

EHARA: A Distributed Energy Harvesting-Aware Routing Algorithm for Sustainable IoT Networks

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Abstract: Managing energy wisely and keeping networks running for the long haul are top priorities in IoT setups, especially when devices pull power from their surroundings. This paper unveils the Energy Harvesting-Aware Routing Algorithm (EHARA), a fresh take on routing that fine-tunes energy use, boosts packet delivery, and cuts down delays. EHARA doesn't stick to rigid paths—it shifts gears based on how much energy nodes are harvesting and storing at any given moment. When pitted against LEACH and EAR in simulations, EHARA comes out ahead with better delivery rates, leaner energy use, and snappier performance. These outcomes underline its knack for stretching network life and sharpening efficiency, positioning it as a solid pick for IoT systems that need to keep going sustainably.

Keywords: Energy-Harvesting IoT, Energy-Aware Routing (EAR), LEACH, Wireless Sensor Networks, Adaptive Routing.

I. INTRODUCTION

The IoT wave has taken over smart cities, hospitals, factories, and eco-monitoring like a boss, connecting everything so smoothly. But here's the catch: keeping those devices powered up is a real headache. Most of them run on tiny batteries or grab energy from things like sunlight, radio waves, heat, or vibrations [1]. That harvesting idea sounds cool, but the energy comes in bursts – not steady at all – and that messes up network management, especially the routing part [2].

Old-school routing tricks are all about saving energy but get totally confused when harvesting rates go up and down [3]. That leaves nodes dead tired, networks breaking apart, and data just hanging there. So, we whipped up EHARA, a distributed routing solution that works like a charm in chaotic, mixed-up IoT setups. It keeps an eye on energy coming in and what's left in the tank, shuffling traffic so no node gets wiped out [4], [11]. Forget centralized control – EHARA lets nodes work together like a team, dodging scalability headaches and those single-point breakdowns that mess up big networks [5], [7]. Plus, it's got some tricks to fight off energy-draining attacks [6-8], [3].

Conventional routing techniques mostly aim to lower energy consumption, but they often find difficulty when energy levels vary in energy-harvesting nodes. Apart from resource waste, this reduces the lifetime of the network and undermines data dependability [3], [9].

We present EHARA, a novel routing method meant to solve these problems by improving energy efficiency, network coverage, and data integrity protection in certain Internet of Things (IoT) contexts. EHARA guarantees best energy distribution over the network by using real-time energy collecting data [4, 16].

EHARA's distributed architecture provides higher robustness and fits for large-scale IoT applications than centralised solutions [5, 12]. Moreover, integrated security features that guard against energy-draining assaults [6-8] [14] help the network to be strong.

TABLE I. KEY BENEFITS OF ENERGY-EFFICIENT ROUTING IN IOT NETWORKS

Benefit	Description
Prolonged Network Lifetime	Optimized routing reduces energy use, supporting extended operation of IoT nodes [6-8].
Reduced Maintenance Costs	Energy-aware routing decreases the need for manual battery replacements, cutting maintenance expenses [6-8].
Sustainable and Eco-Friendly Operation	Using renewable energy sources lessens dependence on traditional power supplies [6-8].
Scalability and Reliability	Effective energy management supports large-scale deployments without network interruptions [6-8].
Enhanced Quality of Service (QoS)	A well-designed routing protocol balances energy efficiency with essential QoS factors like latency, throughput, and packet delivery ratio [6-8].

Energy harvesting offers a sustainable approach to powering IoT networks and diminishes dependence on batteries; however, it introduces a range of challenges, especially concerning routing and network optimisation. These challenges persist even in light of the sustainability advantages provided by energy harvesting for battery-operated IoT networks.

TABLE II.

Concept	Description
One-size-fits-all Routing	A uniform routing approach fails to effectively address the diverse conditions present throughout the network [9-10].
Overloaded Nodes	In the absence of adaptive mechanisms, specific nodes could experience excessive strain, resulting in early energy depletion and potentially triggering network fragmentation [9-10].
Energy Efficiency & QoS Balance	Routing needs to achieve a careful equilibrium between optimising energy efficiency and fulfilling Quality of Service (QoS) criteria, which include latency, packet delivery ratio, and throughput [9-10].
Security-aware Routing	In the absence of security-awareness in routing, there is a risk that malicious nodes could take advantage of energy-related metrics, which may lead to disruptions in the network's operations [9-10].
Fluctuations in Energy	Conventional energy-aware routing approaches do not adequately consider variations in energy levels, potentially resulting in network instability [9-10].

In this paper, we bring you the design principles, mathematical modeling, and performance evaluation of EHARA – a solution we've put together to sort out real-world headaches [11]. Through proper simulations, we show how it



beats the socks off existing energy-aware routing protocols, giving solid boosts to network lifetime, packet delivery ratio, and energy efficiency [6], [16]. Our work is all about helping build self-sustaining, energy-efficient, and secure IoT networks that folks can count on for all kinds of daily needs [1], [13].

