IoT devices [16, 98], eliminating the need for batteries and ensuring a constant energy supply to power sensor devices. By leveraging this technique, networks can operate perpetually, overcoming the limitations of finite battery life and enabling sustained functionality in IoT deployments.

Several techniques have been employed to improve energy efficiency and extend the network lifespan, with a focus on utilizing energy harvesting techniques. Notable research in this area includes studies conducted by [26, 28, 38, 55]. These works explore the application of energy harvesting techniques to enhance energy efficiency and prolong the operational lifespan of networks through the creation and selection of efficient link. During the link selection process, the authors used different parameters, such as shortest distance and energy harvesting rate [26], shortest distance and maximum current energy [28], shortest distance, transmission cost, and energy harvesting [38], residual energy and shortest distance [55], energy harvesting, energy consumption, and energy classification [50]. In our work, we select the efficient link by considering the closest angle among neighbors to the destination node.

The contributions of this paper include:

- The state-of-the-art routing techniques such as [24, 26, 28, 38, 38, 39, 54–59, 66, 101] have been investigated to find their limitations and to propose a better solution.
- A distributed neighbor discovery algorithm is presented to find the neighbors of each node with necessary information such as distance and angle.
- To enhance energy efficiency in IoT-based WSNs within smart cities, Location Centric Energy Harvesting Aware (LCEHA) Routing Protocol is presented. This protocol incorporates a cost metric based on the closest angle to the destination to determine the optimal routes toward the destination node.
- The LCEHA technique performs well in terms of energy efficiency, consumes less energy while transmitting data, and achieves maximum data packet sending rate.

5.1 System Model and Preliminaries

The system model can be modeled as a graph G = (V, E), where V represents the rechargeable nodes, and E represents the links between two nodes. The notation for the wireless link between nodes i and $j \in V$ is denoted as e(i, j). Each sensor node can sense the given area and upload the sensed data to the sink node. Additionally, each node can recharge from a renewable energy source. Many energy harvesting techniques, such as wind,solar, thermal, and RF, have been introduced. However, the RF based EH technique has garnered tremendous attention from researchers due to its easy availability (from TV, radio stations, and Wireless frequencies).

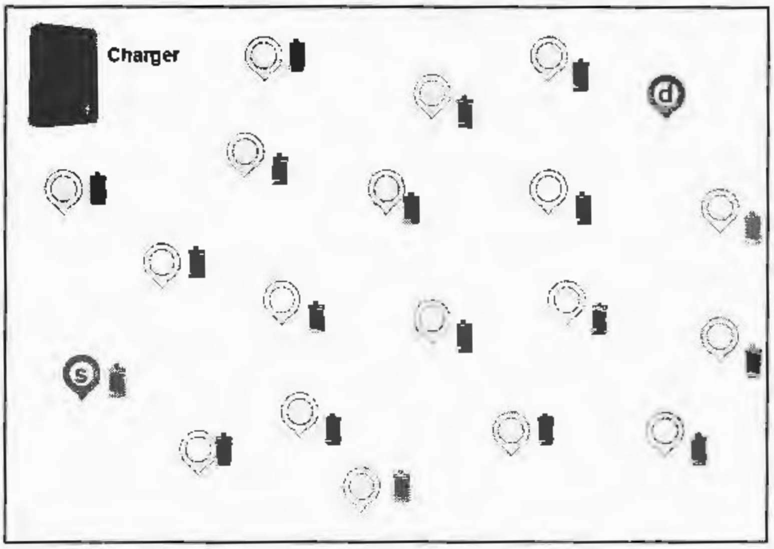

Figure 5.1: System Model of Proposed Work

The nodes are powered with energy harvesting circuits and harvest energy regularly. There are three components of the Energy harvesting model: the energy source (RF, solar, thermal), the energy harvesting hardware (*Powercast* TX91501 *Powercast* Transmitter, P2110 receiver), and the energy storage devices. [16, 17]. The energy harvesting hardware is responsible for transforming energy into electricity and storing it in the storage device (batteries, capacitors). The Powercast company [17] introduced the energy harvesting devices used in many applications such as smart buildings and smart health. The company provides an energy transmitter with a central frequency of 815 MHz with 3W EIRP emitting power signals with an antenna having 60° horizontal and 60° vertical beam patterns. The evaluation board (energy harvesting hardware) converts RF energy into DC with capacitor-regulated voltage output up to 5.25 V and output current up to 50 mA to

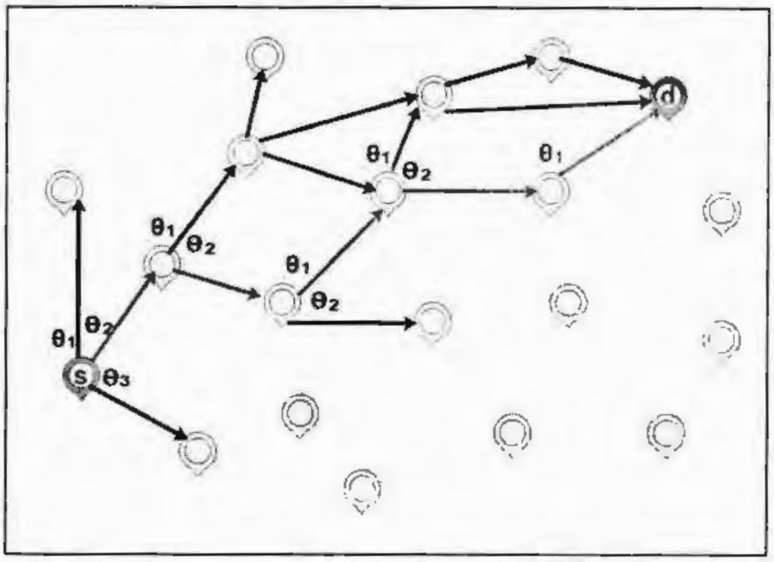

Figure 5.2: Angle Selection Model

charge the capacitor of size 50 mF. A sensor board is also provided for sensing the environment, such as temperature, humidity, and light. The Powecast technology company used the Friis space equation 4.1 for the energy transmission model.

He et al. [91] presented an empirical model and improved Eq. (4.2) by introducing polarization loss and signal power rectifying and converting to electrical energy before it can be used.

Let v_k be the set of IoT devices and v_{km}, $v_{kn} \epsilon v_k$ then the Eq. (4.2) can be write as follow:

$$P_r = \frac{\alpha P_t(v_{km})}{(\|v_{km} - v_{kn}\| + \beta)^2} \tag{5.1}$$

where $P_t(v_{km})$ represents the transmission power of device v_{km}, $\|v_{km} - v_{kn}\|$ represents the distance between node v_{km} and node v_{kn}, $\alpha = \frac{G_t G_r \eta}{L_p}(\frac{\lambda}{4\pi})^2$.

The distance between v_{km} and v_{kn} is essential in energy consumption. The authors in [26] state that the received power falls off as the square of the distance between v_{km} and v_{kn}. Therefore, more energy will be consumed as the distance increases because it requires much power to transmit a packet. A neighbor table is created to store the information of nodes with a short distance; in other words, each node will store the information of neighbor nodes whose RSSI is high. As demonstrated in the work of [16], a node near the charger device can harvest much energy compared to a node located farther away.

The proposals in [102, 103] classified the Received Signal Strength Indicator (RSSI) into different levels: "excellent," "very good," "good," "low," "shallow," and no signal. The RSSI level of $-75dBm$ is chosen for our work, which falls under the "good" category. This choice allows us to set a threshold for nodes to store information about the maximum number of neighboring nodes. The advantage of using this threshold is that it ensures that at least one efficient link is available to forward data packets. Focusing on nodes with a "good" RSSI level increases the likelihood of reliable data transmission connections. It, in turn, leads to better overall network performance and data forwarding efficiency in our research. The distance between two nodes can be calculated using Eq. (5.1), which is written as:

$$\|v_{km} - v_{kn}\| = \frac{\sqrt{\alpha P_t(v_{km})}}{P_r} - \beta \tag{5.2}$$

Eq. (5.2) can also be used to calculate the distance between source node and destination as:

$$D_{s_n - d_n} = \|\frac{\sqrt{\alpha P_t(S)}}{P_r} - \beta\| \tag{5.3}$$

Eq. (5.4) can be used to calculate the distance between the sender and receiver.

$$d_{s_n - d_n} = \|\frac{\sqrt{\alpha P_t(S)}}{P_r} - \beta\| \tag{5.4}$$

During network operations, a node may reach a dead state, so each node needs to update its energy requirements from RF-EH. For this purpose, the time between two consecutive periodic energy updates plays a vital role in the EH technique. The energy update interval time is proportional to the distance. The update interval is short if the distance is large, and vice versa. The update interval is also related to communication complexity. When a small value is assigned to the update interval when the distance is long between nodes, the communication complexity increases, whereas, for a large value, when the distance is short, the communication complexity decreases. It is because the update interval is used to harvest energy from the energy source, so it will take a long time when the update interval is long and reduce communication complexity when the update interval is short. Mathematically, this problem can be described as follows:

Let U be the time to update energy by each node. The t_d is the distance between each node, and D is the distance between the source and destination node.

$$U = \begin{cases} 1 & if t_d \geq D \\ i+1 & if t_d < D \end{cases} \tag{5.5}$$

where i is related to the distance factor, it increases when t_d decreases.

5.1.1 Energy Consumption Model

Energy consumption is crucial in designing an efficient energy harvesting-aware routing protocol. Each node should know the energy consumption rate when transmitting and receiving a packet. Most of the node's energy is consumed through packet transmission, reception, internal processes, and node modes (sleeping, working, recharging).

This study uses the radio model proposed by Heinzelman et al. [69], which describes the relationship between energy consumption and data transmission.

$$P_{tx}(k, d) = (p_t + \epsilon + d^4) \times k \tag{5.6}$$

$$P_{Rx}(k) = p_r \times k \tag{5.7}$$

Eq. (5.6) is used to calculate the energy consumption for data transmission, while Eq. (5.7) is used for the energy consumption at the receiving node. These are the general forms of energy consumption equations for communication. Various factors can increase or decrease energy consumption during transmission and receiving operations. These factors should be taken into account by network designers. The energy consumption of the radio channel is determined by considering essential aspects such as the number and distance to neighbors, transmission rate, receive rate, and the optimal size of data and message packets. The text below provides a detailed discussion of each factor.

Energy consumption by Processing Unit:

$$E_{cp} = \sum E_{ecpu} \times \sum A_t \tag{5.8}$$

where E_{ecpu} is the power consumption of the processing unit and A_t is the active processing time.

The power consumption of the processing unit (E_{ecpu}) depends on various factors, including the hardware design, clock frequency, and computational workload. It is typically provided by the manufacturer or determined through measurements.

The active processing time (A_t) refers to the duration the processing unit executes computations or processing tasks.

Energy Consumption by Transmission of Packets

$$E_{cs} = \sum E_{ecppt} \times \sum T_{spkt} \tag{5.9}$$

where E_{ecppt} is the energy consumed per packet transmission and T_{spkt} is the number of packets transmitted.

Energy Consumption by Receiving of Packets

$$E_{cr} = \sum E_{ecppr} \times \sum T_{rpkt} \tag{5.10}$$

where E_{ecppr} is the energy consumed per packet receiving and T_{rpkt} is the number of packets received.

Energy Consumption by Discovering Neighbor Nodes Discovering and maintaining network nodes is a crucial aspect of network maintenance. It ensures the continuous and uninterrupted operation of the network. This phenomenon can be understood and expressed through an equation that combines the factors of node discovery and ongoing maintenance. By effectively discovering new nodes and proactively maintaining the network's functionality, the proposed manuscript can optimize the overall performance and reliability of the network.

$$E_{cns} = (\sum E_{ecppt} \times \sum T_{spkt}) \times T_{tpkt} \tag{5.11}$$

T_{tpki} represents the time required for the neighbor discovery process. Allocating one second for the neighbor discovery process corresponds to transmitting a single packet within that time frame. However, extending the neighbor discovery process to ten seconds allows transmitting multiple packets over this extended duration.

And for packet receiving:

$$E_{cnr} = (\sum E_{ecppr} \times \sum T_{rpkt}) \times T_{rpkt} \tag{5.12}$$

The overall energy consumption can be expressed as follows:

$$E_c = \begin{cases} E_{cp} + E_{cs} + E_{cns} & \text{if } n \in N \text{ is sender node} \\ E_{cp} + E_{cr} + E_{cnr} & \text{if } n \in N \text{ is receiving node} \\ 0 & \text{if dead} \end{cases} \tag{5.13}$$

The primary causes of energy inefficiency in IoT-based EH WSNs are idle listening, unnecessary traffic overhearing, packet collisions, and the overhead of control packets during transmission, reception, and listening [104]. Idle listening occurs when Nodes constantly listen for incoming frames without data transmission, depleting the energy. Collision occurs when multiple nearby stations transmit simultaneously, causing energy loss. Over-hearing means Nodes unintentionally overhear broadcast messages, leading to energy waste. Control packet overhead: occurs when using fewer control packets in data transmission reduces energy consumption [105].

