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RESEARCH ARTICLE

# Location Centric Energy Harvesting Aware Routing Protocol for IoT in Smart Cities

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**ABSTRACT** Battery technology revolutionized power storage for various purposes, including uninterrupted IoT-based Wireless Sensor Networks (WSNs) operations. However, limited energy sources pose a challenge for sensor nodes. To overcome this, researchers introduced Energy Harvesting (EH) in IoT-based WSNs, enabling them to overcome energy limitations and recharge IoT devices. The shift towards energy harvesting-aware routing is necessary to achieve a near-perpetual network environment. In light of the energy consumption of IoT-based WSN nodes, a simple energy-efficient routing technique is proposed to consume less energy. The protocol incorporates efficient link selection based on the closest angle to the destination node and is divided into two main parts: distributed neighbor discovery and routing processes. By incorporating EH techniques, the proposed model aims to improve network longevity. Experimental results demonstrate successful routing and promising outcomes in terms of energy and utilization techniques.

**INDEX TERMS** The Internet of Things, smart cities, energy harvesting, routing protocol, energy efficiency.

## I. INTRODUCTION

The Internet of Things (IoT) has gained significant attention in recent years, with researchers predicting that the industry will consist of around 29.7 billion devices by 2027 [1]. IoT has brought about a revolution in our daily lives, offering immense convenience to humanity [2]. 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 (EH) has emerged as a solution for low-power electronic devices and sensors. Sensors can recharge their batteries by harnessing energy from sources like solar, thermal, wind power, and even radio frequencies (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 [3], [4], [5], [6], [7].

Energy efficiency is critical for IoT devices to ensure uninterrupted network operations, including 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 [8].

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

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RF sources. RF energy harvesting, in particular, offers a solution for zero-energy IoT devices [4], [8], 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, focusing on energy harvesting techniques. Notable research includes studies conducted by [9], [10], [11], and [12]. These works explore the application of energy harvesting techniques to enhance energy efficiency and prolong networks' operational lifespan by creating and selecting efficient links. During the link selection process, the authors used different parameters, such as shortest distance and energy harvesting rate [9], shortest distance and maximum current energy [10], shortest distance, transmission cost, and energy harvesting [11], residual energy and shortest distance [12], energy harvesting, energy consumption, and energy classification [13]. The proposed work selects 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 [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], and [23] 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.

The rest of the paper is organized as follows: Section II is based on the literature review, Section III presents the system model and preliminaries, Section IV introduces the proposed neighbor discovery and routing algorithms, Section V presents the analysis of the performance of the proposed algorithm, and finally, Section VI presents the conclusion.

## II. LITERATURE REVIEW

Nguyen et al. [9] introduced the Energy Harvesting Aware Routing Algorithm (EHARA), which considers the battery level of nodes 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 (EH) 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.

Yallappa and Naik [10] 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 could be more potent.

Gong et al. [11] 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.

Tang et al. [14] 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 needed to be considered. Moreover, the problems of limited data buffer capacity and long transmission delay are identified [13].

In [15], 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. 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 [16] 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 needs more traversal of additional nodes, handling the addition of new nodes, and limited scalability in large-scale networks.

The authors in [12] 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 [17], the author introduces an energy-aware routing protocol EAQ-AODV employing Q-learning for cluster head selection and incorporates parameters like residual energy, common channel, number of hops, licensed channel, communication range, and trust factor to establish optimal routing paths. The protocol learns from past experiences to make informed decisions using the Q-learning approach. One challenge of this proposal is frequent updates and overhead during network changes.

The article in [18] 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). It divides the network area into virtual concentric rings, and each ring is further divided into sectors called clusters. The node closest to the midpoint of each sector is selected as the cluster head, and data from each sector are aggregated and forwarded to the sink node using angular inclination routing. The paper must address the extensive communication overhead associated with cluster data aggregation and routing. In large-scale sensor networks, excessive overhead might lead to inefficiencies.

The authors in [19] 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. The proposal needs scalability, route maintenance, and border node-related problems.