Here's how the rest of the paper rolls out: Section 2 checks out what others have been up to in this field [2], [3]. In Section 3, we take you through our system model and spell out the problem we're cracking [4]. Section 4 lifts the lid on the EHARA algorithm and explains how it gets the job done [11]. Section 5 jumps into the simulations and spills what we found out [9], [12]. Finally, Section 6 ties it all up with our conclusions.

II. RELATED WORK

Lately, energy harvesting's been a hot ticket for making IoT networks last longer and lean greener, and plenty of folks have thrown their hats in the ring to figure out how to route data smarter in these setups. This section digs into eight standout efforts that have shaped the landscape of energy-harvesting-aware routing, giving us a benchmark to see where EHARA fits.

First up, Nguyen et al. [11] rolled out a routing scheme that keeps an eye on how much energy nodes can snag from their surroundings. Their simple but clever concept is to keep IoT wireless sensor networks (WSNs) running with smarter power plays using what you know about harvesting, hence extending the lifetime of networks. Then there is Saleh's team [12] with EHEARA, a variation on grouping based much on solar power confidence. By putting nodes together and utilising nearby energy, they hope to increase dependability and prevent the battery blues impacting IoT devices.

Zhang and colleagues [13] went further, devising a mathematical design of network infrastructure capable of coping with intermittent energy harvesting. On the subject of security, Mujeeb et al. [14] developed EHTARA, which combines trust validation with energy smarts in order to combat hazards in energy-assisted networks while simultaneously protecting the validity of information. They contend that the key to maintaining the viability of Internet of Things networks is sharp and flexible techniques.

Zhang's other team [15] went sci-fi with GAP, a multi-agent reinforcement learning task. Managing energy and multi-hop routing simultaneously maximises communication throughput without wasting gathered power across scattered IoT devices. Back to Nguyen's team [16], they pitched an earlier EHARA flavor with an "energy back-off" twist. This distributed setup leans on the messy mix of node harvesting quirks to boost performance without a central chokehold.

For the low-power crowd, Capuzzo et al. [17] zeroed in on LoRaWAN nodes that ditch batteries altogether. Their energy-aware packet schedulers tweak communication timing based on real harvest hauls, cranking up packet counts, and tightening send gaps for leaner, meaner IoT action. Lastly, T V and Prasad [18] brought the Zero Energy Network (ZEN) stack to the table—a full-on combo of an energy-savvy MAC layer, a tweaked AODVjr routing plan with harvest forecasts, and a clever app to pinch power pennies. They showed WSNs can stand on their own, fueled just by what they scrounge up.

Table 3 lays it all out side by side—how these approaches stack up on energy smarts, routing tricks, security chops, wins, and weak spots. It's a mixed bag, but it's clear there's no one-size-fits-all yet, setting the stage for our EHARA to strut its stuff.

TABLE III. COMPARISON OF ENERGY-HARVESTING-AWARE ROUTING ALGORITHMS.

Ref.	Approach	Energy Awareness	Routing Strategy	Security Considerations	Performance Improvements	Limitations
[11]	Energy-Harvesting-Aware Routing Algorithm (EHARA)	Yes	Distributed, Energy-Adaptive	Limited security focus	Improved network lifetime and scalability	Does not consider advanced security mechanisms
[12]	Energy Harvesting and Energy Aware Routing Algorithm (EHEARA)	Yes	Clustering-based	No security mechanisms	Enhances energy efficiency using solar harvesting	High dependency on environmental conditions
[13]	Intelligent Networking for EH-Powered IoT	Yes	AI-based Adaptive Routing	No security focus	Dynamic adaptation to energy variations	Computationally expensive for small IoT nodes
[14]	Trust and Energy Aware Routing Algorithm (EHTARA)	Yes	Distributed, Trust-Based	Yes, integrates trust management	Secure and energy-efficient routing	May introduce overhead due to trust management
[15]	Multi-Agent Reinforcement Learning for EH Routing	Yes	Multi-Hop, Learning-Based	No security considerations	Maximizes data transmission and energy allocation	Requires extensive training data
[16]	Distributed EH-Aware Routing for Heterogeneous IoT	Yes	Energy Back-Off Mechanism	No explicit security model	Reduces energy depletion in nodes	High computational complexity
[17]	Energy-Aware Packet Scheduling for LoRaWAN	Yes	Packet Scheduling	No security focus	Reduces transmission delays and optimizes packets per energy unit	Limited to LPWAN scenarios
[18]	Zero Energy Network (ZEN) Stack	Yes	Cross-Layer Optimization	Basic security integration	Ensures long-term sustainability of EH-WSNs	Limited adaptability to heterogeneous networks

III. SYSTEM MODEL AND PROBLEM FORMULATION

Energy harvesting at each IoT node depends on environmental conditions and is modeled as follows: The energy harvested at node i during time slot t is given by:

$$H_i(t) = \eta_i \times P_{source}(t) \times dt \quad (1)$$

where:

- $H_i(t)$ is the harvested energy at node i during time t .
- η_i is the energy conversion efficiency of the harvesting module at node i .
- dt - measures the duration of the energy harvesting process.
- $P_{source}(t)$ represents the power available from the energy source.