In a routing algorithm, when a device transmits a data packet, it selects the most efficient link for forwarding it. Our first step is calculating the efficient link (E_l) based on information obtained from the topology construction algorithm. The device evaluates various factors to determine this efficient link, including the angle to the destination node. By calculating the closest angle to the destination node, the device can make informed decisions on selecting the most suitable link for forwarding the packet towards its intended destination. The node selects the neighbor that forms the closest angle to the destination node, regardless of whether it is the smallest or the most significant angle, maximum or minimum distance. The node identifies the neighbor that points most directly toward the destination node. For this purpose, we use Equation 5.14 to calculate the

Table 5.1: Notations

Symbol	Meaning
E_{cp}	Energy consumption by the node process unit.
E_{cs}	Energy consumption by packet transmission.
E_{cr}	Energy consumption by receiving a packet.
E_{cns}	Energy consumption by sender nodes while discovering neighbor nodes.
E_{cnr}	Energy consumption by the receiver node while discovering neighbor nodes.
T_{en}	Total energy consumption per node.
E_c	Total energy consumption by nodes after Energy Harvesting.
T_θ	The angle between the source and destination nodes.
N_b	Neighbor node information in the neighbor table.
A_{si}	Selected address of the closest angle node.
A_{ci}	Current node address.
A_{ni}	Neighbor node address.
A_d	Destination node address.
O_θ	Optimal angle.
Add_{t_θ}	Address of the neighbor node with the optimal angle.

angle between the source and destination nodes.

$$T_\theta = arctan(\frac{x_2 - x_1}{y_2 - y_1}) \tag{5.14}$$

where x_1, y_1 are the coordinates of one node and x_2, y_2 are the coordinates of second node. When each node receives a packet, it calculates the angle between itself and the sender node using the following equation:

$$t_\theta = arctan(\frac{x_2 - x_1}{y_2 - y_1}) \tag{5.15}$$

5.1.2 Node Energy Harvesting Model

The energy harvesting model represents harvesting energy from the environment and converting it into usable electrical energy. A general representation of the energy harvesting equation is as follows:

$$E_h = \eta \times P_h \times t \tag{5.16}$$

where η represents the energy conversion efficiency, P_h represents the harvested power, and t represents the harvesting time duration. This equation calculates the total harvested energy by multiplying the harvested power with the harvesting time duration, considering the energy conversion efficiency (η), which represents the efficiency of converting harvested power into usable electrical energy. The energy conversion efficiency (η) in the context of energy harvesting represents the efficiency with which harvested power is converted into usable electrical energy.

The expression for η can be derived by considering the energy harvesting process's power conversion losses or inefficiencies. In this case, the equation for η can be expressed as:

$$\eta = P_{output}/P_{input} \tag{5.17}$$

P_{output} represents the usable electrical power obtained from the energy harvesting process, and P_{input} represents the total harvested power, including the energy obtained from the environment. This equation, η, is the usable electrical power output ratio to the total harvested power input. It measures the efficiency with which the harvested power is converted into usable energy.

P_h can be obtained from RF energy harvesting. In RF energy harvesting, the harvested power (P_h) can be estimated based on the received RF signal strength and the efficiency of the energy harvesting circuit. The equation for harvested power in RF energy harvesting can be represented as:

$$P_h = C \times |E|^2 \times \eta_r f \tag{5.18}$$

where C represents the capture coefficient or antenna sensitivity, which characterizes the efficiency of capturing the RF energy. Additionally, the antenna structure plays a vital role in the EH process, as mentioned by [16] in their real-world experiments. $|E|^2$ represents the squared magnitude of the electric field strength of the RF signal, which represents the power density of the received RF signal. $\eta_r f$ represents the efficiency of the RF energy harvesting circuit, which accounts for losses and conversion efficiency in the energy harvesting process.

The equation states that the harvested power is proportional to the capture coefficient (C), the square of the electric field strength ($|E|^2$), and the efficiency of the RF energy harvesting circuit ($\eta_r f$). It indicates that a stronger RF signal, higher capture coefficient, and higher energy harvesting circuit efficiency will produce higher harvested power.

After the harvesting process, the total energy of the node can be expressed as follows:

$$T_{en} = E_0 + \sum E_h \tag{5.19}$$

Now, the following equation can be used for the residual energy of the node:

$$E_r = T_{en} - \sum T_{ec} \tag{5.20}$$

This manuscript focuses on reducing the overall energy consumption of individual nodes in the network by targeting parameters described in Eq. (5.13). This work aims to develop and implement energy efficiency strategies and models that optimize these parameters for each node individually, ultimately reducing energy consumption. The aim is to design an efficient routing mechanism that considers energy harvesting considerations, thereby enhancing the overall energy efficiency of the network.

5.2 Location Centric EH Algorithms

This study presents a routing protocol considering energy harvesting when choosing an efficient link for transmitting data to a specific destination. Past studies have explored various techniques for selecting the optimal link, including location or angle-based methods [57–59, 65, 66] and cost metrics-based approaches [24, 26, 28, 38, 38, 39, 54]. However, these methods suffer from several issues, such as problems with selecting the optimal intermediate node, difficulties in maintaining routes, energy wastage, and increased communication complexities.

A two-step approach is proposed where the first step focuses on discovering neighboring nodes using broadcast packets to the neighboring nodes. Once the neighbors are identified, in the second step, the protocol utilizes the gathered information from the neighbor discovery process to intelligently transmit the data packets to the intended destination node. This twofold strategy aims to overcome the limitations of past methods and provide a more efficient and effective solution for data dissemination in an energy-constrained environment.

5.2.1 Distributed Neighbor Discovery Algorithm

The neighbor discovery algorithm is employed to identify the neighboring nodes and facilitate the exchange of crucial information such as distance calculation, Received Signal Strength Indication (RSSI), current energy levels, and energy harvesting rate. The neighbor discovery algorithm is a crucial component in our work, as it significantly contributes to packet forwarding efficiency and helps us overcome various challenges. By implementing this algorithm, issues like extra node traversal, which leads to energy savings, reduced packet loss, and minimized delays, can be avoided. The main idea is as follows:

Each node initiates the process by broadcasting a packet (P_{kt}), which other nodes receive and process. Upon receiving a packet, a node calculates relevant information, including distance, RSSI, the angle between sender and receiver, and its remaining energy. The distance, RSSI, and angle are calculated locally, while the current remaining energy is transmitted within the packet header. Initially, all nodes will broadcast a packet (lines 1-5 in algorithm 3) in time T_n, and each node within the transmission range will receive this packet. When a node receives a packet, it will calculate the distance using Eq. (5.1) and the angle using Eq. (5.15) (lines 6 to 17) based on the XY-coordinates of the current node ($c_n x, c_n y$) and the receiver node ($r_n x, r_n y$). Consequently, all necessary information is collected about distance, angle, and current remaining in the neighbor table after this process. The neighbor table can be updated after every time T.

In this algorithm, energy harvesting plays an important role. If the distance is large, it wastes more energy than a short distance. However, using energy harvesting, we can replenish the node's energy.

5.2.2 Route Discovery Algorithm

The main idea of algorithm 4 is to find the efficient path between the source and destination nodes considering the energy harvesting factor. In this process, two packets can be used: the initialization ($Init_{pkt}$) and reply (Rep_{pkt}) packets. These packets collect and share/calculate information with other nodes, which includes distance, current energy, and location. The process of this algorithm

Algorithm 3 Neighbor Discovery Algorithm

Input: A set of nodes N with unique Node IDs and Time T.
Output: A Neighbor Table with Angle information of neighbors.

1: At time T.
2: In Sender Mode
3: **for** $n \leftarrow 1$ to N **do**
4:     Broadcast P_{kt}
5: **end for**
6: In Receiver Mode
7: $N_b \leftarrow \emptyset$
8: **while** Nodes are receiving P_{kt} **do**
9:     $n_i \leftarrow A_{ni}$ {Information of sender node, ID,IP etc.}
10:     Calculate Angle t_θ between sender and receiver nodes as:
11:     Calculate slope $S_l \leftarrow m = \frac{x_2 - x_1}{y_2 - y_1}$
12:     **if** $S_l < 0$ **then**
13:         $t_\theta \leftarrow \arctan(S_l) + 360$
14:     **else**
15:         $t_\theta \leftarrow \arctan(S_l)$
16:     **end if**
17:     $N_b \longleftarrow n_i, t_\theta$
18: **end while**

is twofold: finding the route and sending data. The purpose is to find an optimal route, also called an efficient link, through a process that mostly depends on neighbor information obtained using Algorithm 3 and forwards packets based on this information. Let O_θ be the optimal angle in neighbor nodes then the following equation is used to select the optimal intermediate node for packet forwarding.

$$O_\theta = \min_{i \in \{1,2,\ldots,|N_b|\}} |T_\theta - t_{\theta_i}| \tag{5.21}$$

The proposed work divides the network into source, receiver, and destination nodes with energy harvesting capabilities. When a source node has some data packets (P_{kt}) to send to the destination node (line 3), it will check its neighbor table for angles. Without neighbors, the broadcast mechanism will transmit the initialization packet (lines 4-5). If the source node has neighbors, it will first calculate the angle between the source node and the destination node (lines 7-12), then it will find the closest angle to the destination among the neighbor nodes' angles (lines 13-29).

When a node receives the initialization packet, it will check whether it is the destination node (lines 28-29). If it is the destination node, it will transmit the reply packet; otherwise, the node selects the neighbor that forms the closest angle to the destination node, regardless of whether it is the smallest or the largest angle. Essentially, the node identifies the neighbor that points most directly towards the destination node and forwards the packet to them (the same as lines 7-29). The main advantage of this process is that when a link breakage occurs, there is no need to reconstruct the route. At least one closest angle exists in the neighbor table, ensuring that the possibility of longer routes exists but will not exceed those from past research. During this process, each node will update its neighbor table every time T by receiving packets from neighbors.

5.3 Experiments and Results

The simulation used a 100×100m area as shown in Fig. 5.1 in the NS3 environment. For tracing energy consumption during simulations, a `BasicEnergySource` object with an initial energy of 1.2 Joules is installed on each node, and the remaining energy is monitored throughout the simulation. Additionally, a `WifiRadioEnergyModel` was installed on each node to examine WiFi radio energy consumption. WiFi radios consume energy during packet transmission, so the transmit current, receive current, and idle current are set to 2 mA, 2 mA, and 0.27 mA, respectively. A `BasicEnergyHarvester` object used for energy harvesting was also installed with parameters `harvestingUpdateInterval` set to 1 and `HarvestablePower` ranging from 0.0 to 0.1. Table 5.1 represents the detailed simulation parameters. In our simulation scenarios, there is only one sink and multiple nodes.

5.3.1 Performance Metrics

Performance metrics for the proposed approach include energy consumption, network lifetime, packet lost ratio (PLR), throughput, and delivery delay.

Energy Consumption *Energy consumption* can be defined as the total energy consumed by all nodes participating in data delivery.

Packet Loss Ratio *Packet Loss Ratio (PLR)* can be defined as the ratio of lost packets to the total number of sent packets.

Algorithm 4 Data Transmission with Route Discovery Algorithm

Input: Destination Node Address A_d, Information of Neighbor Nodes N_b, Source Node Coordinates (x_1, y_1), Destination Node Coordinates (x_2, y_2), Time T, Data Packet D_{pkt}.

Output: Optimal Route for Data Transmission.

At $\tau \in T_n$ where $n = 1, 2, 3, \cdots T_n$, a node wants to send a data packet (D_{pkt}).
In Source Mode
if Route to A_d is available **then**
  Transmit D_{pkt} through the existing route.
else
  Start the O_n procedure.
  if $N_b \leq 1$ **then**
    Broadcast $Init_{pkt}$
  else
    Calculate the angle T_θ between source and destination node as:
    Calculate slope $S_l \leftarrow m = \frac{x_2 - x_1}{y_2 - y_1}$
    if $S_l < 0$ **then**
      $T_\theta \leftarrow \arctan(S_l) + 360$
    else
      $T_\theta \leftarrow \arctan(S_l)$
    end if
    for t_{θ_i} of $n_i \in N_b$ **do**
      $O_\theta \leftarrow \min_{i \in \{1,2,\ldots,|N_b|\}} |T_\theta - t_{\theta_i}|$
      if O_θ is the minimum so far **then**
        $A_{doi} \leftarrow A_{ni}$ {Where A_{ni} is the address of node $n_i \in N_b$ which has the smallest value}
        $O_n \leftarrow O_\theta$ {Update the node with minimum O_θ}
      end if
    end for
    Send $Init_{pkt}$ to A_{doi} {Send the packet to the optimal node with minimum O_θ}
  end if
  End of the O_n Procedure.
  In Receiver Mode
  if Received packet at node A_{ci} is the destination node A_d **then**
    Send Rep_{pkt} to Source Node
  else
    Start the O_n procedure.
  end if
end if

Throughput *Throughput* can be defined as the amount of data (in Mb/s) that can be successfully transmitted or processed over a network within a given time frame. The formula is given in 3.1.

Packet Latency Time *Packet Latency Time* refers to the time a packet travels from the source node to the destination node, which can be calculated using the equation in 3.2 and is typically measured in milliseconds.

5.3.2 LCEHA Performance under different Distance Parameters

The optimal distance between nodes is crucial for ensuring efficient communication and data transfer within routing protocols. A well-managed spacing between nodes contributes to a streamlined flow of information, enhancing the overall performance of routing protocols and harvesting enough energy from the harvester. When the distance between nodes increases beyond the recommended threshold, the efficiency of routing protocols starts to decline.

The impact of expanding node distances extends beyond a single performance metric, affecting various aspects of the routing protocol's overall effectiveness. Maintaining an appropriate proximity between nodes promotes faster data transmission, minimizes latency, and improves network responsiveness. This section will explore various distance parameters to assess their impact on the performance metrics.

Fig. 5.3 represents the average energy consumption of nodes. It illustrates that the energy consumption is higher when the nodes are closer to each other. Due to the small distance between nodes, many problems occur, such as Idle listening, collision of packets, overhearing, and packet overhead, as discussed in section 5.1.1. As a result, the nodes can waste their energy resources. However, compared with existing works [26, 28, 38, 55], our performance is better. It is worth noting that when the number of nodes exceeds sixty, the energy consumption decreases. It can be attributed to a reduction in energy consumption per node. When the energy consumption per node decreases as the number of nodes increases, it can reduce the overall energy consumption of the network. In other words, our purpose is to reduce E_c by reducing the per-node values of E_{cp}, E_{cs}, and E_{cr} in Eq. (5.13). In Fig. 5.2, only those nodes in the direction of the destination node are selected, while the remaining nodes do not take part. The improved results can be attributed to the energy harvesting process, which prevents the energy level of a node from reaching zero. In other words, the energy-harvesting mechanism ensures that nodes in the network do not completely deplete their energy reserves. This prevention of energy depletion is a crucial factor contributing to the enhanced system or algorithm performance. By maintaining a certain level of energy in the nodes, they can continue to function and participate in the network operations effectively, leading to better overall outcomes. Consequently, the energy of other nodes can be saved, thus impacting the overall energy consumption.