Redjimi et al. [20] 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 [13], the author claims existing studies on EH-WSN must adequately address the relationship between energy state and data buffer constraints. Consequently, they must effectively resolve energy efficiency issues and long end-to-end delays. The author proposes a novel routing protocol based on a greedy strategy for energy-efficient EH-WSN, considering energy harvesting, energy consumption, and energy classification factors 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 still needs to be 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.

Zungeru et al. [24] proposed a novel RF energy harvesting aware algorithm named Improved Energy Efficient Ant Based Routing (IEEABR) to optimize the efficient utilization and management of harvested and available energy. Their proposal focuses on enhancing the energy efficiency of routing in EH scenarios. In this approach, most packets are broadcast, increasing energy consumption.

In [25], the author proposed a Fuzzy logic-based adaptive duty cycling for sustainability in energy harvesting sensor networks. The harvesting model forecasts the amount of energy that can be collected from a renewable energy source and estimates the remaining available energy for a future period by incorporating the predicted harvesting energy, an energy consumption model, and the current residual energy. However, the paper must provide a solution for determining the nearest or farthest node to harvest energy. It means that when a node is closer to the energy harvester, it may harvest more energy compared to a farther away node.

The authors in [26] 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, node-connectivity information, and data routing information to optimize transmitter placement and address energy-hole issues. Similarly, the authors in [27] focused on improving the performance of IoT systems by combining cognitive radio (CR), energy harvesting (EH), 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 [28] 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, 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.

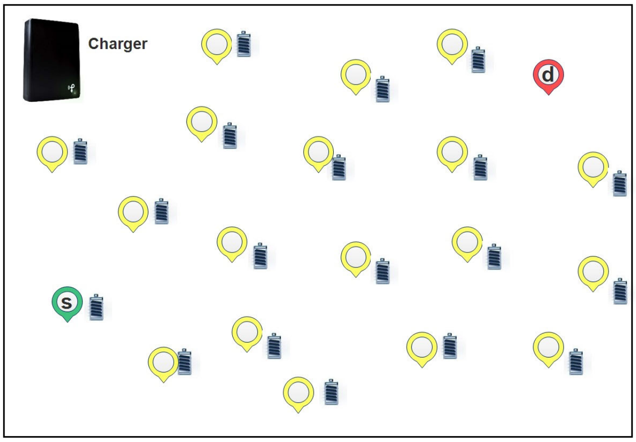

**FIGURE 1.** System model of proposed work.

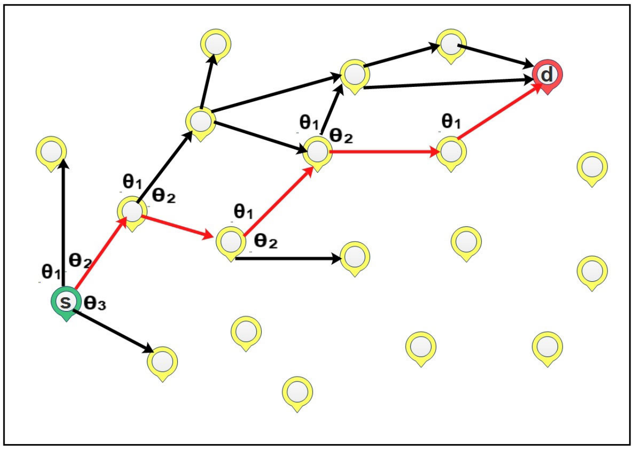

**FIGURE 2.** Angle selection model.

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 and Kumar [23] shares similarities with the proposed approach in this article. However, there is a difference in terms of 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 instead 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 need to be in the direction of the destination node.

## III. 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 solar, thermal, and flow-based, have been introduced. However, the Radio Frequency (RF) based EH technique has garnered tremendous attention from researchers due to its easy availability (from TV, radio, and Wireless frequencies).