The total energy consumption at node i is modeled as:

$$C_i(t) = W_{tx} \times T_{tx} + W_{rx} \times T_{rx} + W_{comp} \times T_{comp} \quad (2)$$

where:

- T_{comp} is the time spent on data processing.
- W_{comp} represents power consumption for computation.
- W_{rx} and W_{tx} are the reception and transmission power, respectively.
- T_{rx} and T_{tx} denote the reception and transmission times.

For sustainable network operation, the energy neutrality constraint must be satisfied:

$$Energy_i(t+1) = \min(Energy_i(t) + H_i(t) - C_i(t), Energy_{max}) \quad (3)$$

where $Energy_{max}$ signifies maximum energy storage capacity of node i .

Several performance measures are considered in order to assess EHARA's efficacy:

- Network Lifetime: The duration until the initial node exhausts its energy is defined as:

$$T_{lifetime} = \min \{ t \mid E_i(t) = 0 \} \quad (4)$$

- Energy Consumption per Packet: The average energy consumed per successfully delivered packet is:

$$E_{avg} = \frac{\sum C_i}{N_{delivered}} \quad (5)$$

- Packet Delivery Ratio (PDR): The proportion of successfully received packets to the total number of transmitted packets.

$$PDR = \frac{N_{received}}{N_{sent}} \times 100\% \quad (6)$$

- The average time a packet spends moving from source to destination is known as end-to-end delay.

$$DE_{end} = \frac{\sum T_{arrival} - T_{sent}}{N_{delivered}} \quad (7)$$

- Throughput: The rate at which data is successfully conveyed is being referred to as throughput.

$$Throughput = \frac{\sum S_j}{T_{total}} \quad (8)$$

IV. PROPOSED EHARA ALGORITHM

EHARA weaves energy harvesting into its route-picking process, aiming to find the best paths while keeping energy use in check. It's built to handle growth across all kinds of IoT networks, boost energy savings, and keep things running longer. [11][16].

TABLE IV. KEY FEATURES OF EHARA: MAKING IOT NETWORKS SMARTER AND STRONGER

Aspect	Description
Overview	EHARA can manage growth in any type of IoT environment, increase energy savings, and prolong the life of networks. It carefully selects optimal routes while ensuring uniform distribution of energy by considering energy harvesting. [11][16]
Energy Awareness	EHARA focuses on nodes that have more leftover energy and better energy harvesting potential to keep things running smoothly. [1][12]
Distributed Routing	By steering clear of centralized control, EHARA makes the network more scalable and resilient to failures. [4][7]
Adaptive Path Selection	Routes shift on the fly based on current energy levels and network conditions, adapting to what's happening moment by moment. [4][11]
Load Balancing	EHARA spreads traffic smartly to avoid draining certain nodes too quickly, keeping the network healthier for longer. [6][9]
Security Considerations	It includes basic security measures to guard against attacks that could sap energy, adding a layer of protection. [3][14]

EHARA's routing technique comprises two fundamental phases: node selection and optimal path identification. It emphasises energy saving while concurrently maintaining seamless network operation. EHARA evaluates the subsequent parameters while choosing forwarding nodes:

TABLE V.

Concept	Description
Residual Energy (E_r)	Nodes with more energy in the tank are given the green light, as weaker nodes can slow down the network [1], [12].
Energy Harvesting Rate (H_r)	Nodes with high energy harvesting rates are prioritized as the group's overachievers [11], [18].
Link Stability (L_s)	It picks links that won't drop packets left, right, and centre – reliable connections are the name of the game [9].
Traffic Load (T_l)	Nodes that aren't already overloaded with traffic get chosen, so the network stays balanced and doesn't choke [6], [7].

EHARA also offers several ingenious energy-saving techniques to help to make routing decisions even more ideal:

TABLE VI.

Concept	Description
Dynamic Power Allocation	Nodes adjust their transmission power based on energy availability, prolonging their lifespan like a good budget [8], [11].
Duty with Energy Awareness Cycling	Nodes with low energy take rest periods to conserve power, similar to us relaxing after a long day [6], [10].
Harvested Energy Prediction	Nodes predict how much energy they will harvest in the future, like a farmer checking the weather [13], [15].
Load Balancing	Traffic is evenly distributed among nodes, ensuring no single node gets overwhelmed and uses energy efficiently [6], [9].