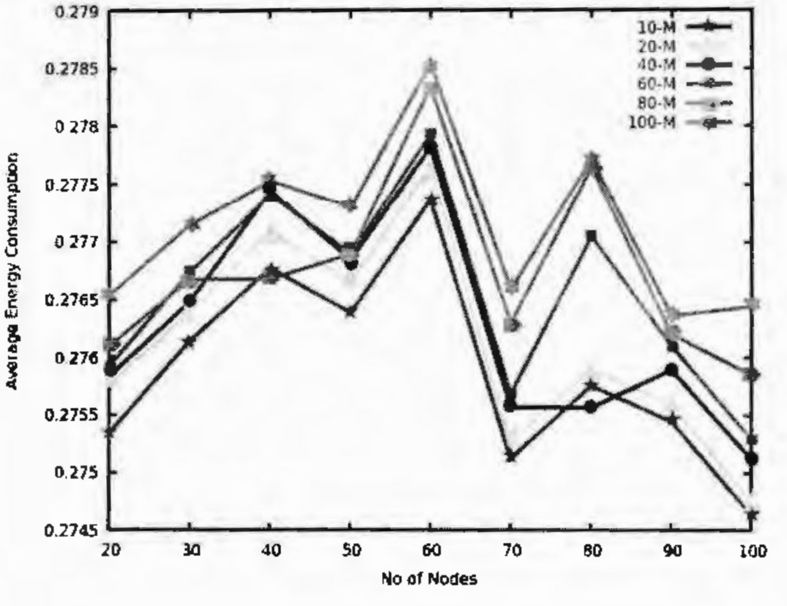

Figure 5.3: Average Energy Consumption With Different Distance Parameters

Fig. 5.4 and Fig. 5.5 depicts the average packet delivery ratio at different distances. In Fig. 5.4, the packet delivery ratio is shown for nodes between ten and forty meters apart. It is worth noting that the system's performance decreases as the network density increases. The high density causes link failure and congestion, which leads to packet drop. The high PDR means a node can harvest enough energy from the energy harvester.

On the other hand, Fig. 5.5 illustrates the average packet delivery ratio for nodes located more than 60 meters away. It is evident from the figure that the packet delivery ratio decreases as the distance between nodes increases.

Fig. 5.6 and Fig. 5.7 illustrate the delay between nodes in different distance scenarios. It can be observed that as the distance between nodes increases, the delay also increases.

The relationship between distance and delay is evident in both figures. As the nodes are placed further apart, the time required for data packets to travel between them becomes longer, resulting in increased delays. It can be attributed to the large propagation distance and potentially higher transmission power required for maintaining signal strength over greater distances.

Fig. 5.8 and Fig. 5.9 depict the average throughput between nodes in different scenarios according

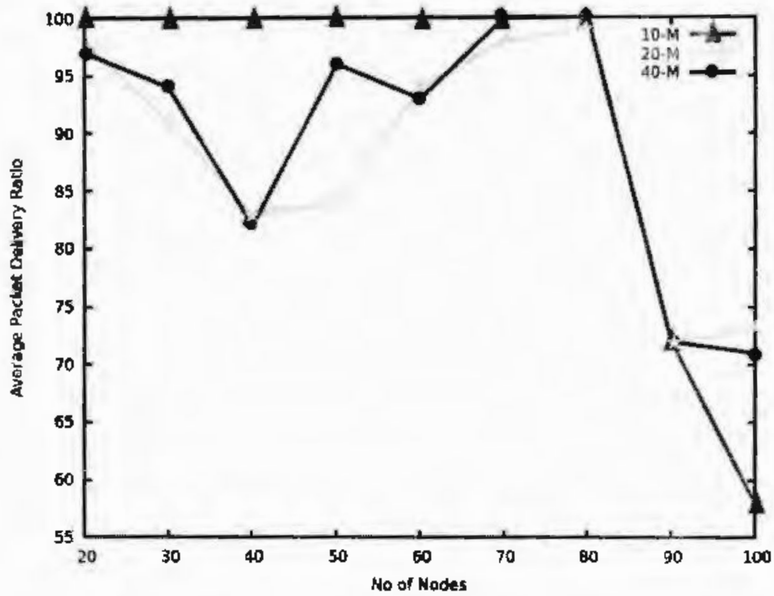

Figure 5.4: Average Packet Delivery Ratio With 10, 20, 40 M Distance Parameters

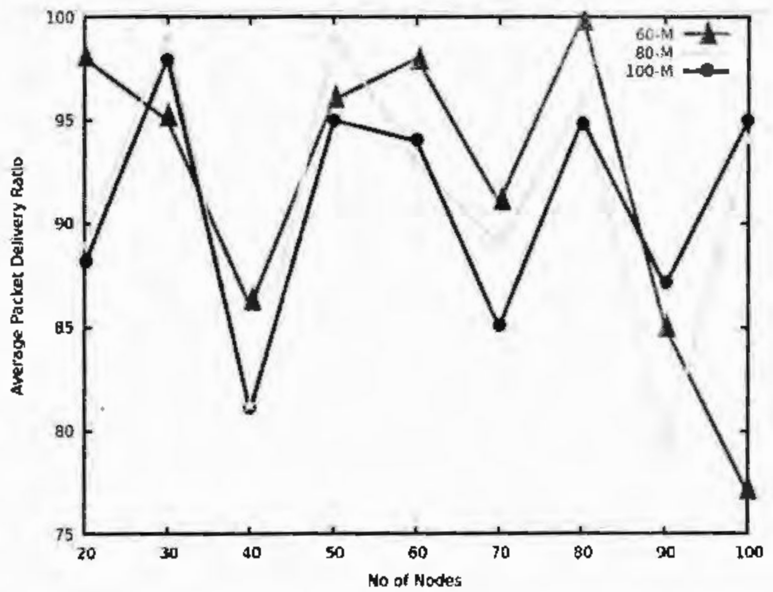

Figure 5.5: Average Packet Delivery Ratio With 60, 80, 100 M Distance Parameters

to Eq. (3.1). It is evident from the figures that our work performs better when the distance between nodes is small and the network density is low. In such scenarios, the average throughput is higher

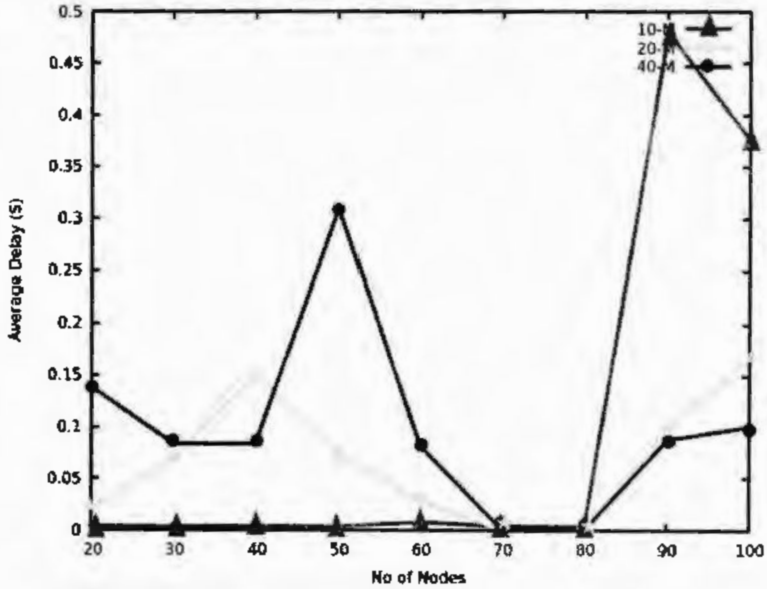

Figure 5.6: Average Delay With 10, 20, 40 M Distance Parameters

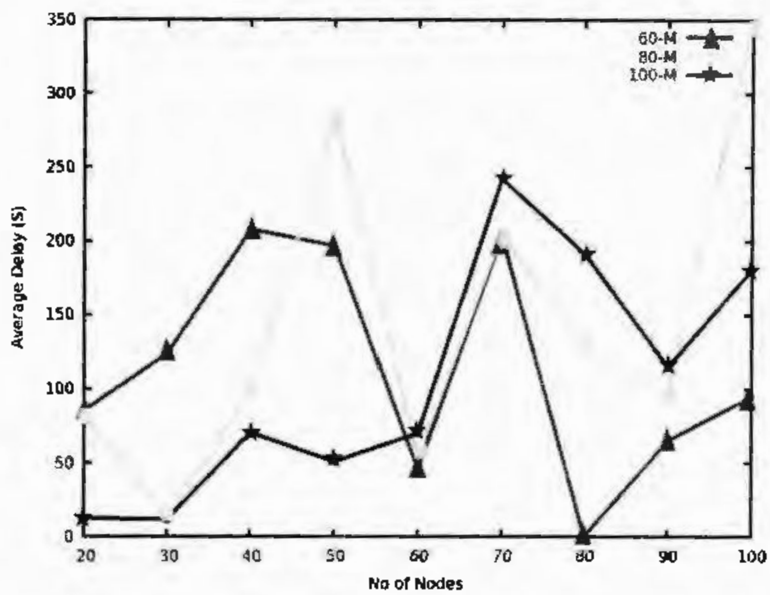

Figure 5.7: Average Delay With 60, 80, 100 M Distance Parameters

due to reduced transmission power requirements and improved signal strength over shorter distances. Moreover, a lower network density reduces congestion and improves overall throughput.

Therefore, based on the analysis of these figures, our work demonstrates superior performance in scenarios characterized by smaller distances between nodes and lower network density.

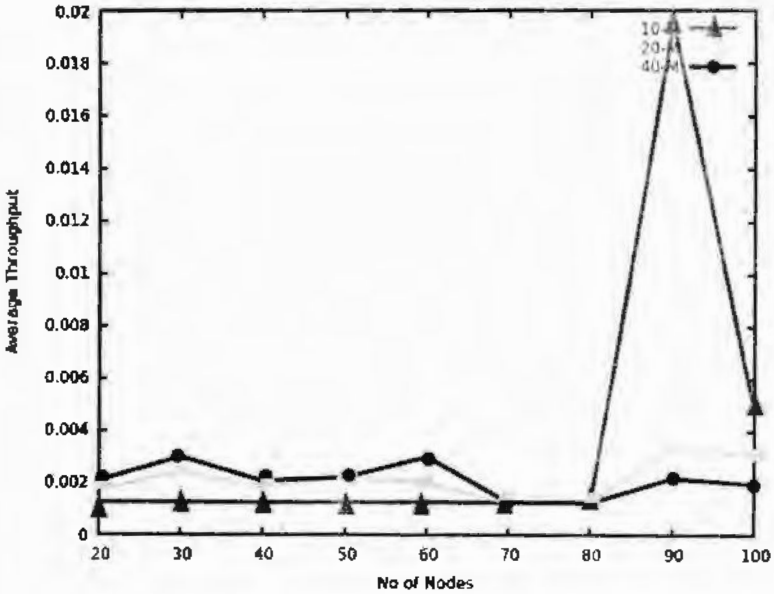

Figure 5.8: Average Throughput With 10, 20, 40 M Distance Parameters

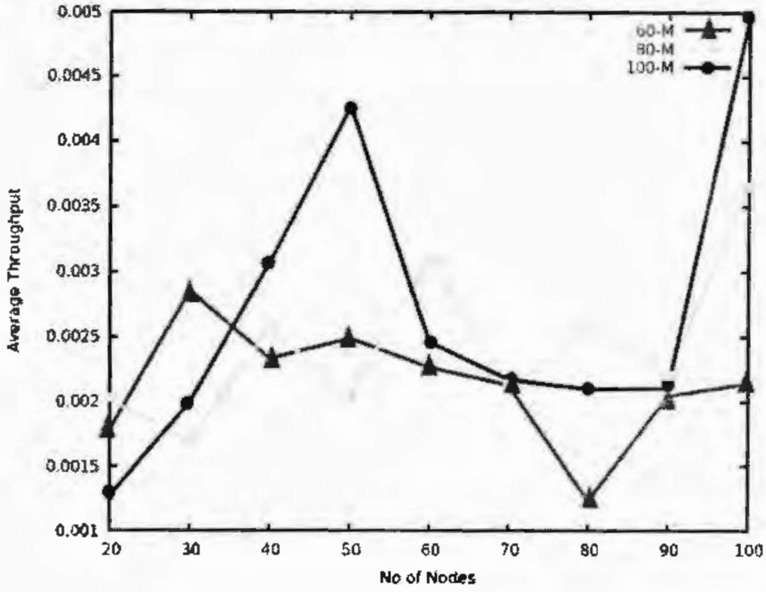

Figure 5.9: Average Throughput With 60, 80, 100 M Distance Parameters

Fig. 5.10 provides an overview of the average packet loss rate (PLR) across various scenarios. It shows a clear correlation between the distance between nodes and the PLR and between node density and the PLR. When the distance between nodes increases, the PLR also increases, indicating a higher likelihood of packet loss over longer distances. Similarly, as the node density in the network increases, the PLR also rises, suggesting that a higher concentration of nodes can lead to more packet loss. Upon closer examination, specific points in the network exhibit notable trends. For instance, when the distance between nodes is ten meters and 100 nodes present, the PLR experiences a significant increase. However, as the distance gradually increases to 20, 40, 60, 80, and 100 meters, the PLR decreases steadily. The lowest PLR is observed when the distance between nodes reaches 100 meters, and there are 100 nodes in the network.

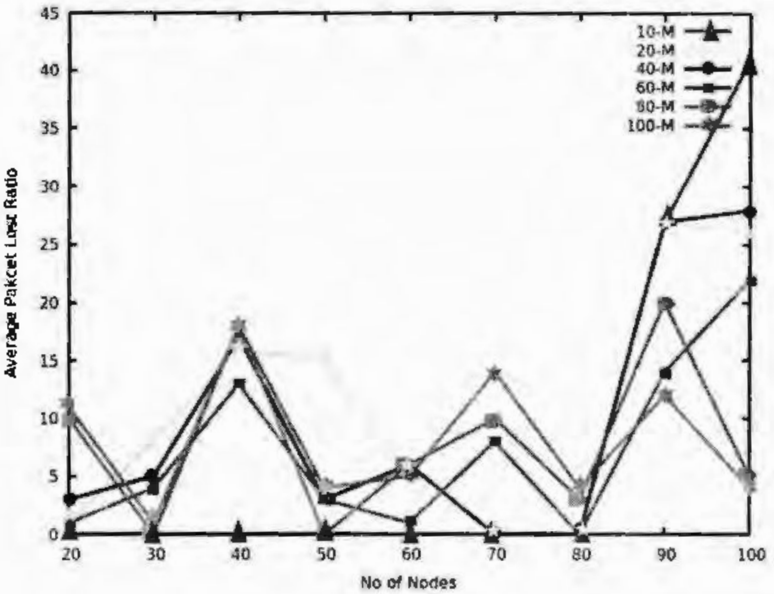

Figure 5.10: Packet Loss Ratio of 10,20,40,60,80,100 Meters Distance Parameters

5.3.3 Comparisons of EHARA, R-MPRT mode, AODV-EHA, and CFS

The work has been compared with EHARA [26], AODV-EHA [38], CFS [28], and R-MPRT [55] because these works are related to energy harvesting techniques. Fig. 5.11 and Table 5.2 represent average energy consumption comparison with EHARA, R-MPART, AODV-EHA, and cfs. Our work given shows outstanding performance compared to others. It is because the proposed work ignores the path reconstruction process, controls the broadcasting of packets by each node, and avoids traversing nodes that are not in the direction of destination nodes. Additionally, our work reduces packet sending, which is essential to our energy efficiency.