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 [8], [29]. The energy harvesting hardware is responsible for transforming energy into electricity and storing it in the storage device (batteries, capacitors). The Powercast company [29] 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 $60^{\circ}$ horizontal and $60^{\circ}$ 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 charge the capacitor of size 50 mF. A sensor board is also provided for sensing the environment, such as temperature, humidity, light. The Powecast technology company used the Friis space equation for the energy transmission model.

$$P_r = \frac{G_s G_r \eta}{Lp}\left(\frac{\lambda}{4\pi(d+\beta)}\right)^2 P_0 \tag{1}$$

where $P_0$ is the source power, $P_r$ is the received power, $\lambda$ is the wavelength $G_s$is the source antenna gain power, $G_r$ is the receiver antenna received power, $d$ is the sensor-charger distance, and $L_p$ is the polarization loss. $\eta$ parameter is used for short-distance transmission.

He et al. [30] presented an empirical model and improved Eq. (1) by introducing polarization loss and signal power rectifying and converting to electrical energy before it can be used.

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

where $\eta$ is rectifier efficiency, $L_p$ represents polarization loss, and $\beta$ is a parameter to adjust the Friis free space equation for short-distance transmission.

Let $v_k$ be the set of IoT devices and $v_{km}, v_{kn} \epsilon v_k$ then the Eq. (2) can be write as follow:

$$P_r = \frac{\alpha P_t(v_{km})}{(\|v_{km} - v_{kn}\| + \beta)^2} \tag{3}$$

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 [31] 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 [8], a node near the charger device can harvest much energy compared to a node located farther away.

The proposals in [32] and [33] classified the Received Signal Strength Indicator (RSSI) into different levels: "excellent," "very good," "good," "low," "very low," 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 or higher 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. (3), which is written as:

$$\|v_{km} - v_{kn}\| = \frac{\sqrt{\alpha P_t(v_{km})}}{P_r} - \beta \tag{4}$$

Eq. (4) can also be used to calculate the distance between source node and destination as:

$$D_{s_n - d_n} = \|\frac{\sqrt{\alpha P_t(S)}}{P_r} - \beta\| \tag{5}$$

Eq. (6) can be used to calculate the distance between the sender and receiver.

$$d_{s_n - d_n} = \|\frac{\sqrt{\alpha P_t(S)}}{P_r} - \beta\| \tag{6}$$

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.

$$U = \begin{cases} 1 & if t_d \geq D \\ i+1 & if t_d < D \end{cases} \tag{7}$$

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

### A. 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. [34], which describes the relationship between energy consumption and data transmission.

$$P_{tx}(k, d) = (p_t + \epsilon + d^4) \times k \tag{8}$$

$$P_{Rx}(k) = p_r \times k \tag{9}$$

Eq. (8) is used to calculate the energy consumption for data transmission, while Eq. (9) 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.

#### 1) ENERGY CONSUMPTION BY PROCESSING UNIT

$$E_{cp} = \sum E_{ecpu} \times \sum A_t \tag{10}$$

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.

### 2) ENERGY CONSUMPTION BY TRANSMISSION OF PACKETS

$$E_{cs} = \sum E_{ecppt} \times \sum T_{spkt} \tag{11}$$

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

### 3) ENERGY CONSUMPTION BY RECEIVING OF PACKETS

$$E_{cr} = \sum E_{ecppr} \times \sum T_{rpkt} \tag{12}$$

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

### 4) 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.

$$E_{cns} = (\sum E_{ecppt} \times \sum T_{spkt}) \times T_{tpkt} \tag{13}$$

$T_{tpki}$ represents the time required for the neighbor discovery process. Allocating 1 second for the neighbor discovery process corresponds to transmitting a single packet within that time frame. However, extending the neighbor discovery process to 10 seconds allows transmitting multiple packets over this extended duration.

And for packet receiving:

$$E_{cnr} = (\sum E_{ecppr} \times \sum T_{rpkt}) \times T_{rpkt} \tag{14}$$

The overall energy consumption can be expressed as follows:

$$E_c = \begin{cases} E_{cp} + E_{cs} + E_{cns} & \text{if } n \in N \text{ is sender node} \\ E_{cp} + E_{cr} + E_{cnr} & \text{if } n \in N \text{ is receiving node} \\ 0 & \text{if dead} \end{cases} \tag{15}$$

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 [35]. 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 [36].