V. SIMULATION AND PERFORMANCE EVALUATION

The simulation setup and parameters are detailed in Table 7.

TABLE VII. SIMULATION PARAMETERS.

Parameter	Value
Network Area	$100 \times 100 m^2$
Number of Nodes	100
Initial Energy per Node	1 J
Packet Size	512 bytes
Transmission Power	0.1 W
Reception Power	0.05 W
Energy Harvesting Rate	0.01 J/s
Simulation Time	1000 s

The nodes are deployed randomly in a fixed area, and each node is capable of energy harvesting with a predefined rate. The traffic model assumes constant bit rate (CBR) packet transmission with an interval of 1 second. The performance of EHARA is compared with traditional routing protocols such as Low-Energy Adaptive Clustering Hierarchy (LEACH) and Energy-Aware Routing (EAR).

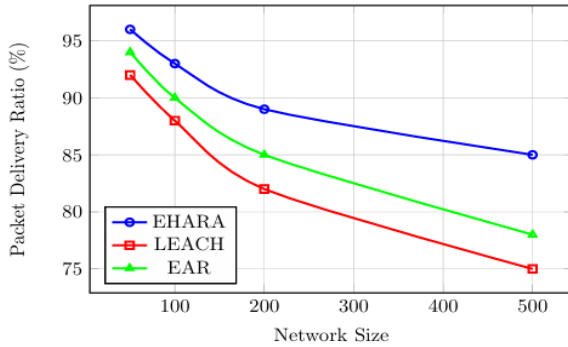


Fig. 1. Packet delivery ratio vs. network size.

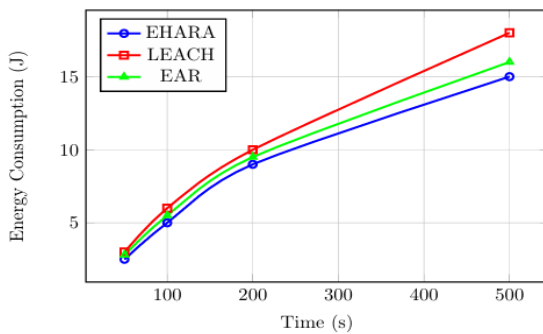


Fig. 2. Energy consumption over time.

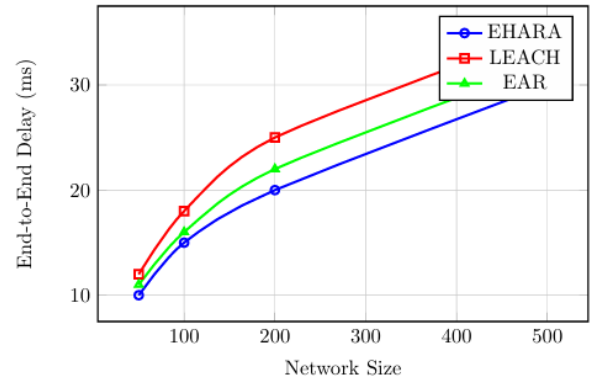


Fig. 3. End-to-end delay vs. network size.

From the results (Figures 1-3) it is observed that

- EHARA maintains a higher PDR compared to LEACH and EAR, especially in larger networks, due to its adaptive energy-aware routing.
- EHARA exhibits lower energy consumption over time, which helps prolong the network lifetime by optimizing energy utilization.
- As network size increases, EHARA ensures lower end-to-end delay, while LEACH and EAR suffer from increased latency due to inefficient routing decisions.
- Separating the decision-making process from the transmission process in EHARA enables adaptive path selection, which improves balance energy loading on nodes, hence limit energy consumption and maintain network functionality.
- In general, EHARA does much better than LEACH and EAR in the important performance evaluations, which substantiate why it should be regarded as a better routing protocol designed for energy harvesting IoT networks.

VI. CONCLUSION AND FUTURE DIRECTIONS

We've made a great IoT network solution called EHARA. It uses less energy and lasts longer because it smartly changes route decisions based on how much energy nodes are pulling in and how much they still have left in their reserves. When it comes to things like packet delivery rate, energy use, and end-to-end delay, EHARA is much better than LEACH and EAR.

It's just a better choice for IoT setups that use energy that has been collected. Nodes don't give up too soon because the program does a good job of balancing their energy. This keeps the network going strong. It also picks the fastest lines to avoid traffic and cut down on wait times, ensuring that data always gets through.

In general, EHARA is a good, scalable routing option for eco-friendly IoT apps that keeps networks running smoothly and extends their life. We will be making small changes to EHARA to make it work better in more difficult IoT situations, such as networks with moving nodes and different types of energy sources.

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