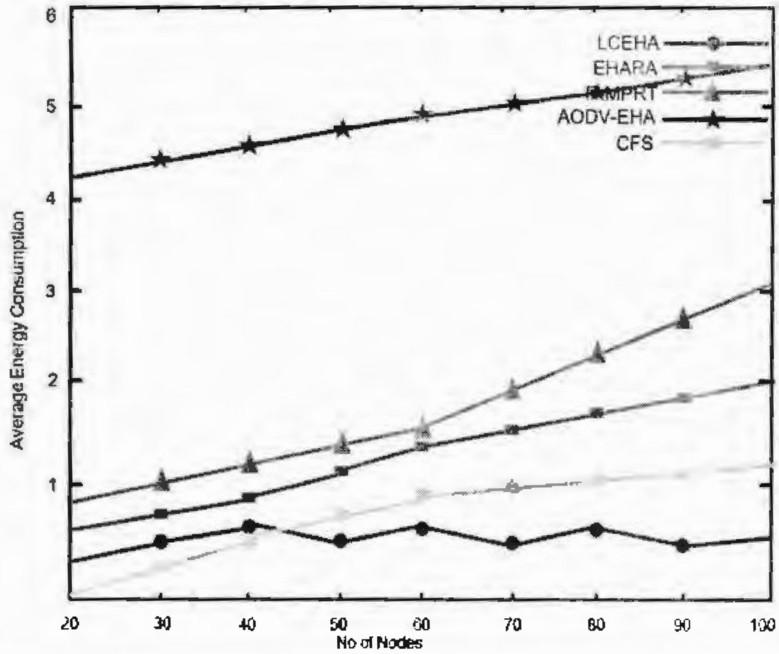

Figure 5.11: Average Energy Consumption Comparison with Proposed and Existing Works

Table 5.2: Comparison of LCEHA with existing approaches in terms of energy consumption.

Model	Energy Consumption
R-MRPT	6.450
AODV-EHA	2.764
EHARA	1.324
CFS	0.740
LCEHA	0.277

Fig. 5.12 and Table 5.3 represent average packet loss ratio comparison under different numbers of sensor nodes with EHARA, R-MPRT, and AODV-EHA. The results show a minimum packet loss ratio compared to others. The figure shows that the performance decreases as the number of nodes increases, although a zero PLR ratio is achieved for some simulations. From 20 to 70 nodes, our PLR ratio is zero, while others have more than zero. It is because at least one link exists between the source and destination nodes by sending packets through neighbor nodes. Based on the provided figure, our work is not well-suited for a dense network due to challenges such as

congestion and collision. Referring to Fig. 5.10, which displays the PLR for various distance levels, it has been observed that when the distance between nodes is ten meters, and there are 100 nodes in the network, the PLR increases significantly (peaks). As the distance increases to ten, forty, and sixty meters, the PLR decreases gradually. The lowest PLR is achieved when the distance between nodes is 100 meters and there are 100 nodes in the network.

The high PLR at small distances can be attributed to idle listening, collisions, over-hearing, and control packet overhead. Addressing and mitigating these issues can reduce the PLR to nearly zero and improve the network's overall performance.

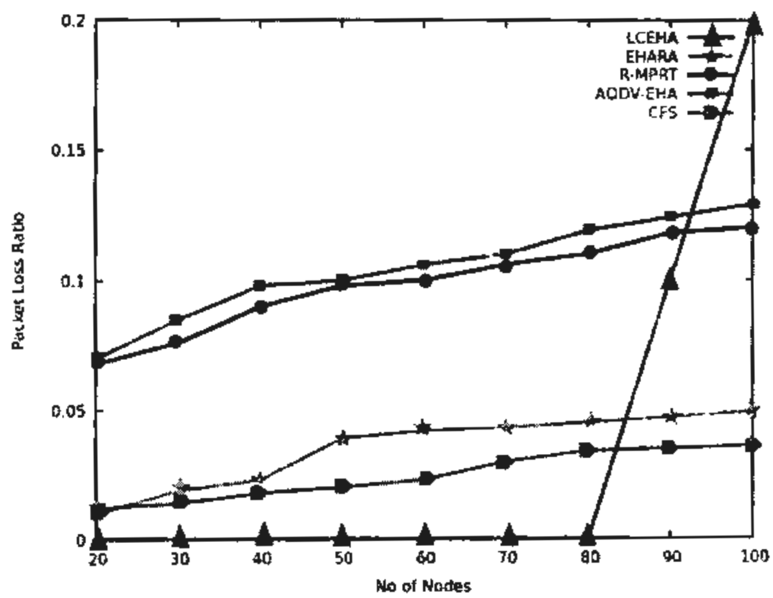

Figure 5.12: Packet Loss Ratio Comparison with Proposed and Existing Works

Table 5.3: Comparison of LCEHA with existing approaches in terms of packet loss ratio.

Model	Average PLR
R-MRPT	0.120
AODV-EHA	0.126
EHARA	0.052
CFS	0.034
LCEHA	(0% up to 80 nodes, then it increase the PLR

Fig. 5.13 and Table 5.4 illustrate the average throughput comparison between our work and other studies, demonstrating that our work outperforms the others. The proposed model evaluated the

closest angle path to enhance the routing process, which proved highly effective in finding optimal solutions and achieving a high throughput. Consequently, it can be inferred that the proposed model surpasses the existing routing mechanisms discussed in prior research, providing more precise and efficient routing decisions. This research contributes valuable insights to enhance network performance and optimize routing strategies.

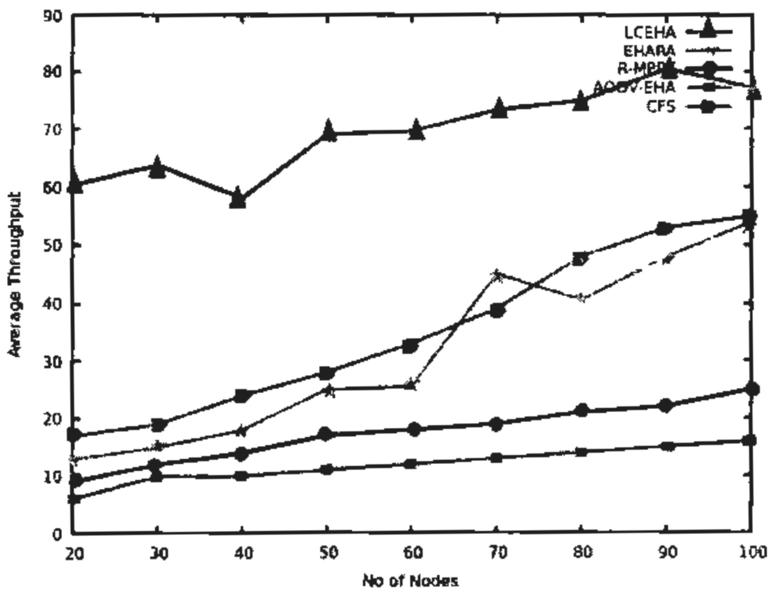

Figure 5.13: Average Throughput Comparison with Proposed and Existing Works

Table 5.4: Comparison of LCEHA with existing approaches in terms of throughput.

Model	**Average Throughput**
R-MRPT	24.833
AODV-EHA	15.926
EHARA	52.980
CFS	54.405
LCEHA	69.64

5.4 Chapter Summary

This chapter presents a location-centric energy harvesting aware routing (LCEHA) protocol to address energy utilization, lifetime enhancement, route setup delay minimization, and routing success probability maximization in the WSN-based IoT paradigm. The proposed work ensured the energy utilization factor of all nodes in the network. The proposed solution is distributed neighbor discovery and routing using neighbor information. The proposed approach is comparatively analyzed against the existing state-of-the-art. The experimental results show that the proposed work has promising results and improves energy efficiency, packet loss ratio, throughput, and delay, leading to improved network lifetime. In the future, a 3D environment may be used to check the energy efficiency of the proposed scenario.

Chapter 6

ELEH K-Means Clustering for IoT in Smart Cities

The IoT-based networks have gained significant attention in recent years due to their applications in various domains within smart cities. These domains include but are not limited to smart buildings, smart health, smart transportation, smart grid, battlefield monitoring, bird observation, glacier monitoring, and smart agriculture [16, 97].

The expansion of cities' infrastructure needs has increased demand for IoT devices within IoT networks. IoT-based networks comprise numerous wireless sensing nodes or electromechanical systems that detect various physical parameters and send them to a central location. In various smart city applications, such as smart transportation, bird observation, glacier monitoring, and smart transportation, WSNs consist of mobile sensing nodes rather than stationary ones [106].

Energy harvesting techniques are a promising solution for powering IoT-based wireless sensing nodes [107]. In this technique, the IoT-based devices can extract energy from given resources and convert it to DC for replenishment [108, 109]. These resources include the sun, wind, or RF signals. While RF sources provide relatively lower energy than natural sources, their constant availability makes them more reliable. Thus, RF sources are an ideal choice for energizing wireless sensing nodes.

Many challenges in IoT-based Networks have arisen, such as link/path discovery time, delay, packet loss, power consumption, network failures, scalability, and elevated operational costs [100, 110, 111]. Routing in IoT-based networks is crucial in finding the path/link from the source to the destination node, which can decide the protocol's efficiency. If the selected link/path is efficient, it can decrease energy consumption and delay increase PDR, and throughput. The routing process must be efficient; however, it should also reduce the number of messages exchanged while finding new or rebuilding broken paths. The more messages exchanged, the more the energy consumption.

An efficient link/path selection strategy is crucial to efficiently tackle energy consumption, discovery time of link/path, delay, packet loss, and network failure problems. An optimal link/path selection strategy can improve network performance, leading to longer network life.

The research community presented location-based link/path selection [112], flat-based link/path selection, and hierarchical-based link/path selection. All nodes participate in the routing process in a flat link/path selection strategy. In location-based, the link/path is selected through location information [112]. In the hierarchical/cluster strategy, the nodes are divided into groups to minimize the energy and solve the scalability problems.

Several clustering techniques such as LEACH, K-means, Kmeans-Leach, and Kmeans-AODV-ACO have been proposed [46, 69–75], each with distinct methods for centroid selection, cluster formation, CH selection, and routing. Centroid selection methods involved random selection, two-dimensional coordinate-based approaches, and considerations of high node density. Cluster formation strategies included adding nodes to clusters closest to centroids, grouping nodes closest to each other, or combining clusters with the nearest minimum average distances. CH selection methods encompass dynamic approaches, multi-criteria methods considering energy, degree, mobility, and packet drop, and selecting nodes with the highest residual energy. Routing techniques ranged from AODV routing and the Firefly Algorithm to utilizing CH selection.

These approaches are practical in solving problems such as prolonging the network lifespan, efficiently dividing the nodes into clusters and better routing techniques. However, these methods suffer from several issues, such as problems with selecting the optimal centroid points, cluster formation, and optimal routing strategy, which can lead to sub-problems such as the construction of optimal path/link during routing, difficulties in maintaining routes, energy wastage, delay, and increased communication complexities. Furthermore, in some studies [46, 74], researchers incorporated mechanisms for re-routing or re-selecting CH in the event of node or link failures. Additionally, this research has introduced a new problem related to cluster selection during routing. This problem can be described as follows: in traditional K-means routing algorithms, the initial cluster for data transmission is chosen randomly. It doesn't take into account the direction of the destination node. This can result in the unnecessary traversal of clusters outside the direct path of the destination node, leading to the wastage of time and energy. In simpler terms, the traditional method of selecting clusters for data transmission doesn't consider the direction of the destination node or whether a cluster is located at the most direct angle to the destination node. This can result in the inefficient use of energy and time, as clusters that don't align with the destination node's direction are unnecessarily accessed during data transmission.

This thesis introduces a solution to tackle the previously mentioned issues. An angle-based approach is used to enhance the selection of clusters for efficient data transmission in the direction of the destination node. The centroids are chosen through the closest angle to the destination. In cluster formation, the nodes with the nearest angle to each other are combined. The nodes with the closest angle to the destination will be chosen in CH selection. The routing is done through the closest CH to the destination node.

The primary contribution of this research work can be summarized as follows:

- To develop a cluster selection mechanism that considers the destination node's direction for more efficient routing in IoT networks.
- Introducing a modified K-means-based location-centric energy harvesting aware cluster protocol (MK-LCEHACP) based routing solution that considers the node's angle. This approach enables multi-hop communications between the cluster and the base station (BS), providing a comprehensive routing solution.
- MK-LCEHACP technique performs well in terms of energy efficiency, consumes less energy while transmitting data, and achieves maximum PDR and throughput rate.

6.1 System model and Preliminaries

This chapter describes the system model for the proposed scheme. The system model can be divided into three parts: The node model, the network model, and the energy consumption model. Each of these models is briefly described as follows.

6.1.1 Node Model

In this study, the devices are considered heterogeneous in IoT networks, and the heterogeneity comes from the initial energy, residual energy, link capacity, energy consumption, sensing capacity, energy harvesting capacity, and even transmission range. The EH module's primary function is to

6.1.3 Energy Consumption Model

The presented work is based on energy harvesting-aware routing, so energy consumption and energy harvesting are crucial factors for designing such protocols. Each node should know the energy consumption rate while participating in the communication process. The communication process is mainly based on packet transmission, reception, internal processes, and the node's operational mode (such as sleeping, working, or recharging).