In a routing algorithm, when a device transmits a data packet, it selects the most efficient link for forwarding the packet. 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 towards the destination node.

**TABLE 1.** **Notations.**

| Symbol | Meaning |
|---|---|
| $E_{cp}$ | Energy consumption by the node process unit. |
| $E_{cs}$ | Energy consumption by the transmission of a packet. |
| $E_{cr}$ | Energy consumption by the reception of 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 (EH). |
| $T_\theta$ | The angle between the sender and receiver. |
| $\mathcal{N}$ | Neighbor node angles 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. |
| $O_\theta$ | Optimal angle. |
| $Add_{t_\theta}$ | Address of the neighbor node that has the optimal angle. |
| $\upsilon$ | Slope of the current node and receiver node. |
| Y | Slope of the source node and destination node. |

$$T_\theta = arctan \frac{\Delta y_{ni}}{\Delta x_{ni}} \tag{16}$$

where $\Delta x_{ni} = \frac{D_{snx2} - D_{snx1}}{D_{rny2} - D_{rny1}}$ and $\Delta y_{yni} = \frac{D_{snx2} - D_{snx1}}{D_{rny2} - D_{rny1}}$ are used to find the slopes through location of nodes.

## B. 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:

$$E_h = \eta \times P_h \times t \tag{17}$$

where $\eta$ 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 ($\eta$), which represents the efficiency of converting harvested power into usable electrical energy. The energy conversion efficiency ($\eta$) in the context of energy harvesting represents the efficiency with which harvested power is converted into usable electrical energy.

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

$$\eta = P_{output}/P_{input} \tag{18}$$

$P_{output}$ 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, $\eta$, is calculated as 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 radio frequency 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:

$$P_h = C \times |E|^2 \times \eta_r f \tag{19}$$

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 [8] 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:

$$T_{en} = E_0 + \sum E_h \tag{20}$$

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

$$E_r = T_{en} - \sum T_{ec} \tag{21}$$

This manuscript focuses on reducing the overall energy consumption of individual nodes in the network by targeting parameters described in Eq. (15). This work aims to develop and implement energy efficiency strategies and models that optimize these parameters for each node individually, ultimately leading to reduced 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.

## IV. 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 [18], [19], [20], [23], [28] and cost metrics-based approaches [9], [10], [11], [12], [13], [14], [17]. 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.

### A. 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 1) 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. (3) and the angle (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 $T$.

**Algorithm 1** Neighbor Discovery Algorithm

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

```
At time $T$.
In Sender Mode
for $n \leftarrow 1$ to$N$ do
    Broadcast $P_{kt}$
end for
In Receiver Mode
$\mathcal{N} \leftarrow \phi$
while Neighbor $n_i$ receive $P_{kt}$ do
    Calculate $d$ As Eq. (4)
    $\upsilon \leftarrow \frac{c_{nx}-r_{nx}}{c_{ny}-r_{ny}}$
    if $\upsilon < 0$ then
        $t_\theta \leftarrow \arctan(\upsilon) + 360$
    else
        $t_\theta \leftarrow \arctan(\upsilon)$
    end if
    $\mathcal{N} \longleftarrow n_i$,$t_\theta$,d
end while
```

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.

### B. ROUTE DISCOVERY ALGORITHM

The main idea of algorithm 2 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 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 1 and forwards packets based on this information.

In the proposed work, the network can be divided 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.