In this study, the radio model presented in the work of Heinzelman et al. [69] is used. This model efficiently describes the relationship between energy consumption and data transmission for energy harvesting-aware routing protocols.

Eq. (5.6) is used to calculate the energy consumption during the packet transmission process in the network, while Eq. (5.7) is used to calculate the energy consumption after a packet receiving process. These equations are the general form for calculating energy consumption in radio-based routing protocols because several important factors can affect the overall energy consumption of the network. These factors include the distance between neighbor nodes, network density, packet transmission and receiving rate, and packet size. These factors are related, so the solution of one factor can lead us to the solution of other factors. For instance, solving the distance between nodes problem can affect (increase) the PDR and reduce energy consumption. If the data problems solved among nodes, then it can also reduce energy consumption. The following sections have described these factors in detail:

Energy Consumption by Processing Unit: The energy consumption by processing unit is represented in Eq. 5.8. The hardware design, clock frequency, and computational workload can affect the energy consumption of the processing unit. The energy consumption rate by these factors can determine the manufacturer or through measurement.

Energy Consumption by Transmission of Packets: The energy consumption by transmission of packets is represented in Eq. 5.9.

Energy Consumption by Receiving of Packets: The energy consumption by receiving a packet by nodes is represented in Eq. 5.10.

Energy Consumption by Discovering Neighbor Nodes: Discovering and maintaining network nodes is a crucial aspect of network maintenance. It ensures the continuous and uninterrupted operation of the network. This phenomenon can be understood and expressed through an equation that combines the factors of node discovery and ongoing maintenance. By effectively discovering new nodes and proactively maintaining the network's functionality, optimizing the overall performance and reliability of the network can be achieved. The energy consumption by discovering neighbor nodes is represented in equation Eq. 5.11. When allocating one second for the neighbor discovery process, it corresponds to the transmission of a single packet within that time frame. However, extending the neighbor discovery process to ten seconds allows for transmitting multiple packets over this extended duration.

And for packet receiving Eq. 5.12 is used.

The overall energy consumption can be expressed as Eq. 5.13.

Table 6.1: Notations

Symbol	**Description**
E_{cp}	Energy consumption by node process unit
E_{cs}	Energy consumption by transmission of packet
E_{cr}	Energy consumption by receiving of packet
E_{cns}	Energy consumption by sender nodes discovering neighbors nodes
E_{cnr}	Energy consumption by receiver node discovering neighbors nodes
T_{en}	Total energy consumption per node
E_c	Total energy consumption by nodes after EH
T_θ	Angle Between Sender and Receiver
N_θ	Neighbor Node Angles in Neighbor Table
A_{si}	Selected Address of Closest Angle Node
A_{ci}	Current Node Address
A_{ni}	Neighbor Node Address
A_d	Destination Node Address

6.1.4 Node Energy Harvesting Model

The energy harvesting model represents harvesting energy from the environment and converting it into usable electrical energy. A general representation of the energy harvesting equation is as follows:

$$E_h = \eta \times P_h \times t \tag{6.1}$$

$(\eta_r f)$. It indicates that a more robust RF signal, higher capture coefficient, and higher energy harvesting circuit efficiency will produce higher harvested power.

After the harvesting process, the total energy of the node can be expressed as follows:

$$T_{en} = E_0 + \sum E_h \tag{6.4}$$

The following equation can be used to compute a node's residual energy.

$$E_r = T_{en} - \sum T_{ec} \tag{6.5}$$

The proposed work reduces the network's energy consumption using different parameters as described in Eq. 5.13. The aim is to develop and implement strategies for energy efficiency that optimize the parameters individually by each node, leading to reduced energy consumption. Further, the proposed techniques aim to design an efficient routing strategy considering energy harvesting to enhance the overall network energy efficiency.

6.2 Proposed Approach

To improve the performance of the clustering approach, this work introduces an approach for selecting optimal clusters based on the closest angle to the destination in IoT-based EH-enabled WSNs. The proposed approach adopts the K-means clustering algorithm incorporating an angle-based mechanism for cluster selection called Location Centeric Energy Harvesting Aware Clustering Protocol (MK-LCEHACP). It combines the strengths of the K-means algorithm with the closest angle-based approach to achieve better clustering in IoT-based EH-enabled WSNs.

K-means clustering is a widely used technique with applications in various fields such as data mining and ad hoc networks, particularly in Mobile Ad Hoc Networks (MANETs). It is recognized for its simplicity in implementation and quick convergence. The primary goal of K-means is to minimize the average squared Euclidean distance between data points and their respective cluster centers. The basic K-means algorithm [35] begins by selecting an initial set of cluster centers, denoted by 'K.' It then proceeds to organize the data into a specified number of clusters (assumed to be 'k'). The fundamental concept involves determining 'k' centroids, with each centroid representing a distinct cluster. Despite its simplicity and efficiency, K-means does have drawbacks that need to be considered, such as the challenges related to node distribution and the fixed nature of CHs and members.

6.2.1 Modified K-means based LCEHACP Algorithms

Algorithm 5 identifies centroid points for the subsequent cluster formation process. It employs two angles: the angle between the source and destination node and the angle between each pair of network nodes. The primary objective is to construct a set of angles between nodes. The algo-

Algorithm 5 Selection of Centroid Points

Input: $X = \{x_1, \ldots, x_n\}$
Output: Centroid Points: M

Calculate Angle T_θ between source and destination nodes as:
Calculate slope $S_l \leftarrow m = \frac{x_2-x_1}{y_2-y_1}$
if $S_l < 0$ **then**
    $T_\theta \leftarrow \arctan(S_l) + 360$
else
    $T_\theta \leftarrow \arctan(S_l)$
end if
for $i = 1$ to n **do**
    Calculate Angle t_θ between current node and all nodes as:
    Calculate slope as $S_l \leftarrow m = \frac{x_2-x_1}{y_2-y_1}$.
    if $S_l < 0$ **then**
        $t_\theta \leftarrow \arctan(S_l) + 360$
    else
        $t_\theta \leftarrow \arctan(S_l)$
    end if
end for
$t_\theta = \{t_{\theta_1}, t_{\theta_2}, t_{\theta_3} \ldots, t_{\theta_n}\}$
Divide t_θ in X groups with same angles.
for $i = 1$ to X **do**
    for $j = 1$ to n **do**
        Select node μ_i among t_θ with smallest angle to destination node as: $\mu_i = |T_\theta - t_{\theta_j}|$
    end for
end for
return $M = \{\mu_1, \mu_2, \ldots, \mu_i\}$

rithm then organizes these angle sets and groups them according to specified criteria, eventually selecting nodes with the smallest angles within their respective sets. These chosen nodes become the centroid points for the clusters.

In simpler terms, the algorithm establishes a measure of angular relationships between nodes, clusters these angles, and strategically chooses nodes with the least angular difference to serve as the initial centers for cluster formation.

From lines 1 to 6, the algorithm computes the angle between the source and destination node in the network. This angle represents the directional relationship between the data transmission's starting point (source) and the endpoint (destination).

Moving on to lines 7 through 14, the algorithm calculates the angles between each node in the network. This step involves determining the angular orientation of every individual node concerning the source and destination.

Finally, lines 15 to 22 depict the process of selecting centroid points. The algorithm forms sets of angles obtained in the previous steps and divides them based on specified criteria. The nodes with the smallest angles within their respective sets are then identified as the centroid points for the subsequent cluster formation.

Algorithm 6 is designed to create clusters and determine the Optimal CH within the network. The algorithm initiates by computing the angle between each node and the previously selected centroid points.

Starting from line 1, the algorithm systematically calculates the angles between every node and each of the chosen centroids. This step provides a measure of the directional orientation of each node concerning the identified cluster centers.

Subsequently, nodes are assigned to specific clusters based on the centroid with the smallest angle, as outlined in lines 3 to 5. This allocation ensures that nodes are grouped with the closest directional alignment centroid.

In lines 7 through 12, the algorithm determines the most forward distance within each formed cluster. This distance calculation considers the proximity of nodes to the destination node, emphasizing the importance of forwarding data efficiently.

The algorithm concludes by selecting the Optimal CH for each cluster. This CH is chosen based on the node within the cluster that possesses the furthest forward distance to the destination node. The algorithm outputs both the created clusters and the identification of the Optimal CH for each cluster.

In summary, Algorithm 6 effectively forms clusters by associating nodes with centroid points and selects an Optimal CH within each cluster based on the node with the greatest forward distance to the destination node.

Algorithm 6 Cluster Formation and Optimal CH Selection

Input: $M = \{\mu_1, \mu_2, \ldots, \mu_k\}$ {Input: Centroid Points}
Input: $X = \{x_1, x_2, \ldots, x_n\}$ {Input: Data Points}
Output: Clusters $C_1, C_2, \ldots, C_k$ and Optimal CH O_{ch}

for $i = 1$ to n **do**
  for $j = 1$ to k **do**
    Calculate $\theta_{ij} \leftarrow \arctan\left(\frac{y_i - \mu_{j,y}}{x_i - \mu_{j,x}}\right)$
  end for
  Assign node to the cluster $C_i = \text{argmin}_j(\theta_{ij})$
end for
for $j = 1$ to k **do**
  Calculate the most forward distance κ_j of nodes in C_j to the destination node
  $\kappa_j = \max_{x_i \in C_j} \text{Distance}(x_i, x_{\text{destination}})$ {Maximum distance within cluster C_j}
end for
$O_{ch} = \text{argmax}_j(\kappa_j)$ {Select the cluster with the most forwarded distance}
return Clusters $C_1, C_2, \ldots, C_k$ and Optimal CH O_{ch}

Finally, the algorithm returns the selected optimal CH. The data packets are sent to CH and finally reach the destination node in the data forwarding algorithm 7.

Algorithm 7 Data Forwarding Algorithm

Input: Optimal route O_{ch} obtained from algorithm 6
Output: Dissemination of data packet

while O_{ch} **do**
  Select the closest CH to the destination node and forward the data packet
  if I am destination **then**
    halt;
  else
    Select the next closest angle to the destination node among neighbor nodes and send the packet to the CH.
  end if
end while

6.3 Results and Analysis

The simulation was conducted in an NS3 environment, covering an area of 100×100 m square meters, as illustrated in Fig. 6.1. Energy-related aspects were closely monitored during the simulations. Each IoT device is equipped with `BasicEnergySource` fixing initial energy with 1.2 Joules, which is used for energy consumption observation in the overall network. Moreover, IoT devices are equipped with `WifiRadioEnergyModel` component, which is used for analyzing the energy consumption during radio operations. Furthermore, `BasicEnergyHarvester` components are also integrated with IoT devices to harvest the energy from RF-based signals. The purpose of this model is to observe the energy consumption and harvesting during packet transmission, with specified current values for transmission, reception, and idle states. Table 6.2 summarizes the simulation parameters used in experiments.

Table 6.2: Simulation parameters for the Proposed work

Parameter	**Value**
Simulator used	NS3
Simulation Area	100×100m, 900×700m
Simulation time	50,200
Number of nodes	20, 30, 40
Minimum speed	28 ms
Network Interface types	Wireless
Initial Transmit Power	0.5

Several performance metrics are used to evaluate the performance of the proposed scheme in different simulation scenarios. The metrics include Energy Consumption, Packet Loss Ratio (PLR), Packet Latency Time (PLT), Throughput, and PDR. The details are described in the following sections:

6.3.1 Energy Consumption

As discussed in section 6.1, the proposed work is based on energy harvesting, so each node should know the energy harvesting and energy consumption rate during communication. This metric decides the efficiency of any routing protocol regarding energy consumption in IoT-based networks.

6.3.2 Packet Loss Ratio

Several factors can degrade the network's reliability, efficiency, and performance in energy harvesting-based routing protocols. These include the distance between nodes, the sink/BS distance from the nodes, the density of the network, and the current energy level. One of the main factors in this is the packet loss ratio (PLR), which is the lost packets that have not reached the destination node during networking.

6.3.3 Throughput

As discussed above, several factors can degrade the network's reliability, efficiency, and performance. Throughput is another factor that can reflect the reliability of the network. In the routing process, sensed data are sensed to the destination node in a given time frame; when these data reach the destination successfully, this is called the network's throughput. Let T_p indicate the throughput parameter, R_x be the total bytes received at the destination node in total time T_n; then the throughput equation can be model as equation 3.1.

6.3.4 Packet Latency Time

Packet Latency Time is when a packet successfully travels from the source node to the destination node. It helps us understand the delay experienced by data packets during transmission. Let D_l be the delay parameter, D_s be the sum of all delay time, and T_x be the total transmitter packet, then the equation for calculating Packet Latency Time is presented in 3.2. The unit of measurement for the Packet Latency Time is milliseconds (ms).

In the context of varying distance parameters, the optimal spacing between nodes plays a crucial role in the efficiency of communication and data transfer within routing protocols. Maintaining the proper node distance ensures smoother information flow, leading to enhanced routing protocol performance and efficient energy harvesting. When node distances exceed recommended thresholds, the efficiency of routing protocols diminishes, affecting multiple performance metrics. The impact of increased node distances extends beyond a single performance metric, influencing aspects like data transmission speed, latency reduction, and network responsiveness. This section explores different distance parameters and analyzes how they affect performance metrics.

Fig. 6.2 illustrates the average energy usage of nodes situated at varying distances. The graph indicates that energy consumption and distance have a direct relationship. As the distance between convert ambient energy sources, such as solar energy, vibration, and electromagnetic waves, into electricity. In this specific case, the EH module utilizes piezoelectric technology to capture RF energy, as referenced in several sources [16, 113]. The electricity generated from this energy harvesting process is then stored in an energy storage unit. Two options are available for this purpose: (i) chemical rechargeable batteries, which store energy through chemical reactions, and (ii) supercapacitors, which store energy in electrostatic energy. Supercapacitors are preferred in this work due to their notable features, including a long cycle life and high power density [16].

6.1.2 Network Model

The system consists of a set of N IoT-based devices deployed in a two-dimensional area. The IoT-based devices are deployed randomly, meaning their locations are not predetermined. Every IoT-based device can move at a random speed in any direction. Initially, all nodes have equal initial energy. All IoT-based devices are equipped with energy harvesting capabilities from the surrounding environment, such as RF. All links are symmetrical, meaning each node can communicate with neighboring nodes.