**Algorithm 2** Route Discovery Algorithm

**Input:** Destination Node Address, Location, Neighbors $\mathcal{N}$, Time $T$.
**Output:** Optimal Route Discovery.

```
1:  At $\tau \leftarrow T_n$ where $n = 1, 2, 3, \cdots T$
2:  In Source Mode
3:  for $P_{kt_i}$ where $i = 1, 2, 3, \cdots$ do
4:      if $\mathcal{N} \leq 1$ then
5:          Broadcast $Init_{pkt}$
6:      else
7:          $\Upsilon \leftarrow \frac{D_{nx}-S_{nx}}{D_{ny}-S_{ny}}$
8:          if $\Upsilon < 0$ then
9:              $T_\theta \leftarrow \arctan(\Upsilon) + 360$
10:         else
11:             $T_\theta \leftarrow \arctan(\Upsilon)$
12:         end if
13:         for $t_\theta \epsilon \mathcal{N}$ do
14:             $T_{small} \leftarrow T_\theta - t_\theta$
15:         end for
16:         for $t_\theta \epsilon \mathcal{N}$ do
17:             $\Re \leftarrow T_\theta - t_\theta$
18:             if $\Re \leq T_{small}$ then
19:                 $T_{small} \leftarrow \Re$
20:                 $O_\theta \leftarrow t_\theta$
21:                 $A_{si} \leftarrow Add_{t_\theta}$
22:             end if
23:         end for
24:         Send $Init_{pkt}$ to $A_{si}$
25:     end if
26: end for
27: In Receiver Mode
28: if $A_{ci} = A_d$ then
29:     Send $Rep_{pkt}$ to Source Node
30: else
31:     The procedure is same as lines 7 to 29
32: end if
```

## V. EXPERIMENTS AND RESULTS

The simulation used a 100 × 100m area as shown in Fig. 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 1 represents the detailed simulation parameters. In our simulation scenarios, there is only one sink and multiple nodes.

### A. PERFORMANCE METRICS

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

#### 1) ENERGY CONSUMPTION

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

#### 2) PACKET LOSS RATIO

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

#### 3) 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 as follows:

$$Throughput = \frac{\sum rxBytes \times 8}{TotalTime \times 1000000.0} \tag{22}$$

#### 4) 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 following equation and results in milliseconds.

$$Delay = \left(\frac{\sum Delaysum}{\sum txPacket}\right) \tag{23}$$

### B. 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.

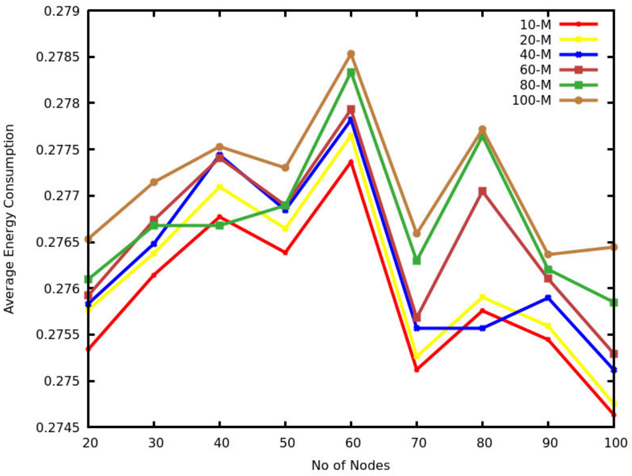

**FIGURE 3.** **Average energy consumption with different distance parameters.**

Fig. 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 III-A. As a result, the nodes can waste their energy resources. However, compared with existing works [9], [10], [11], [12], 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. (15). In Fig. 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.

Fig. 4 and Fig. 5 depicts the average packet delivery ratio at different distances. In Fig. 4, the packet delivery ratio is shown for nodes between 10 and 40 meters apart. It is worth noting that the system's performance decreases as the network density increases. The high density causes link