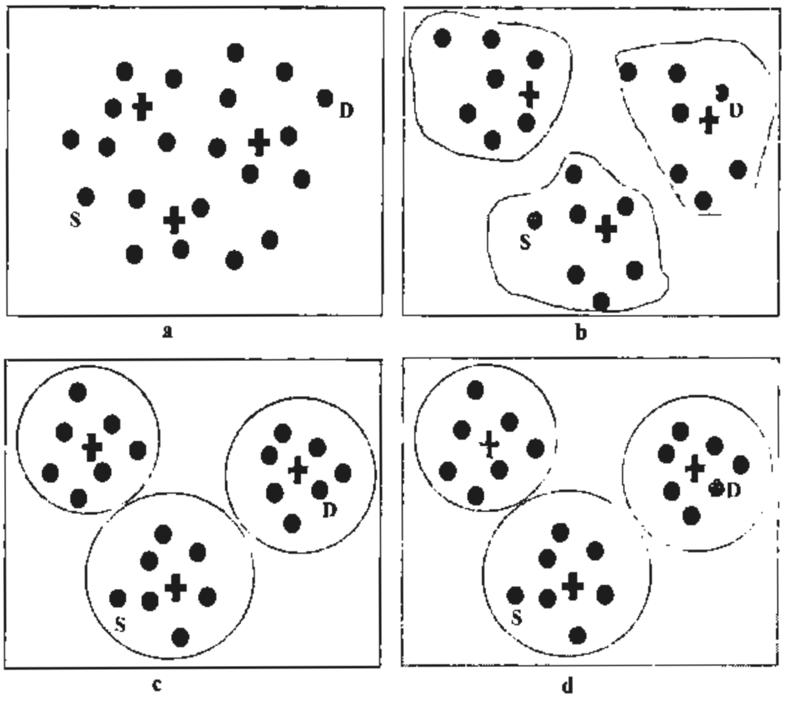

Figure 6.1: Network Model

6.1.3 Energy Consumption Model

The presented work is based on energy harvesting-aware routing, so energy consumption and energy harvesting are crucial factors for designing such protocols. Each node should know the energy consumption rate while participating in the communication process. The communication process is mainly based on packet transmission, reception, internal processes, and the node's operational mode (such as sleeping, working, or recharging).

In this study, the radio model presented in the work of Heinzelman et al. [69] is used. This model efficiently describes the relationship between energy consumption and data transmission for energy harvesting-aware routing protocols.

Eq. (5.6) is used to calculate the energy consumption during the packet transmission process in the network, while Eq. (5.7) is used to calculate the energy consumption after a packet receiving process. These equations are the general form for calculating energy consumption in radio-based routing protocols because several important factors can affect the overall energy consumption of the network. These factors include the distance between neighbor nodes, network density, packet transmission and receiving rate, and packet size. These factors are related, so the solution of one factor can lead us to the solution of other factors. For instance, solving the distance between nodes problem can affect (increase) the PDR and reduce energy consumption. If the data problems solved among nodes, then it can also reduce energy consumption. The following sections have described these factors in detail:

Energy Consumption by Processing Unit: The energy consumption by processing unit is represented in Eq. 5.8. The hardware design, clock frequency, and computational workload can affect the energy consumption of the processing unit. The energy consumption rate by these factors can determine the manufacturer or through measurement.

Energy Consumption by Transmission of Packets: The energy consumption by transmission of packets is represented in Eq. 5.9.

Energy Consumption by Receiving of Packets: The energy consumption by receiving a packet by nodes is represented in Eq. 5.10.

Energy Consumption by Discovering Neighbor Nodes: Discovering and maintaining network nodes is a crucial aspect of network maintenance. It ensures the continuous and uninterrupted operation of the network. This phenomenon can be understood and expressed through an equation that combines the factors of node discovery and ongoing maintenance. By effectively discovering new nodes and proactively maintaining the network's functionality, optimizing the overall performance and reliability of the network can be achieved. The energy consumption by discovering neighbor nodes is represented in equation Eq. 5.11. When allocating one second for the neighbor discovery process, it corresponds to the transmission of a single packet within that time frame. However, extending the neighbor discovery process to ten seconds allows for transmitting multiple packets over this extended duration.

And for packet receiving Eq. 5.12 is used.

The overall energy consumption can be expressed as Eq. 5.13.

Table 6.1: Notations

Symbol	Description
E_{cp}	Energy consumption by node process unit
E_{cs}	Energy consumption by transmission of packet
E_{cr}	Energy consumption by receiving of packet
E_{cns}	Energy consumption by sender nodes discovering neighbors nodes
E_{cnr}	Energy consumption by receiver node discovering neighbors nodes
T_{en}	Total energy consumption per node
E_c	Total energy consumption by nodes after EH
T_θ	Angle Between Sender and Receiver
N_θ	Neighbor Node Angles in Neighbor Table
A_{si}	Selected Address of Closest Angle Node
A_{ci}	Current Node Address
A_{ni}	Neighbor Node Address
A_d	Destination Node Address

6.1.4 Node Energy Harvesting Model

The energy harvesting model represents harvesting energy from the environment and converting it into usable electrical energy. A general representation of the energy harvesting equation is as follows:

$$E_h = \eta \times P_h \times t \tag{6.1}$$

Where η represents the energy conversion efficiency, P_h represents the harvested power, and t represents the harvesting time duration. This equation calculates the total harvested energy with harvested power and total harvesting time duration. The conversion of harvested power into usable electrical energy (in other words, to DC) is also considered in the energy conversion efficiency (η) parameter.

The η can be more elaborated with the power conversion losses or inefficiencies in the energy harvesting. So the equation for η can be model as:

$$\eta = P_o / P_{in} \tag{6.2}$$

Where P_o represents the usable electrical power obtained from the energy harvesting. P_{in} represents the total harvested power, including the energy obtained from the environment. This equation, η, is the usable electrical power output ratio to the total harvested power input. It measures the efficiency with which the harvested power is converted into usable energy.

P_h can be obtained from RF energy harvesting. In RF energy harvesting, the harvested power (P_h) can be estimated based on the received RF signal strength and the efficiency of the energy harvesting circuit. The equation for harvested power in RF energy harvesting can be represented as:

$$P_h = C * |E|^2 * \eta_r f \tag{6.3}$$

where C represents the capture coefficient or antenna sensitivity, which characterizes the efficiency of capturing the RF energy.

The antenna structure plays an essential role in the EH process, as mentioned by [114] in their real-world experiments. $|E|^2$ represents the magnitude squared of the electric field strength of the RF signal, which represents the power density of the received RF signal. $\eta_r f$ represents the efficiency of the RF energy harvesting circuit, which accounts for losses and conversion efficiency in the energy harvesting process.

The equation states that the harvested power is proportional to the capture coefficient (C), the square of the electric field strength ($|E|^2$), and the efficiency of the RF energy harvesting circuit

$(\eta_r f)$. It indicates that a more robust RF signal, higher capture coefficient, and higher energy harvesting circuit efficiency will produce higher harvested power.

After the harvesting process, the total energy of the node can be expressed as follows:

$$T_{en} = E_0 + \sum E_h \tag{6.4}$$

The following equation can be used to compute a node's residual energy.

$$E_r = T_{en} - \sum T_{ec} \tag{6.5}$$

The proposed work reduces the network's energy consumption using different parameters as described in Eq. 5.13. The aim is to develop and implement strategies for energy efficiency that optimize the parameters individually by each node, leading to reduced energy consumption. Further, the proposed techniques aim to design an efficient routing strategy considering energy harvesting to enhance the overall network energy efficiency.

6.2 Proposed Approach

To improve the performance of the clustering approach, this work introduces an approach for selecting optimal clusters based on the closest angle to the destination in IoT-based EH-enabled WSNs. The proposed approach adopts the K-means clustering algorithm incorporating an angle-based mechanism for cluster selection called Location Centeric Energy Harvesting Aware Clustering Protocol (MK-LCEHACP). It combines the strengths of the K-means algorithm with the closest angle-based approach to achieve better clustering in IoT-based EH-enabled WSNs.

K-means clustering is a widely used technique with applications in various fields such as data mining and ad hoc networks, particularly in Mobile Ad Hoc Networks (MANETs). It is recognized for its simplicity in implementation and quick convergence. The primary goal of K-means is to minimize the average squared Euclidean distance between data points and their respective cluster centers. The basic K-means algorithm [35] begins by selecting an initial set of cluster centers, denoted by 'K.' It then proceeds to organize the data into a specified number of clusters (assumed to be 'k'). The fundamental concept involves determining 'k' centroids, with each centroid representing a distinct cluster. Despite its simplicity and efficiency, K-means does have drawbacks that need to be considered, such as the challenges related to node distribution and the fixed nature of CHs and members.

6.2.1 Modified K-means based LCEHACP Algorithms

Algorithm 5 identifies centroid points for the subsequent cluster formation process. It employs two angles: the angle between the source and destination node and the angle between each pair of network nodes. The primary objective is to construct a set of angles between nodes. The algo-

Algorithm 5 Selection of Centroid Points

Input: $X = \{x_1, \ldots, x_n\}$
Output: Centroid Points: M

```
Calculate Angle T_θ between source and destination nodes as:
Calculate slope S_l ← m = (x_2 − x_1)/(y_2 − y_1)
if S_l < 0 then
    T_θ ← arctan(S_l) + 360
else
    T_θ ← arctan(S_l)
end if
for i = 1 to n do
    Calculate Angle t_θ between current node and all nodes as:
    Calculate slope as S_l ← m = (x_2 − x_1)/(y_2 − y_1).
    if S_l < 0 then
        t_θ ← arctan(S_l) + 360
    else
        t_θ ← arctan(S_l)
    end if
end for
t_θ = {t_θ1, t_θ2, t_θ3 ..., t_θn}
Divide t_θ in X groups with same angles.
for i = 1 to X do
    for j = 1 to n do
        Select node μ_i among t_θ with smallest angle to destination node as: μ_i = |T_θ - t_θj|
    end for
end for
return M = {μ_1, μ_2, ..., μ_i}
```

rithm then organizes these angle sets and groups them according to specified criteria, eventually selecting nodes with the smallest angles within their respective sets. These chosen nodes become the centroid points for the clusters.

In simpler terms, the algorithm establishes a measure of angular relationships between nodes, clusters these angles, and strategically chooses nodes with the least angular difference to serve as the initial centers for cluster formation.

From lines 1 to 6, the algorithm computes the angle between the source and destination node in the network. This angle represents the directional relationship between the data transmission's starting point (source) and the endpoint (destination).

Moving on to lines 7 through 14, the algorithm calculates the angles between each node in the network. This step involves determining the angular orientation of every individual node concerning the source and destination.

Finally, lines 15 to 22 depict the process of selecting centroid points. The algorithm forms sets of angles obtained in the previous steps and divides them based on specified criteria. The nodes with the smallest angles within their respective sets are then identified as the centroid points for the subsequent cluster formation.

Algorithm 6 is designed to create clusters and determine the Optimal CH within the network. The algorithm initiates by computing the angle between each node and the previously selected centroid points.

Starting from line 1, the algorithm systematically calculates the angles between every node and each of the chosen centroids. This step provides a measure of the directional orientation of each node concerning the identified cluster centers.

Subsequently, nodes are assigned to specific clusters based on the centroid with the smallest angle, as outlined in lines 3 to 5. This allocation ensures that nodes are grouped with the closest directional alignment centroid.

In lines 7 through 12, the algorithm determines the most forward distance within each formed cluster. This distance calculation considers the proximity of nodes to the destination node, emphasizing the importance of forwarding data efficiently.

The algorithm concludes by selecting the Optimal CH for each cluster. This CH is chosen based on the node within the cluster that possesses the furthest forward distance to the destination node. The algorithm outputs both the created clusters and the identification of the Optimal CH for each cluster.

In summary, Algorithm 6 effectively forms clusters by associating nodes with centroid points and selects an Optimal CH within each cluster based on the node with the greatest forward distance to the destination node.

Algorithm 6 Cluster Formation and Optimal CH Selection

Input: $M = \{\mu_1, \mu_2, \ldots, \mu_k\}$ {Input: Centroid Points}
Input: $X = \{x_1, x_2, \ldots, x_n\}$ {Input: Data Points}
Output: Clusters $C_1, C_2, \ldots, C_k$ and Optimal CH O_{ch}
for $i = 1$ to n **do**
  for $j = 1$ to k **do**
    Calculate $\theta_{ij} \leftarrow \arctan\left(\frac{y_i - \mu_{j,y}}{x_i - \mu_{j,x}}\right)$
  end for
  Assign node to the cluster $C_i = \text{argmin}_j(\theta_{ij})$
end for
for $j = 1$ to k **do**
  Calculate the most forward distance κ_j of nodes in C_j to the destination node
  $\kappa_j = \max_{x_i \in C_j} \text{Distance}(x_i, x_{\text{destination}})$ {Maximum distance within cluster C_j}
end for
$O_{ch} = \text{argmax}_j(\kappa_j)$ {Select the cluster with the most forwarded distance}
return Clusters $C_1, C_2, \ldots, C_k$ and Optimal CH O_{ch}

Finally, the algorithm returns the selected optimal CH. The data packets are sent to CH and finally reach the destination node in the data forwarding algorithm 7.

Algorithm 7 Data Forwarding Algorithm

Input: Optimal route O_{ch} obtained from algorithm 6
Output: Dissemination of data packet
while O_{ch} **do**
  Select the closest CH to the destination node and forward the data packet
  if I am destination **then**
    halt;
  else
    Select the next closest angle to the destination node among neighbor nodes and send the packet to the CH.
  end if
end while

6.3 Results and Analysis

The simulation was conducted in an NS3 environment, covering an area of 100×100 m square meters, as illustrated in Fig. 6.1. Energy-related aspects were closely monitored during the simulations. Each IoT device is equipped with `BasicEnergySource` fixing initial energy with 1.2 Joules, which is used for energy consumption observation in the overall network. Moreover, IoT devices are equipped with `WifiRadioEnergyModel` component, which is used for analyzing the energy consumption during radio operations. Furthermore, `BasicEnergyHarvester` components are also integrated with IoT devices to harvest the energy from RF-based signals. The purpose of this model is to observe the energy consumption and harvesting during packet transmission, with specified current values for transmission, reception, and idle states. Table 6.2 summarizes the simulation parameters used in experiments.