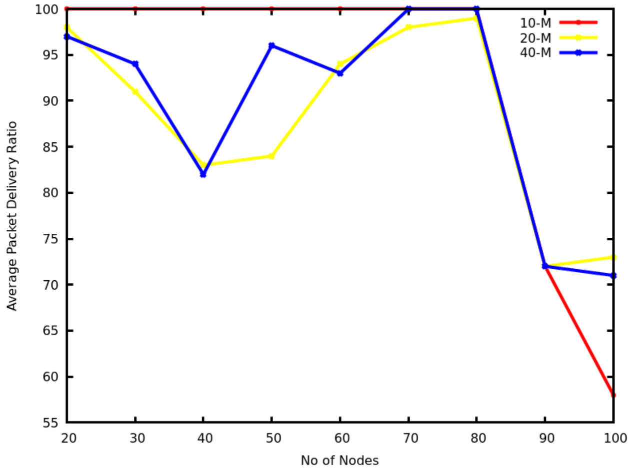

**FIGURE 4.** Average packet delivery ratio with 10, 20, 40 M distance parameters.

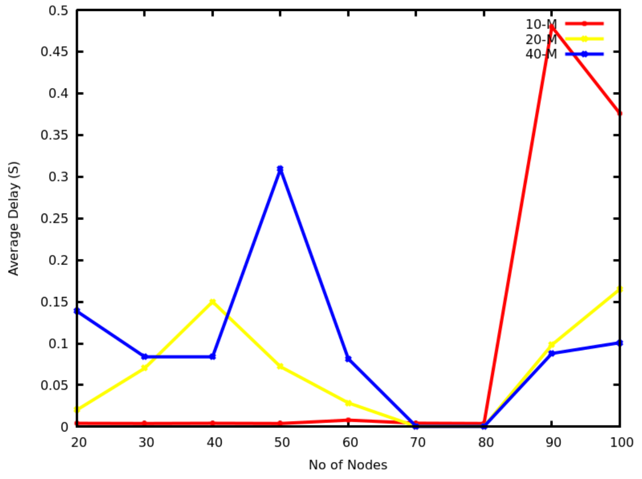

**FIGURE 6.** Average delay with 10, 20, 40 M distance parameters.

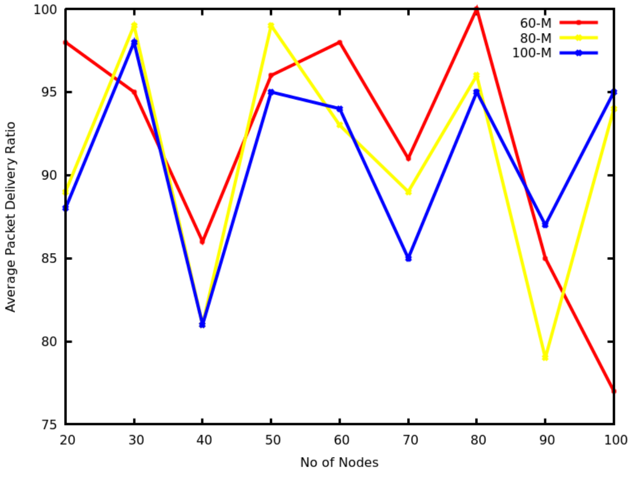

**FIGURE 5.** Average packet delivery ratio with 60, 80, 100 M distance parameters.

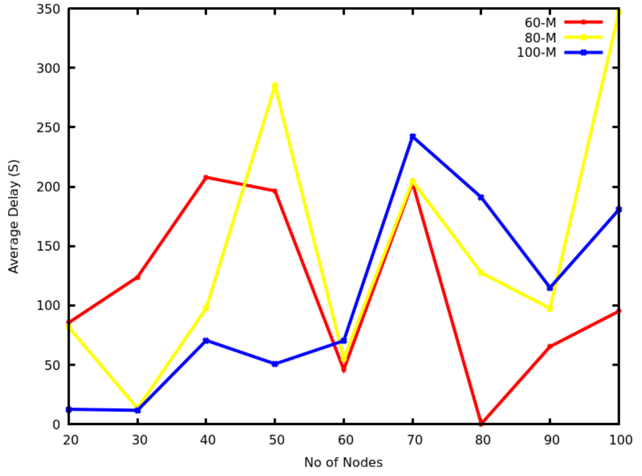

**FIGURE 7.** Average delay with 60, 80, 100 M distance parameters.

failure and congestion, which leads to packet drops. The higher the PDR means that a node can harvest enough energy from the energy harvester.

On the other hand, Fig. 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. 6 and Fig. 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. 8 and Fig. 9 depicts the average throughput between nodes in different scenarios according to Eq. (22). 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 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.

Fig. 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

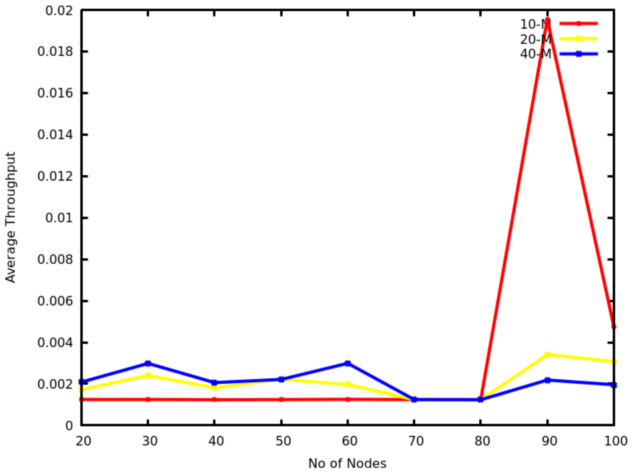

**FIGURE 8.** Average throughput with 10, 20, 40 M distance parameters.

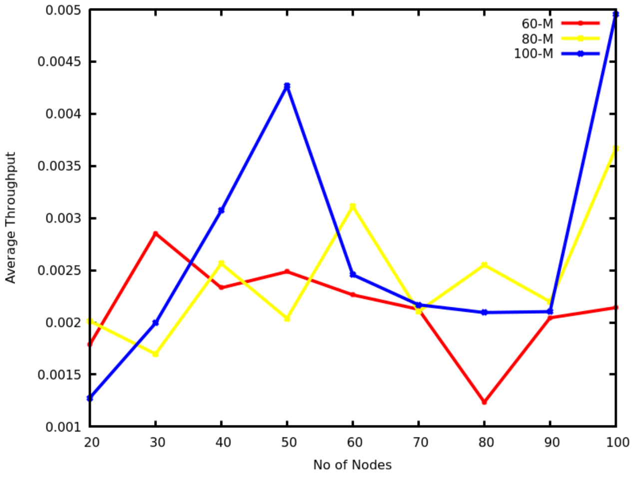

**FIGURE 9.** Average throughput with 60, 80, 100 M distance parameters.

instance, when the distance between nodes is 10 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.

### C. COMPARISONS OF EHARA, R-MPRT MODE, AODV-EHA, AND CFS

The work has been compared with EHARA [9], CFS [10], AODV-EHA [11], and R-MPRT [12] because these works are related to energy harvesting techniques. Fig. 11 and Table 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.