Table 6.2: Simulation parameters for the Proposed work

Parameter	**Value**
Simulator used	NS3
Simulation Area	100×100m, 900×700m
Simulation time	50,200
Number of nodes	20, 30, 40
Minimum speed	28 ms
Network Interface types	Wireless
Initial Transmit Power	0.5

Several performance metrics are used to evaluate the performance of the proposed scheme in different simulation scenarios. The metrics include Energy Consumption, Packet Loss Ratio (PLR), Packet Latency Time (PLT), Throughput, and PDR. The details are described in the following sections:

6.3.1 Energy Consumption

As discussed in section 6.1, the proposed work is based on energy harvesting, so each node should know the energy harvesting and energy consumption rate during communication. This metric decides the efficiency of any routing protocol regarding energy consumption in IoT-based networks.

6.3.2 Packet Loss Ratio

Several factors can degrade the network's reliability, efficiency, and performance in energy harvesting-based routing protocols. These include the distance between nodes, the sink/BS distance from the nodes, the density of the network, and the current energy level. One of the main factors in this is the packet loss ratio (PLR), which is the lost packets that have not reached the destination node during networking.

6.3.3 Throughput

As discussed above, several factors can degrade the network's reliability, efficiency, and performance. Throughput is another factor that can reflect the reliability of the network. In the routing process, sensed data are sensed to the destination node in a given time frame; when these data reach the destination successfully, this is called the network's throughput. Let T_p indicate the throughput parameter, R_x be the total bytes received at the destination node in total time T_n; then the throughput equation can be model as equation 3.1.

6.3.4 Packet Latency Time

Packet Latency Time is when a packet successfully travels from the source node to the destination node. It helps us understand the delay experienced by data packets during transmission. Let D_l be the delay parameter, D_s be the sum of all delay time, and T_x be the total transmitter packet, then the equation for calculating Packet Latency Time is presented in 3.2. The unit of measurement for the Packet Latency Time is milliseconds (ms).

In the context of varying distance parameters, the optimal spacing between nodes plays a crucial role in the efficiency of communication and data transfer within routing protocols. Maintaining the proper node distance ensures smoother information flow, leading to enhanced routing protocol performance and efficient energy harvesting. When node distances exceed recommended thresholds, the efficiency of routing protocols diminishes, affecting multiple performance metrics. The impact of increased node distances extends beyond a single performance metric, influencing aspects like data transmission speed, latency reduction, and network responsiveness. This section explores different distance parameters and analyzes how they affect performance metrics.

Fig. 6.2 illustrates the average energy usage of nodes situated at varying distances. The graph indicates that energy consumption and distance have a direct relationship. As the distance between nodes increases, along with the number of nodes present, there is a noticeable rise in energy consumption as depicted in the red lines of the figure, as depicted by the red lines in the figure. An interesting observation we've made is that beyond the point of having thirty nodes, the energy consumption for nodes positioned at a distance of ten units starts to rise more rapidly compared to the others. This phenomenon can be attributed to the high density of nodes concentrated in a relatively small area. This leads to increased energy usage due to the heightened likelihood of congested link failures and repeated packet transmissions, which waste energy.

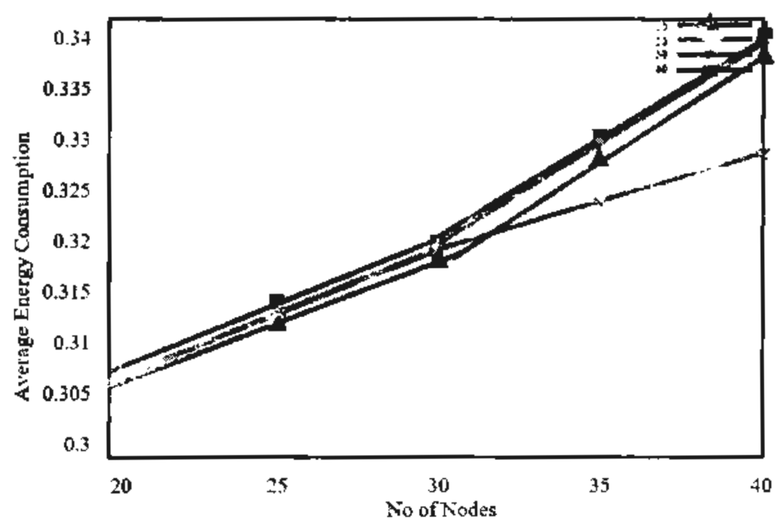

Figure 6.2: Average Energy Consumption with Different Distance Parameters.

Fig. 6.3 presents the average packet delivery ratio (PDR) of nodes placed at different distances. The graph demonstrates that the PDR remains consistently above 96 percent. This indicates that most of the sent packets successfully reach their intended destinations. Such a high PDR showcases the reliability and effectiveness of the communication performance among nodes, regardless of the varying distances between them. This consistent performance suggests that the routing protocol is robust and capable of maintaining efficient packet delivery across the network, ensuring minimal packet loss and high communication integrity. The ability to sustain a PDR above 96 percent across different distances highlights the protocol's resilience and its suitability for scenarios where reliable data transmission is crucial.

Fig. 6.4 displays the average time delay observed between nodes. In other words, the graph represents the average time data travels from one node to another within the network. Fig. 6.5 depicts the average throughput of nodes. In simpler terms, the graph illustrates the average rate at which

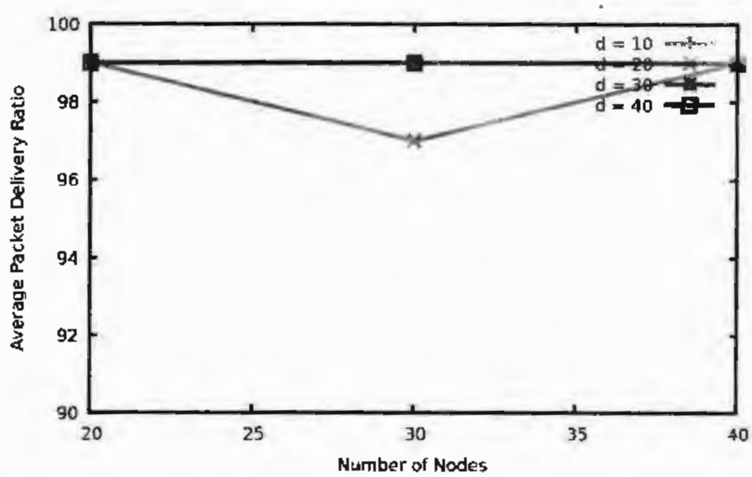

Figure 6.3: Average Packet Delivery Ratio.

data is successfully transmitted and received by nodes within the network.

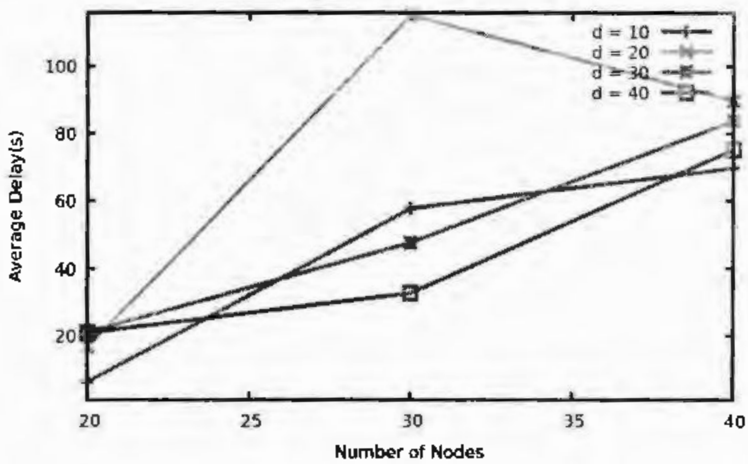

Figure 6.4: Average Delay with Different Distance Parameters.

A comparison is performed between the proposed research outcomes and the methodologies outlined in MKMFA [68], K-Means AODV [74], and IPC-KMAN [46]. The evaluation focused on metrics including packet delivery ratio and throughput, demonstrating that the proposed approach achieves a significantly higher packet delivery ratio than the aforementioned methods.

The information presented in Fig. 6.6 and Table 6.3 provides a visual and tabulated representation of the average PDR compared to existing approaches. These results serve as substantial evidence

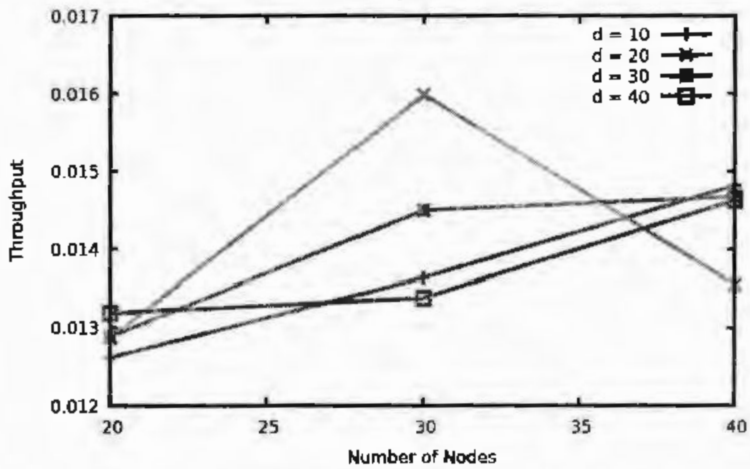

Figure 6.5: Average Throughput with Different Distance Parameters.

supporting the claim that the proposed work surpasses existing methods in terms of PDR.

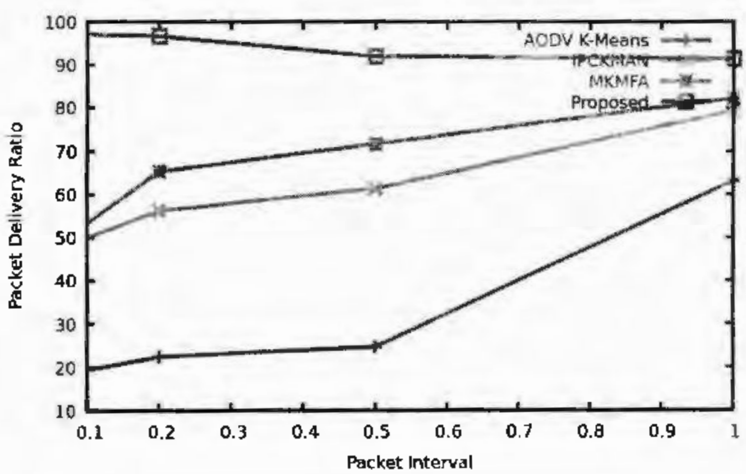

Figure 6.6: Average Packet Delivery Ratio.

Table 6.3 illustrates that the proposed work achieved the highest PDR rate compared to three counterpart schemes: MKMFA, AODV K-means, and IPC-KMAN [15, 31, 32], respectively. The presented approach achieved a significantly higher PDR of 91% compared to AODV K-means, which had a PDR of 63%, indicating a 44.83% improvement. Similarly, compared to IPC-KMAN with a PDR of 79%, the proposed approach showed a 15.13% enhancement in PDR. Additionally, in contrast to MKMFA, with a PDR of 82%, the proposed approach exhibited an 11.02% improvement

Table 6.3: Comparison of different model with the proposed model in terms of Packet Delivery Factor

Packet interval	AODV K-Means	IPCKMAN	MKMFA	Proposed
1	63.12	79.40	82.34	91.42
0.5	24.67	61.34	71.65	91.95
0.2	22.45	56.34	65.35	96.66
0.077	18.66	48.63	50.67	97.11

in PDR.

The results depicted in Fig. 6.7 and table 6.4 illustrate the average throughput comparison between proposed approach and existing methods. These findings serve as substantial evidence to support the better performance of the proposed work compared to others.

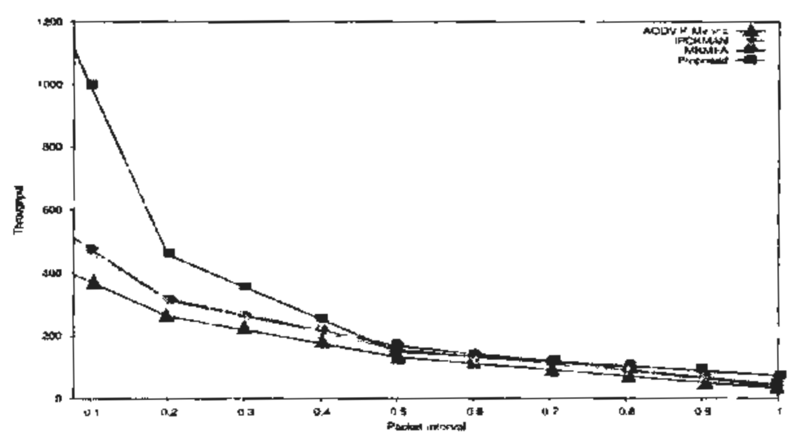

Figure 6.7: Average Throughput.

Table 6.4: Comparative analysis of different models with the proposed model in terms of throughput

Packet interval	AODV K-Means	IPCKMAN	MKMFA	Proposed
1	30.45	38.00	42.12	71.77
0.5	131.45	156.34	167.34	149.439
0.2	262.45	312.34	316.35	457.339
0.077	395.01	494.56	511.47	1110.75

The Table 6.4 illustrates that the proposed work achieved the highest throughput rate compared to three counterpart schemes: MKMFA, AODV K-means, and IPC-KMAN [15, 31, 32], respectively.

The proposed work achieved a 135.70% improvement compared to AODV K-mean, an 88.87% improvement compared to IPC-KMAN, and a 70.39% improvement compared to MKMFA.

6.4 Chapter Summery

Clustering enhances network performance by involving only CH in the routing process, especially those with the closest angle to the destination node. The MKMFA algorithm, as proposed, reduces the necessary number of clustering in the network operations, resulting in fewer transmissions needed for clustering due to the consideration of the closest angle to the destination. The performance of the ELEHCP algorithm is compared to the existing AODV K-meansmodel and IPC-KMAN. The proposed approach demonstrates better performance in packet delivery and throughput aspects. Subsequent research will explore more effective solutions within the clustering framework to enhance the efficiency of the routing process. The presented approach achieved a performance improvement of 44.83% over AODV K-means, 15.13% over IPC-KMAN, and 11.02% over MKMFA in terms of Packet Delivery Rate (PDR).