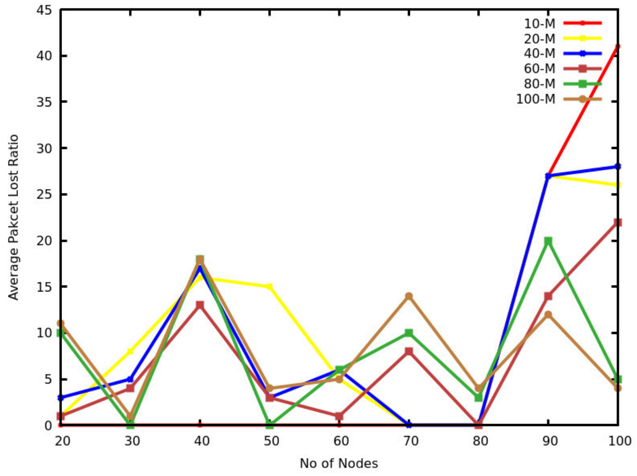

**FIGURE 10.** Packet loss ratio of 10,20,40,60,80,100 meters distance parameters.

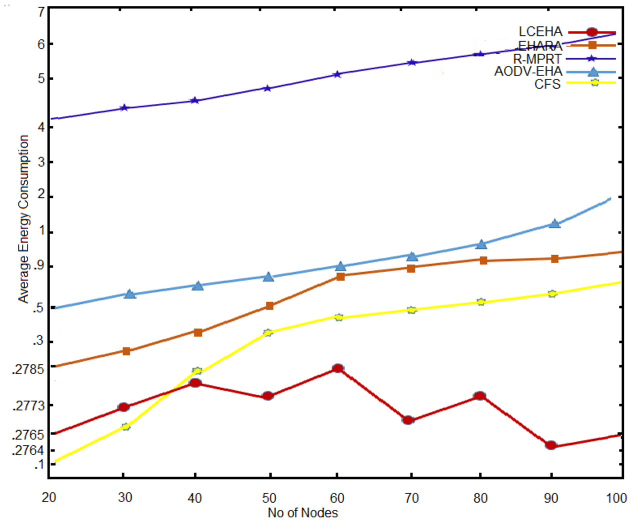

**FIGURE 11.** Average energy consumption comparison with proposed and existing works.

**TABLE 2.** Energy consumption comparison with existing and proposed.

| Model | Energy Consumption |
|---|---|
| R-MPRT | 6.450 |
| AODV-EHA | 2.764 |
| EHARA | 1.324 |
| CFS | 0.740 |
| Proposed (LCEHA) | 0.277 |

Fig. 12 and Table 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,

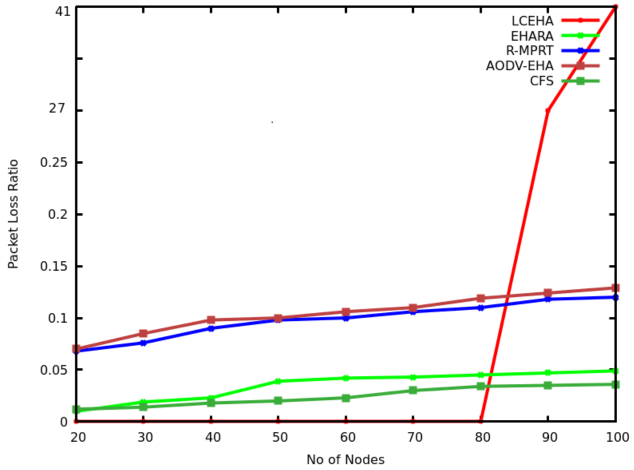

**FIGURE 12.** Packet loss ratio comparison with proposed and existing works.

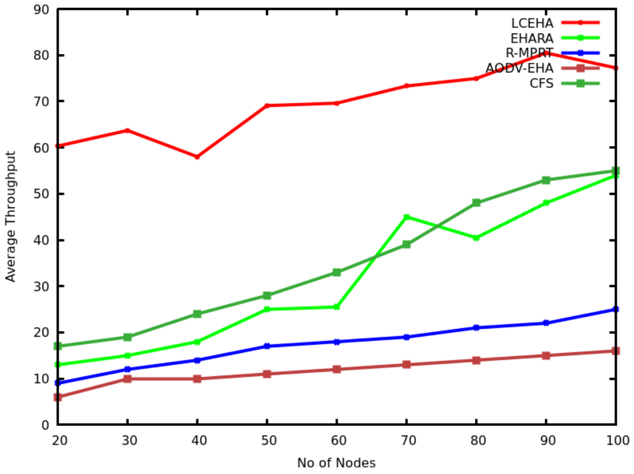

**FIGURE 13.** Average throughput comparison with proposed and existing works.

**TABLE 3.** Packet loss ratio comparison with existing and proposed.

| 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 increases the PLR |

**TABLE 4.** Throughput comparison with existing and proposed works.

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

while others have more than zero. It is because at least one link exists between the source node 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. 10, which displays the PLR for various distance levels, it has been observed that when the distance between nodes is 10 meters, and there are 100 nodes in the network, the PLR increases significantly (peaks). As the distance increases to 20, 40, and 60 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. By addressing and mitigating these issues, it is possible to reduce the PLR to nearly zero and improve the network's overall performance.

Fig. 13 and Table 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.

## VI. CONCLUSION

This article 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.

## CONFLICT INTEREST

The authors declare that they have no conflicts of interest to report regarding the present study.

## ACKNOWLEDGMENT

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