Chapter 7

Effectiveness of the Proposed Approach

This chapter evaluates the effectiveness of the proposed routing protocols based on the research questions and objectives presented. The proposed work is a complete set of those works necessary for EH-aware routing protocols. It includes the charger placement strategy, which is integral to EH-aware routing. Next, a flat-based EH-aware routing protocol is presented that uses the angle information of the destination node. Lastly, a hierarchical approach is presented for EH-aware routing protocols.

7.1 Charger Placement Strategies

EH-aware devices are deployed randomly according to protocol requirements, and the chargers are placed according to these EH-aware devices for charging. The charger propagates the signal, and EH-aware devices gain these signals. Antennas accomplish this process, so the role of antennas becomes crucial here. The antennas capture these signals, and the EH circuit converts them into usable electric energy for charging. When the EH-enabled IoT devices are charged, they participate in communication and sensing processes. The above discussion raises the question: "How can we effectively determine the best placement of a charger to resolve the dilemma of charging both the nearest and farthest nodes? How can an optimal charging tour be formulated to identify the best charger positions and uncover the charging areas or points that remain within the charger's line of sight from any location as the charger moves?" In this study, we are familiar with Powercast technology company's devices. This is a complete set called the P2110 developing kit, which includes an RF energy transmitter, evaluation board, wireless sensor board, antennas (dipole, patch), and access point. So, in this study, we are familiar with two types of antennas: dipole and patch. The dipole antenna is flat, omnidirectional, and vertically polarized, and the gain power is 1.0 dBi with a 360-degree reception beam pattern. The patch antenna is two-layered, directional, and vertically polarized, and the gain power is 6.1 dBi with a 120-degree reception beam pattern. The beam pattern of the Powercast energy transmitter is 60 degrees in vertical polarization, operating within the frequency range of 915 MHz.

One of the most critical problems in EH-aware routing protocols is a suitable place for the charger to charge EH-enabled IoT devices. Many researchers used different techniques for charger placement, such as mobile charger [18] and regional-based [51, 52], but these authors should have considered the dipole and patch antenna beam patterns. For example, the author of [18] used a mobile charger to charge nodes coming in the shortest path, but what about the farthest node currently situated from the mobile charger? So we need an optimal solution as presented in chapter 4.

The Powercast evaluation board contains capacitors, which make these devices zero energy capable. This means it will die when it does not receive any energy. For this purpose, our focus is on finding optimal points for charger placement and enabling IoT device placement from which these devices obtain energy regularly. Here, the optimal points for the charger and EH allow devices to are those from which the EH devices regularly receive the power from the charger. At any time when the charger moves from the optimal points, it dies. Also, when the charger moves farthest from the EH enable device, it degrades its performance, which can be realized from the sense data sending process to the laptop through the terminal. In case of halt, the computer does not receive any sensed data, and in case of receiving less energy, the sense data sending process becomes slow. The sensed data-sending process halts when the EH devices die and degrade in two cases: when the charger beam patterns are not in the direction of the EH enable device beam pattern and when the EH enable device becomes farthest from the charger. The farthest-nearest problem can be solved by mobile charger by keeping the dipole and patch antenna beam pattern in mind and by removing the limitations discussed in table 2.1 of [18, 51, 52].

So, in summary, the above discussion leads us to two problems: the farthest device charging and the beam pattern direction. In chapter 4, We have conducted real-world test beds for these problem solutions, compared them with current works [115] based on real-world test beds, and found that our work has better results. In the presented work, the charger tour on given points, the points for the dipole antenna of the evaluation board obtain enough energy to charge the capacitor and perform the sensed data-sending process in their calculated points. At the same time, the points for the patch antenna are within the given range; also, the evaluation board can charge the capacitor and operate efficiently.

In the works of [2, 21, 22], the grid area is static, as is our circular area. In the grid area, efforts were made to find the best grid point for charger deployment to cover more devices within the cone area for regular energy harvesting. In contrast, our objective is to incorporate an optimal charger placement strategy into energy-harvesting-aware routing protocols, utilizing real-world testbeds to enhance node energy harvesting efficiency and address the Farthest-Nearest Problem related to node-to-charger distance. The grid area is static, as is our circular area. The circular charger area increases the average EH rate of all nodes because the farthest node from the charger becomes the nearest node during the circular tour.

7.2 Flat based Routing Protocols

Efficient link selection decisions are important for routing protocols, particularly in EH-aware routing. It is the base for any routing protocol, which decides the efficiency of routing protocols because this link selection decision can affect the main routing performance parameters such as packet delivery ratio, throughput, delay, and, most importantly, energy consumption. The energy consumption of a node can be divided into Energy consumption by Processing Unit, Energy Consumption by Transmission of Packets, Energy Consumption by Receiving of Packets, and Energy Consumption by Discovering Neighbor Nodes situations discussed detailed in section 5.1.1. The equation is as follows:

$$E_c = \begin{cases} E_{cp} + E_{rs} + E_{cns} & \text{if } n \in N \text{ is sender node} \\ E_{cp} + E_{cr} + E_{cnr} & \text{if } n \in N \text{ is receiving node} \\ 0 & \text{if dead} \end{cases} \tag{7.1}$$

The primary causes of energy inefficiency in IoT-based EH WSNs are idle listening, unnecessary traffic overhearing, packet collisions, and the overhead of control packets during transmission, reception, and listening [104]. Idle listening occurs when Nodes constantly listen for incoming frames without data transmission, depleting the energy. Collision occurs when multiple nearby stations transmit simultaneously, causing energy loss. Over-hearing means Nodes unintentionally overhear broadcast messages, leading to energy waste. Control packet overhead: occurs when using fewer control packets in data transmission reduces energy consumption [105].

The main purpose of this work is to minimize the energy consumption during E_{cp}, E_{cs}, E_{cns} when a node performs as sender and E_{cp}, E_{cr}, and E_{cnr} when a node performs as receiving node. Also, an efficient link selection process can tackle idle listening, unnecessary traffic overhearing, packet collisions, and overhearing of control packets during transmission and reception problems that can reduce overall energy consumption. So, solutions to these problems can also improve PDF throughput and minimize delay.

The works of [26] are based on selecting efficient links by keeping distance, battery level, and energy harvesting rate parameters in mind. The work of [38] is based on selecting efficient link by keeping transmission range, estimation of transmission cost from the current node (m^{th} node) to its next hop, the average number of retries, the minimum required radio transmission power, circuit processing power, receiving the power of the next node, the time required to deliver a packet, and energy harvesting considerations parameters in mind, the work of [28] is based on selecting efficient link by keeping distance and maximum current energy parameter in mind, the work of [55] is based on selecting efficient link by keeping residual energy of nodes in mind. The above discussion leads us to the question: How can an energy-harvesting-aware, location-based routing algorithm be developed to guide node traversal within directions to the destination node?

The presented work in chapter 5 targeted an area or location for packet sending to the destination node and bound the packets to be sent or received by, at most, a minimum number of nodes. This technique avoids idle listening, unnecessary traffic overhearing, and the overhead of control packets during transmission, reception, and listening. Furthermore, the energy consumption during the neighbor discovery process (E_{cns}, E_{cnr}) can be reduced by sending minimum packets. In sending and receiving packets, E_{cs} and E_{cr} can be reduced by sending minimum packets or only to the nodes that become in the direction/location of the destination node. So only those nodes will participate in the network process, which becomes the destination node, and the other nodes will be in sleep mode; ultimately, this technique reduced the E_{cs} and E_{cr}. The results of the presented work are evidence that our energy reduction techniques reduce energy consumption efficiently. The presented work achieved 0% PLR up to eighty nodes, minimum delay, maximum throughput, and energy utilization improvements compared to [26, 28, 38, 55] works. So ultimately, this can achieve the objective of developing an energy-harvesting-aware routing protocol that optimally considers node locations and angles during path/link selection, aiming to minimize packet transmissions, avoid extra node traversals, and prevent path reconstruction.

7.3 Hierarchical/Cluster-based Routing Protocols

Efficient CH selection decisions are crucial in cluster-based routing protocols, particularly in EH-aware cluster-based routing. It is the base for any hierarchical routing protocol, which decides the efficiency of routing protocols because this CH selection decision can affect the main routing performance parameters such as packet delivery ratio, throughput, delay, and, most importantly, energy consumption. The energy consumption of a node can be divided into Energy consumption by Processing Unit, Energy Consumption by Transmission of Packets, Energy Consumption by Receiving Packets, and Energy Consumption by Discovering Neighbor node situations. This discussion raises tbe question: How can an energy-harvesting-aware, location-based clustering routing algorithm be devised to select the closest CH to the destination node location?

The main purpose of this work is to divide the nodes into clusters according to their proximity angles and select the CH that leads to the direction of the destination node. By using this technique, we can save more energy by keeping those nodes in sleep modes, which do not become in the direction of the destination node. We have compared our work with MKMFA [15], K-means AODV [31], and IPC-KMAN [32]. The proposed work achieved a packet delivery ratio of 91% in packet interval 1 second, 97% in .077 seconds packet interval, and better throughput. So from these results, the objective of developing an energy-harvesting-aware, cluster-based routing protocol that optimally considers destination node locations during CH selection, aiming to minimize packet transmissions and node traversals and avoid path reconstruction, is achieved.

Chapter 8

Conclusion and Future Work

In conclusion, this thesis has comprehensively explored the intricate challenges of deploying sensor nodes within demanding environments, particularly in smart cities and IoT-based Wireless Sensor Networks (WSNs). The demand for efficient and sustainable data collection and monitoring solutions becomes paramount as our world becomes increasingly interconnected.

Wireless sensor technology and IoT fusion have undeniably enabled remote and challenging settings monitoring. Still, it has also brought to the forefront a range of obstacles stemming from the inherent limitations of sensor nodes. At the heart of these challenges lies the critical issue of energy preservation. The finite battery capacity, constrained data storage, limited computational capabilities, and restricted communication range of sensor nodes all underscore the necessity for meticulous energy management strategies.

8.1 Key Issues

This thesis addresses three main issues after extensively reviewing the current research in energy harvesting-aware routing protocols.

First: Energy-harvesting-aware routing protocols face the problem of Timely Energy Needs Monitoring and Predictions. IoT devices have varying energy needs due to long-distance data transmission and computations. Energy harvesting mostly depends on charger placement. It is proved that the received signal strength is inversely proportional to the square of transmission distance. Obviously, the farthest nodes from the charger and sink usually harvest less energy and consume more energy for sending data to the sink node. On the other hand, the nodes near the chargers harvest more energy than the farthest nodes.

This thesis aims to find the optimal placement for chargers and devices to solve the nearest-farthest problem between charger and devices for efficient network operations.

Second: In most energy harvesting-aware routing protocols, when a device is in the recharge state, it stops all activities and becomes unavailable for routing activities, leading to the routing path breakage. This phenomenon leads us to problems such as link/node failure, dynamic topology, charging latency, communication delay, and topology maintenance. Besides these problems, we have investigated another problem: traversing extra nodes that need not be traversed after the link/node failure. This problem can be defined more precisely as, in previous research, all nodes participate in the routing process, even those nodes that do not become in the direction of the destination node or need not be traversed. In case of node/link failure, it again traverses all nodes, and again, those nodes that do not become in the direction of the destination node or need not be traversed. Consequently, in each stage, a huge amount of energy is wasted.

This thesis aims to find an optimal link that tackles all the above issues.

Third: In hierarchical routing, most researchers select the routing path through distance, energy, traffic parameters, etc., but the problem of traversing extra nodes exists, as discussed above. Therefore, an approach is required that creates and selection clusters only in the direction of the destination device. Also, the approach avoids the new route reconstruction in case of CH failure.

This thesis aims to find an optimal link that only selects the CH in the direction of the destination node.

8.2 Key Findings

Throughout this thesis, we have responded to these issues with a multi-faceted approach that has yielded significant contributions in the realms of energy efficiency and energy harvesting. Our work has encompassed three pivotal contributions:

First, the optimal placement of chargers and sensor devices is addressed, recognizing the crucial role of energy scavenging and mobility. By introducing mobile charging techniques and innovative algorithms for directional and omnidirectional antennae, we have sought to extend the operational lifespan of sensor networks. While our current solution applies to 2D environments, future work will expand into 3D scenarios and involve comparisons with state-of-the-art solutions. The detailed description is presented in chapter 4.

Second, a location-centric energy harvesting aware routing (LCEHA) protocol is proposed, which tackles various challenges in WSN-based IoT networks, such as energy utilization, lifetime enhancement, route setup delay minimization, and routing success probability maximization. Through distributed neighbor discovery and routing using neighbor information, our approach has demonstrated promising results in terms of energy efficiency, packet loss ratio, throughput, and delay, ultimately leading to improved network lifetime. Future research will explore the applicability of our solution in 3D environments. This work is more discussed in chapter 5.

Third, our investigation into clustering techniques has shown the potential to enhance network performance by involving CHs with the closest angle to the destination node. The MKMFA algorithm has efficiently reduced the number of clustering operations required for network operation, resulting in fewer transmissions for clustering. Comparative analysis against existing models has shown superior packet delivery and throughput performance. Future research endeavors will delve further into clustering frameworks to enhance the efficiency of the routing process. For more detail, please refer to chapter 6.

In an ever-evolving landscape of IoT-based WSNs, these contributions collectively contribute to advancing energy-efficient and sustainable solutions for smart cities and challenging environments. As the IoT ecosystem expands, our research serves as a stepping stone toward addressing the pressing challenges of energy preservation and network efficiency, contributing to realizing more efficient and secure smart city applications.

8.3 Future Work

As we look ahead, several promising avenues for future research emerge from the foundation laid in this thesis: **3D Environment Extensions:** Expanding our solutions to 3D environments is a natural progression, considering urban environments' increasingly complex and three-dimensional nature. This extension will provide a more comprehensive understanding of energy efficiency and mobility challenges in real-world scenarios.

Scalability and Robustness: Investigating the scalability of our solutions to accommodate larger networks and ensuring robustness under adverse conditions will be essential for practical deployment in smart city contexts.

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